Search for new cosmic-ray acceleration sites within the Galactic plane 4FGL sources

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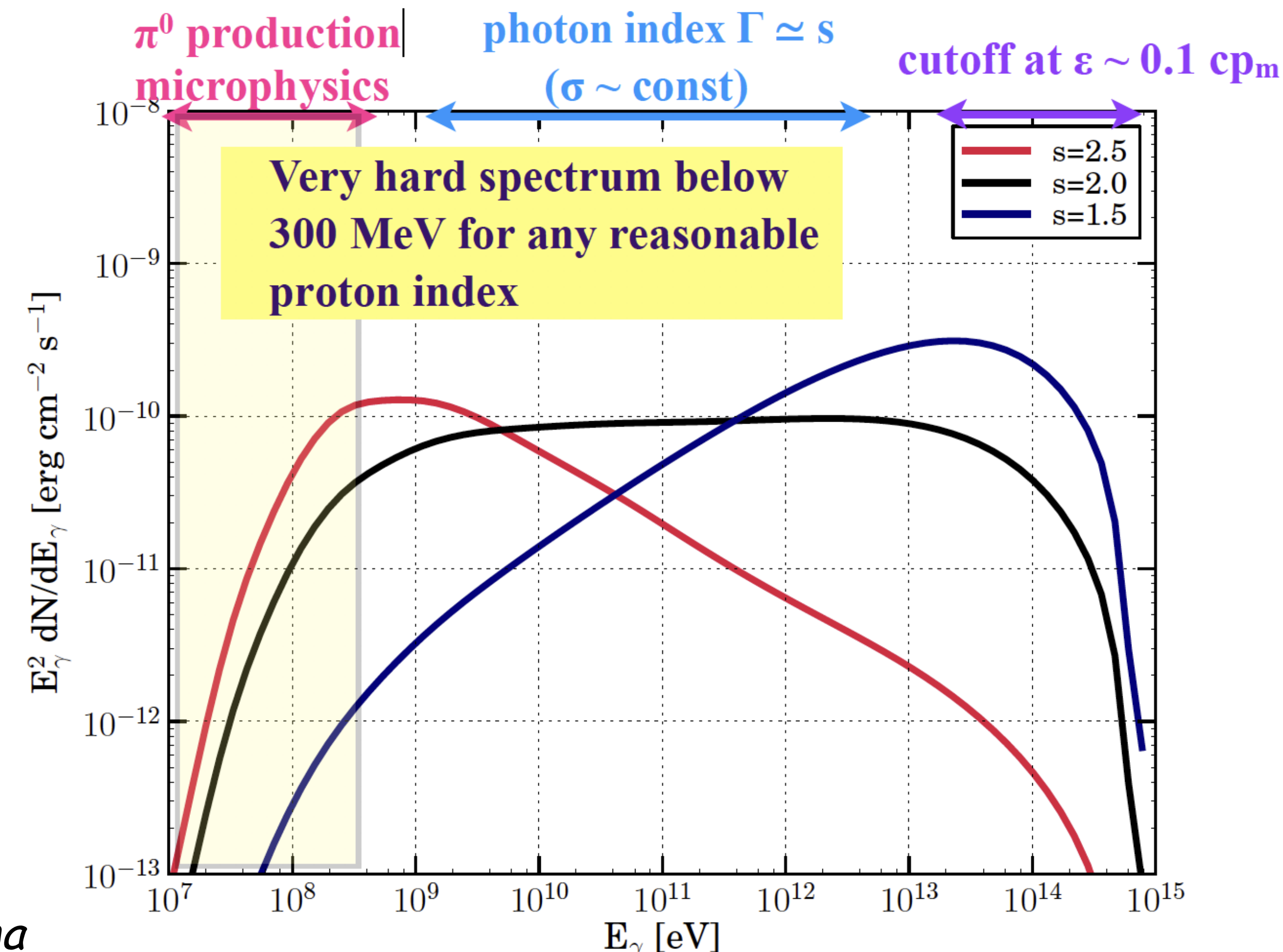
π^0-decay gamma-rays: probe of accelerated protons

γ-ray spectral shape is determined solely by dN/dp (proton spectrum)

$dN/dp \propto p^{-s} \exp(-p/p_m)$ s=1.5, 2.0, 2.5, cp_m = 1 PeV … $dN_\gamma/d\varepsilon$

$dN_\gamma/d\varepsilon$: symmetric about 68 MeV

$\varepsilon^2 \, dN_\gamma/d\varepsilon$: hard spectrum below 300 MeV



Credit : Y. Uchiyama

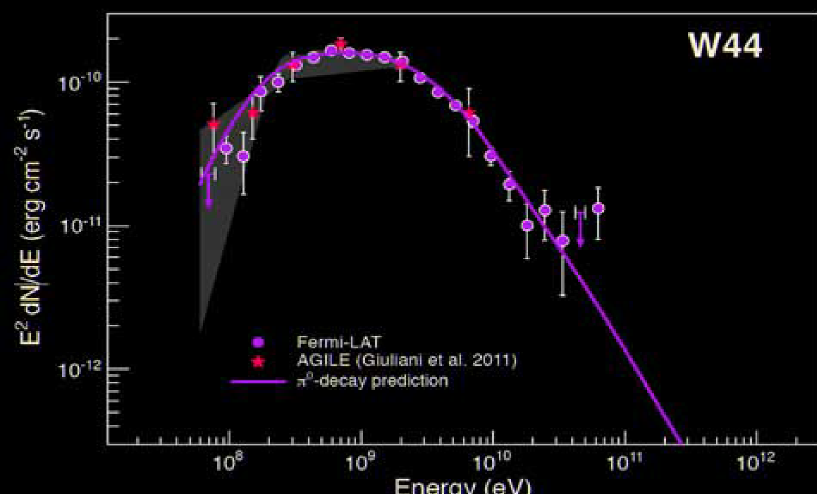
NASA press release (Feb 2013) : CR protons in SNRs

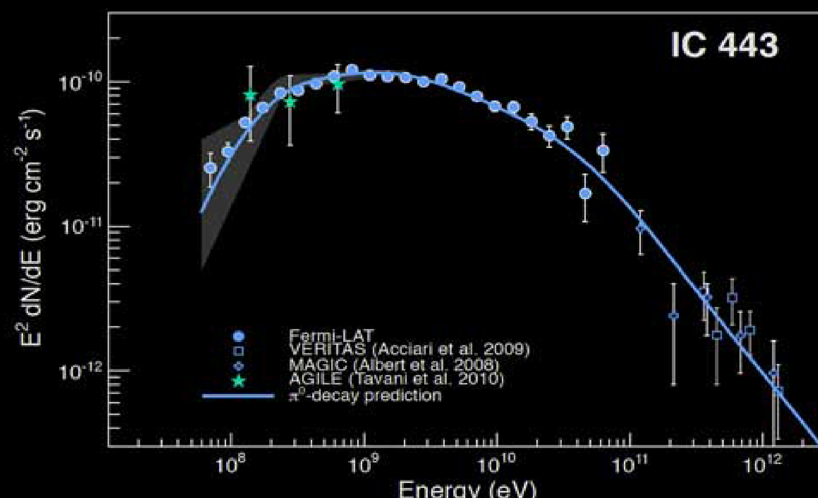
« NASA's Fermi Proves Supernova Remnants Produce Cosmic Rays »

Supernova W44 & IC 443 Neutral Pion Decay Spectral Fit

Image data from ESA Herschel and XMM-Newton

Image data from Chandra X-ray





Looking for low-energy spectral breaks

Aim:

- Search for low energy spectral break among Galactic 4FGL sources
- 4FGL sources tested: Significance (300 MeV – 1 GeV) > 3σ between [-5°, 5°] in latitude => 311 candidates
- Use the 4FGL catalog and the associated diffuse backgrounds released

Why ?

1- 4FGL spectra are performed between 50 MeV and 1 TeV => they are dominated by photons close to the pivot energy (~1 GeV) and could miss spectral breaks

2- Even if a curvature is detected, the 4FGL catalog only provides the fit with a LogParabola (or a super exponential cut-off)

3- Low energy spectral breaks are expected for proton-proton interaction which can help constrain the nature of UNID 4FGL sources

Data analysis

Data selection:

- Pass 8 data between 50 MeV and 1 GeV in a 20x20° binned analysis
- PSF3 & PSF2 source events
- Zmax = 80°
- Files produced for the 4FGL catalog for 3 components: PSF3 (50 – 100 MeV, 3 energy bins), PSF3 (100 MeV - 1 GeV, 9 energy bins), PSF2 (100 MeV – 1 GeV, 9 energy bins)
- edisp_bins = - 3
- IRF : P8R3_SOURCE_V3 with associated galactic and isotropic diffuses
- gtlike summed analysis with 0.2° bin size with fermipy

Iterative procedure in a few words:

- Optimize the ROI (x2)
- Look for additional sources with TS > 16 and re-optimize ROI
- Test for a PL and a LogP
- If $\Delta TS_{LogP-PL} > 9$, test for a SBPL and a SBPL with Index2 fixed at 2

If TS > 25

=> Select candidates with $\Delta TS_{SBPL-PL} > 12$ and $\Delta TS_{SBPL2-PL} > 9$ (equivalent to a 3σ threshold)

Many different checks

Systematics :

- Test all sources with $\Delta TS_{SBPL-PL}$ > 12 or $\Delta TS_{SBPL2-PL}$ > 9 with the « old » diffuse model rescaled for Pass 8 source analysis gll_iem_v06.fits => redo the whole pipeline

- Test all sources with $\Delta TS_{SBPL-PL}$ > 12 or $\Delta TS_{SBPL2-PL}$ > 9 with the bracket IRFs associated with the effective area (symmetrically bracket the standard effective area and flip from one extreme to the other at the measured value of the break energy) => start from the optimized ROI

=> We only keep the candidates that also show $\Delta TS_{SBPL-PL}$ > 12 or $\Delta TS_{SBPL2-PL}$ > 9 with both checks

Tests with simulations :

The goal was to test the effect of the number of bins as well as the edisp_bins on the results using 200 simulations of IC443

These simulations help to decide on the final configuration used : edisp_bins=-3 and 12 energy bins

The famous pion-bump of IC 443

Middle-aged SNR with characteristic pion bump signature (Ackermann et al. 2013)

Very significant break detected with our pipeline :

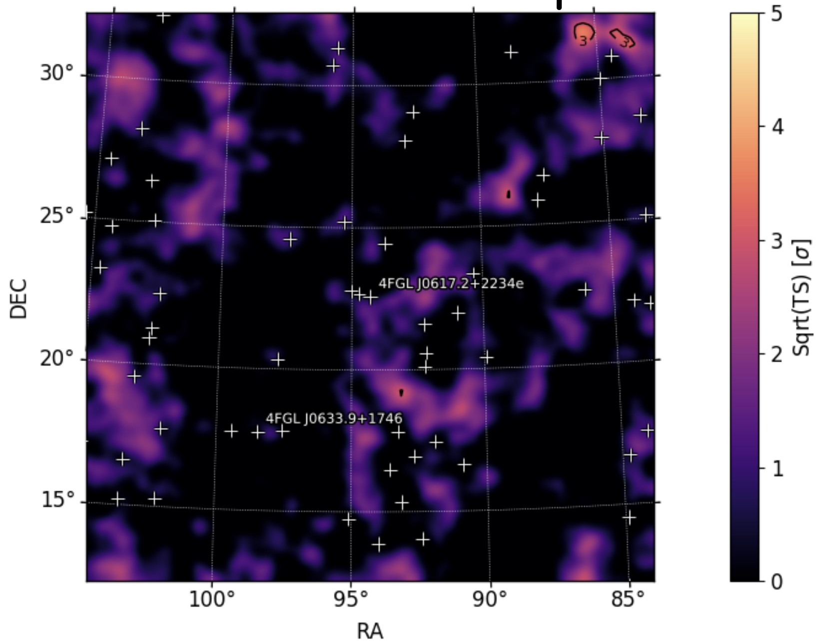
$\Delta TS_{LogP\text{-}PL} = 93$; $\Delta TS_{SBPL\text{-}PL} = 99$; $\Delta TS_{SBPL2\text{-}PL} = 80$

$E_{break} = 276 \pm 19 \pm 3$ MeV

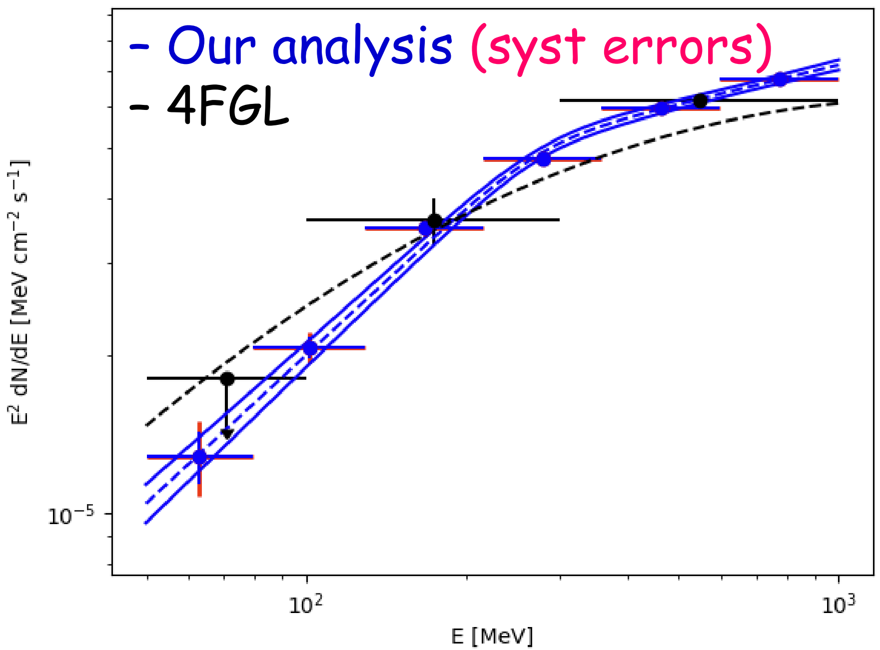
$\Gamma_1 = 1.06 \pm 0.05 \pm 0.03$; $\Gamma_2 = 1.75 \pm 0.03 \pm 0.03$

(Credit: Chandra X-ray: NASA/CXC/B.Gaensler et al; ROSAT X-ray: NASA/ROSAT/Asaoka & Aschenbach; Radio Wide: NRC/DRAO/D.Leahy; Optical: DSS)

Residual TS map



Spectral Energy Distribution



A binary system : Eta Carinae

System composed by a Luminous Blue Variable (LBV)

O- or B-type companion star

Orbital period of ~5.5 years

Collision region of the stellar winds => efficient particle acceleration

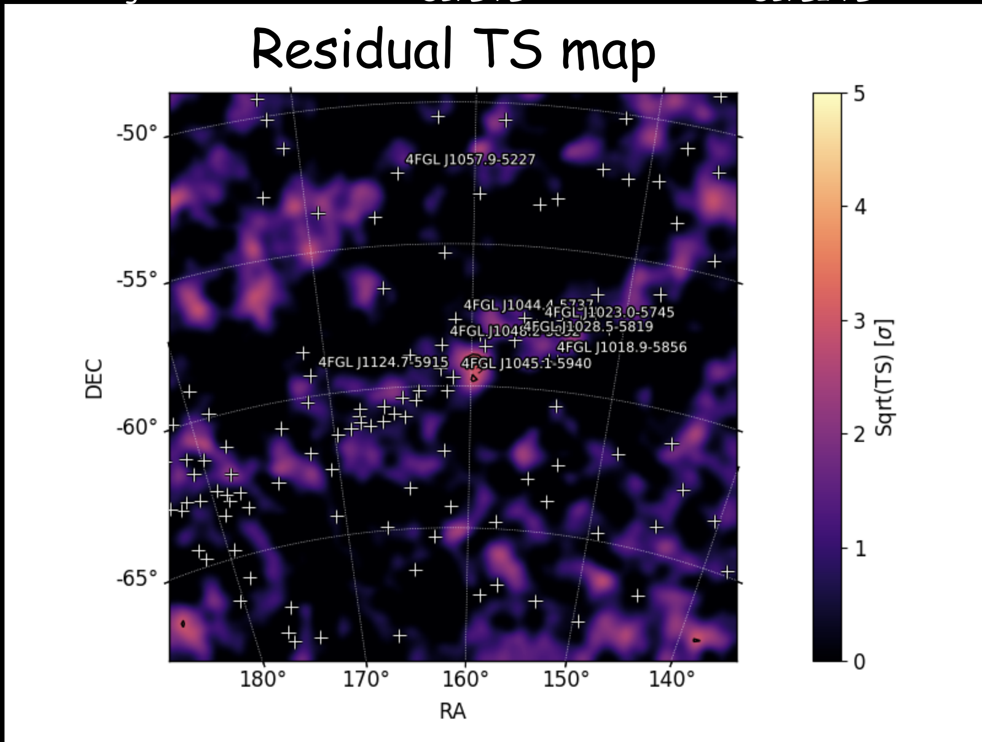
Detected in X-rays, HE gamma-rays with Fermi and TeV with H.E.S.S.

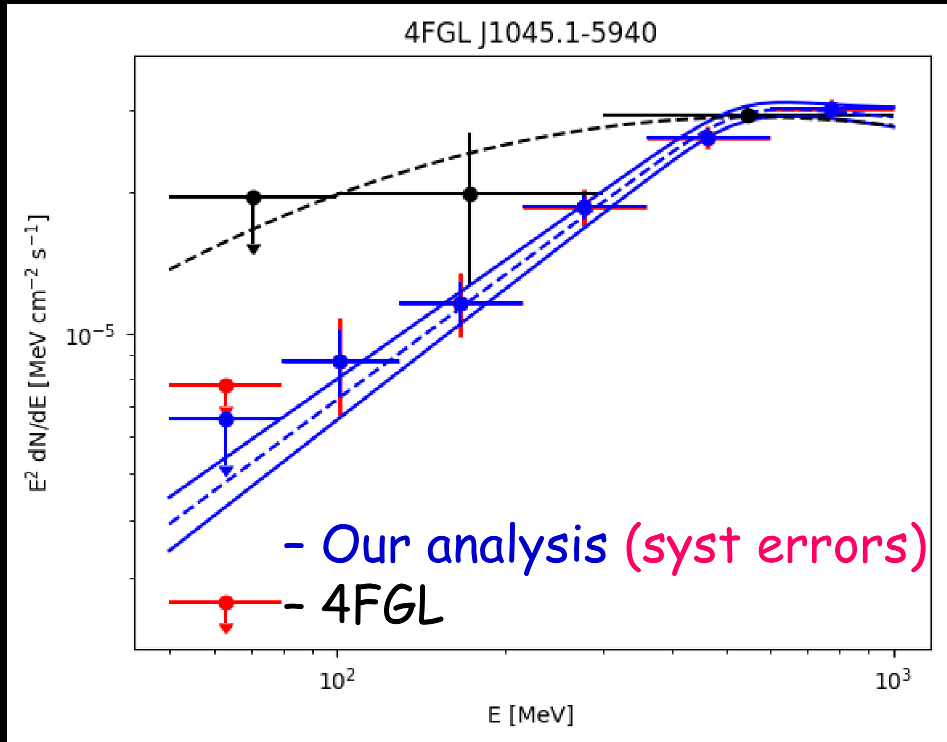
Humphreys & Martin 2012 ; Reitberger et al. 2015 / Balbo & Walter 2017 ; Abdalla et al., 2020

Credit: Nathan Smith (University of California, Berkeley), and NASA

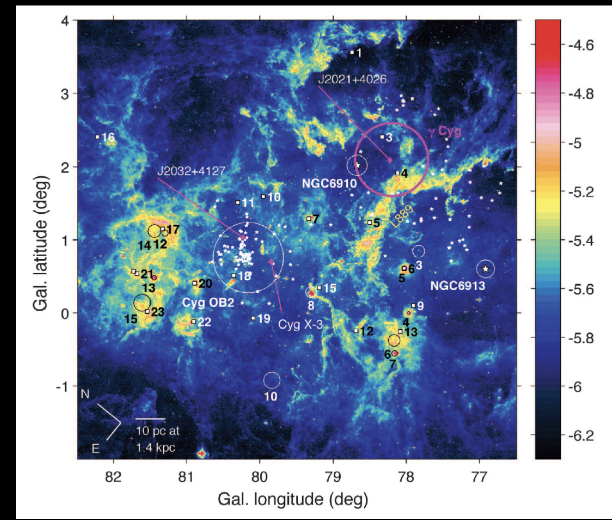
Significant spectral break detected with our pipeline :

$\Delta TS_{LogP\text{-}PL}$ = 16; $\Delta TS_{SBPL\text{-}PL}$ = 19; $\Delta TS_{SBPL2\text{-}PL}$ = 17





A star forming region : Cygnus



Region located in the Local Arm of the Galaxy at ~1.4 kpc

LAT discovery of a 50-pc wide cocoon of freshly-accelerated CRs

Ackermann et al. 2011

VHE detection of a counterpart HAWC J2030+409

Abeysekara et al. 2021

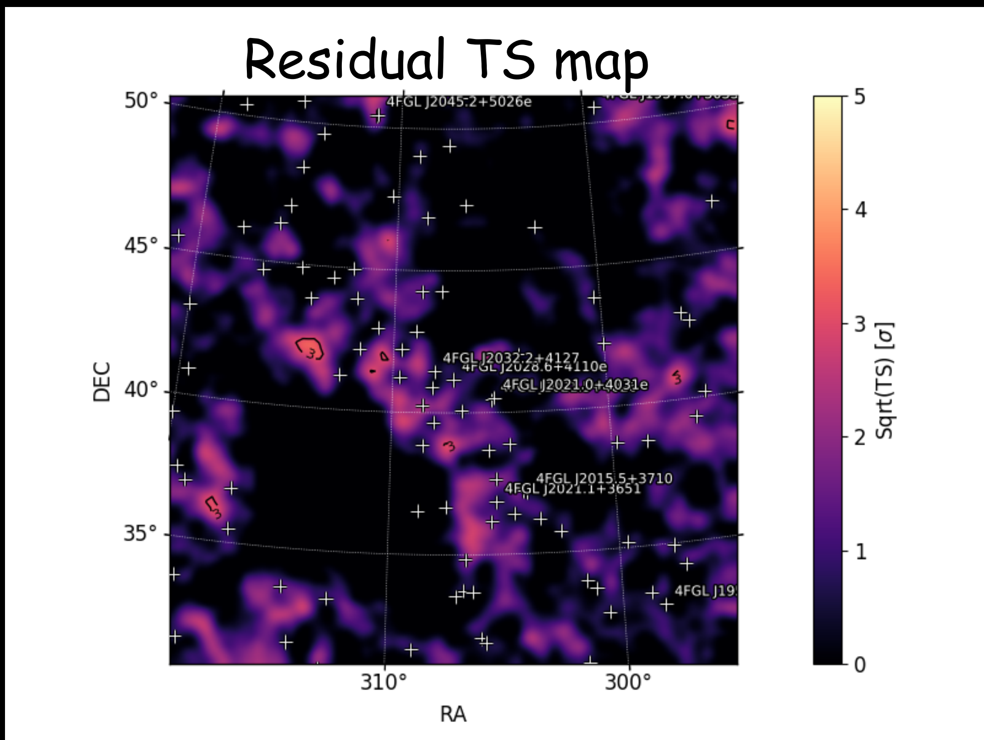
LAT+HAWC emissions likely due to hadronic interactions

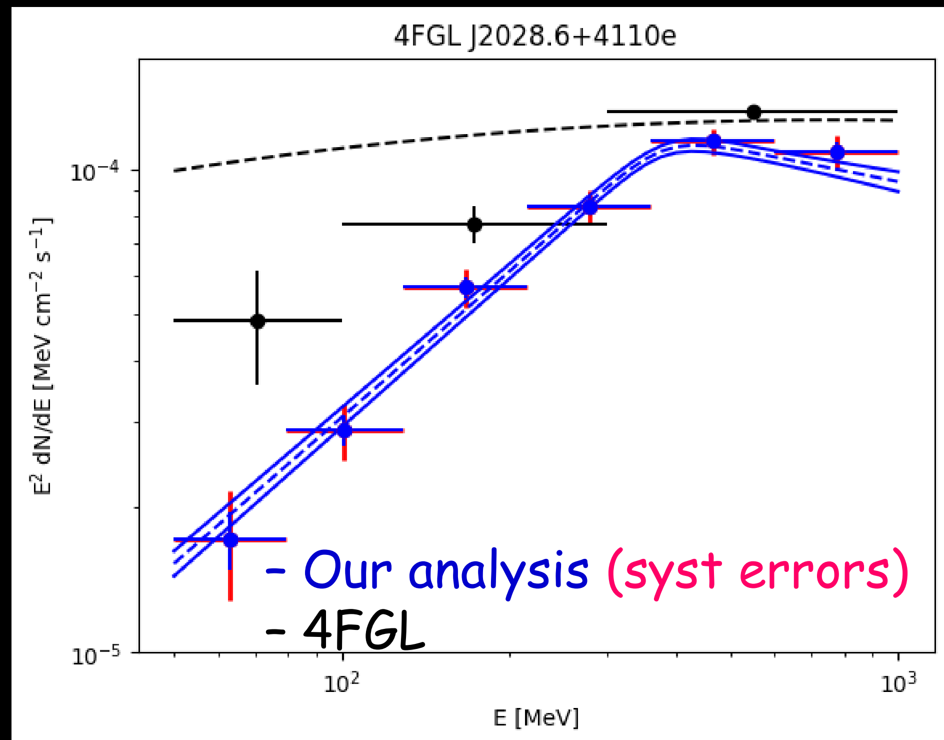
Coincident with LHAASO J2032+4102 with E_{max} = 1.42 ± 0.13 PeV

Zhen Cao et al. 2021

Significant spectral break detected with our pipeline :

$\Delta TS_{LogP-PL}$ = 120; $\Delta TS_{SBPL-PL}$ = 106; $\Delta TS_{SBPL2-PL}$ = 99





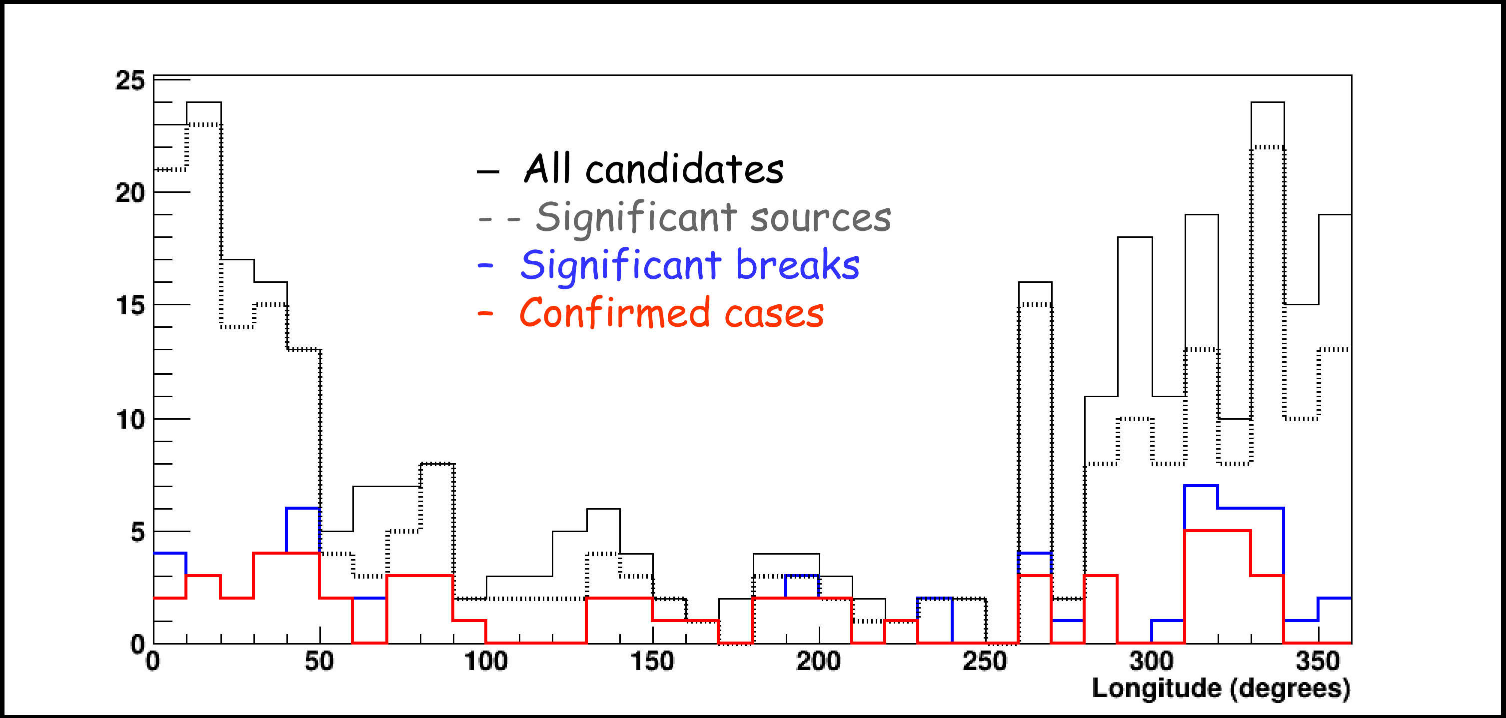
Results

Analysis carried on 311 candidates

77 sources have $\Delta TS_{SBPL-PL} > 12$ or $\Delta TS_{SBPL2-PL} > 9$

56 sources are confirmed by our systematics study

Sources showing breaks are distributed uniformly in Galactic longitude



Population study

Among these 56 candidates :

10 sources are firm SNR identifications

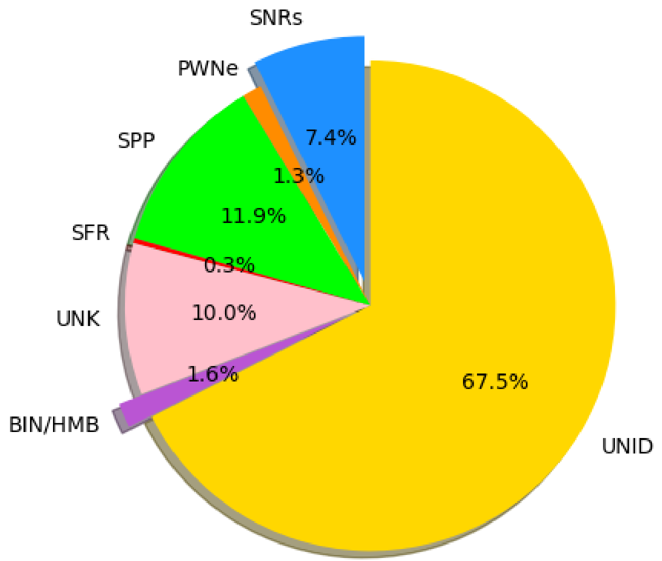
3 are associated with SNRs

6 are SPP (SNRs or PWNe candidates)

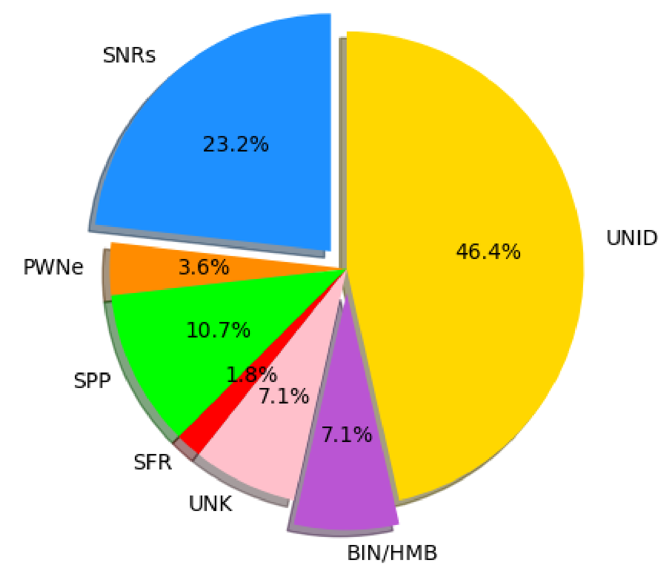
This makes SNRs the dominant class of sources showing spectral breaks in this analysis

Despite their small fractions, binaries also seem to contribute significantly

Population class of the 311 sources analyzed



Population class of the 56 candidates detected



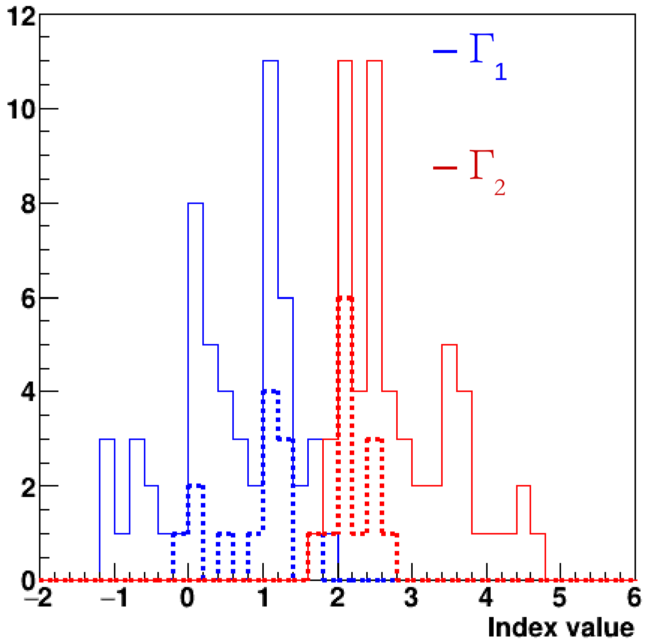
Spectral Results of the confirmed cases

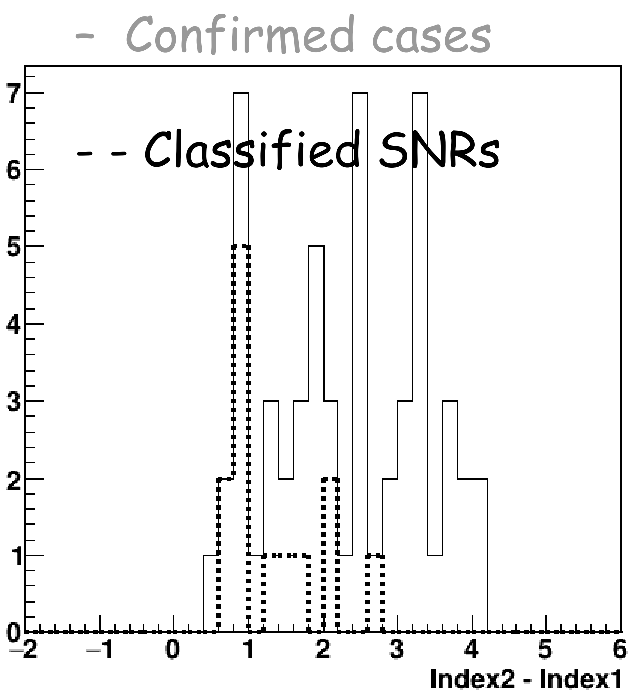
Double-peaked distribution for Γ_1 and Γ_2

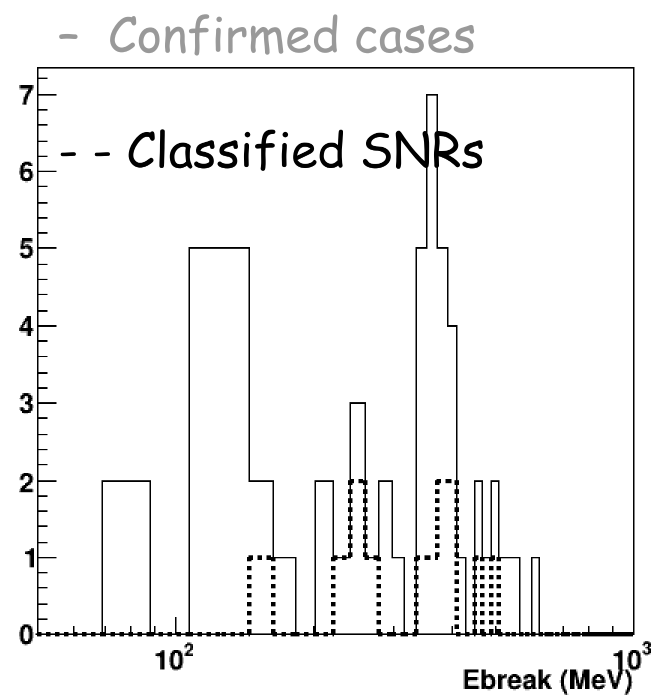
Distribution of Γ_2 restricted to classified SNRs contains a single peak at ~2.1

Distribution of $\Gamma_2 - \Gamma_1$: a peak at ~1 is highly pronounced for identified SNRs, with an additional small peak at~2

Relatively uniform distribution of break energy between 80 MeV and 600 MeV







Conclusions

311 sources analyzed between 50 MeV and 1 GeV

77 sources show a significant break using the Galactic diffuse and the IRFs released by the LAT collaboration

56 sources are confirmed by our systematic studies (IRFs + Diffuse)

SNR is the dominant class of identified sources in this analysis

Binaries could also play a significant role

Need to confirm them all by looking at the density of the surrounding environment