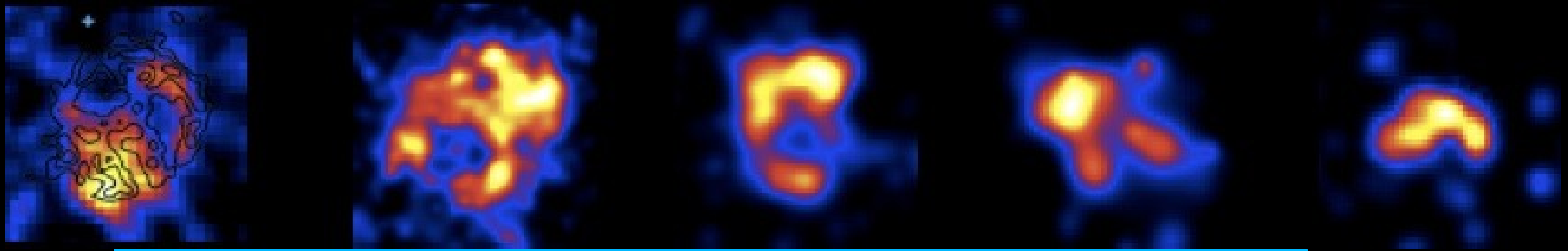
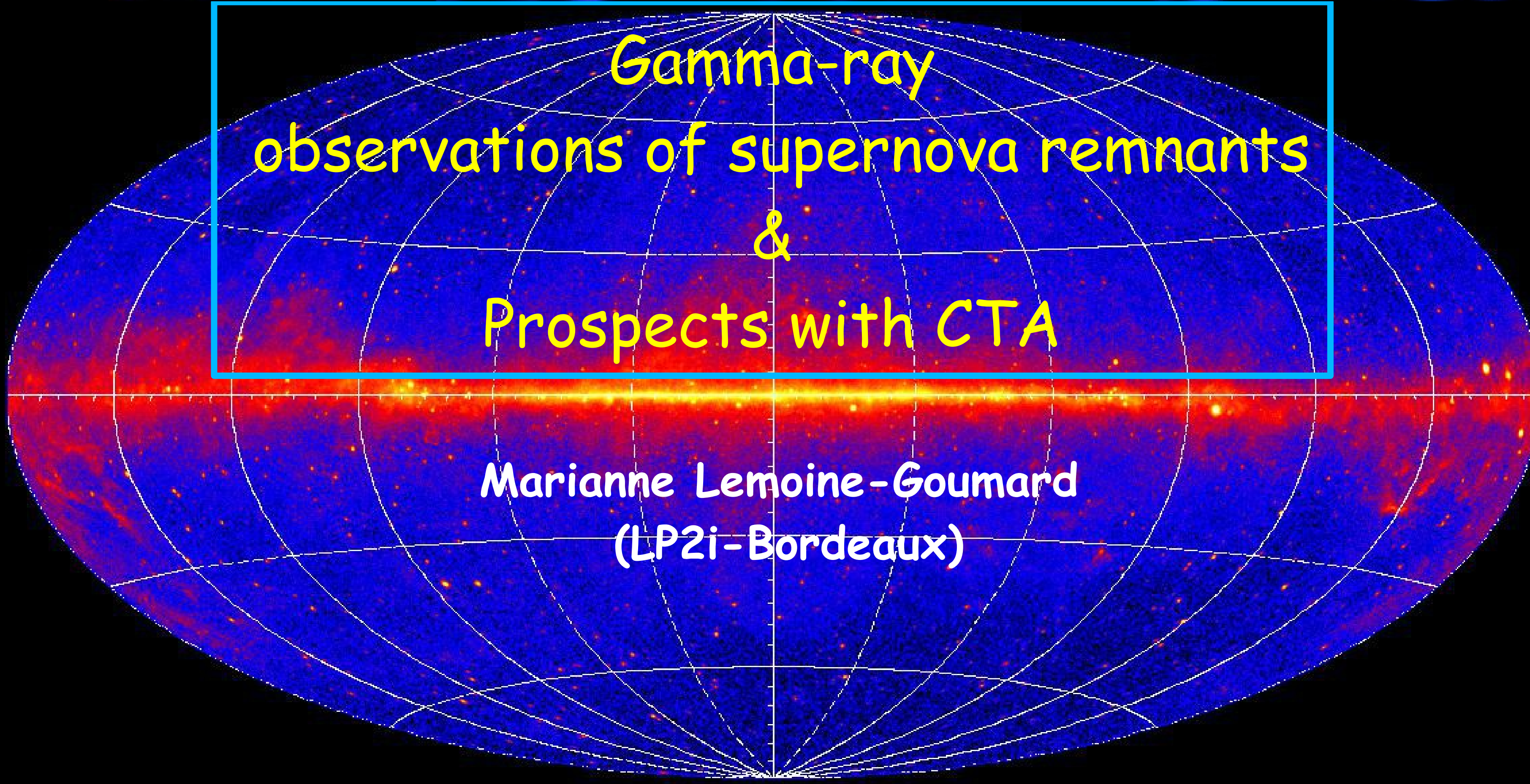
GeV
Fermi

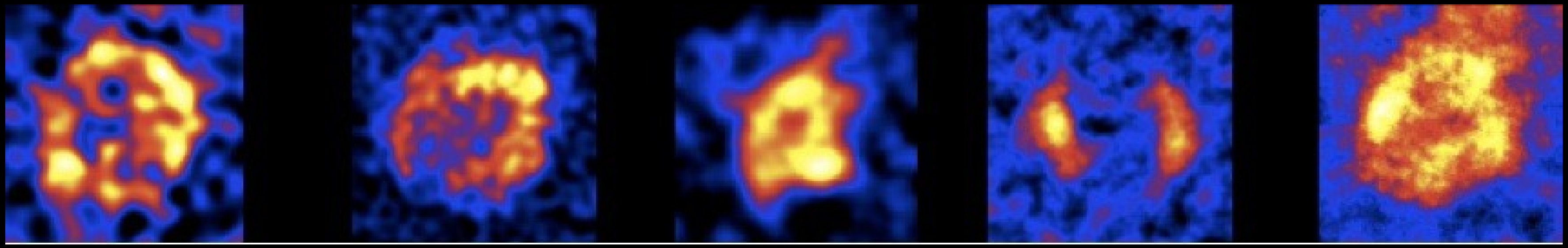




Gamma-ray observations of supernova remnants & Prospects with CTA

Marianne Lemoine-Goumard
(LP2i-Bordeaux)

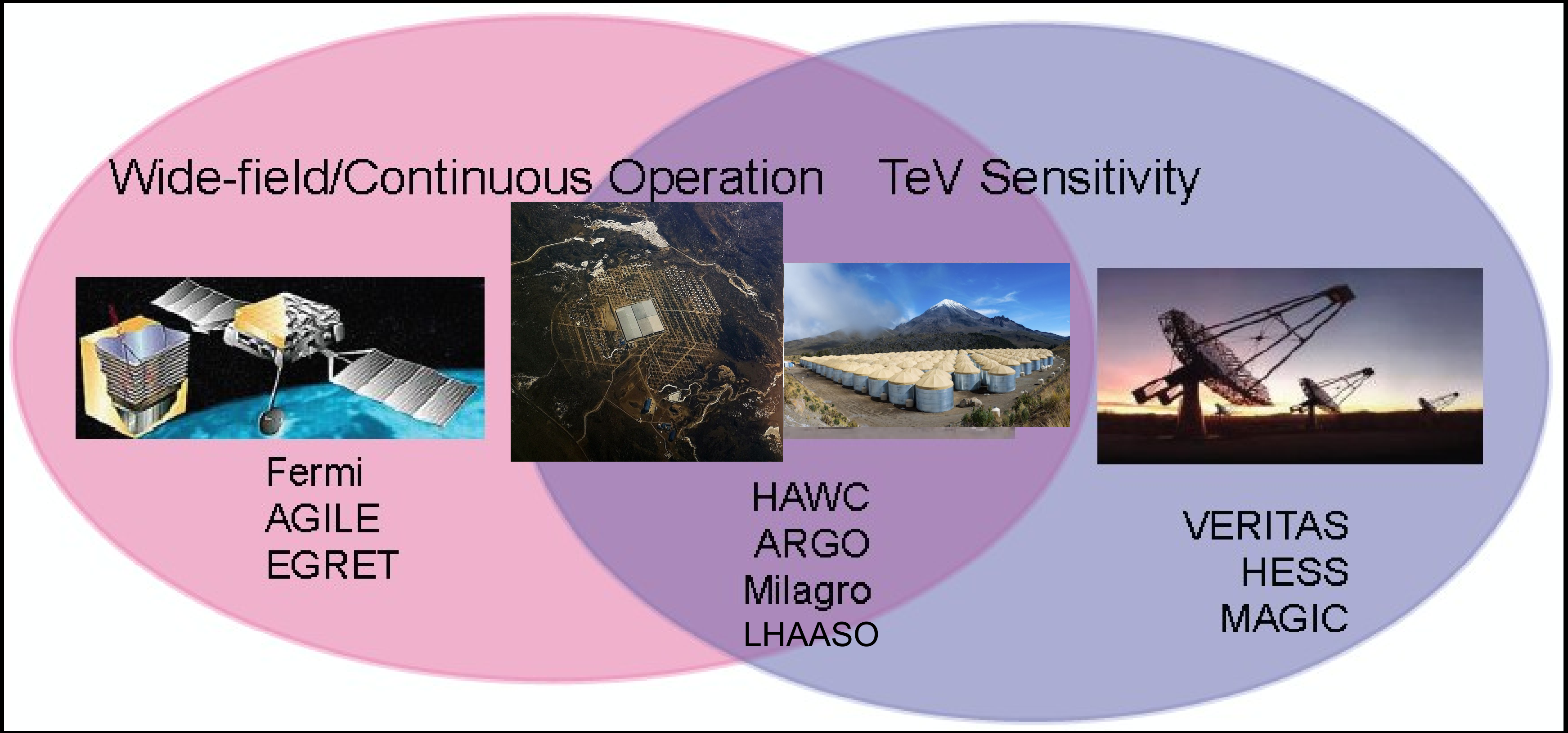
TeV
HESS



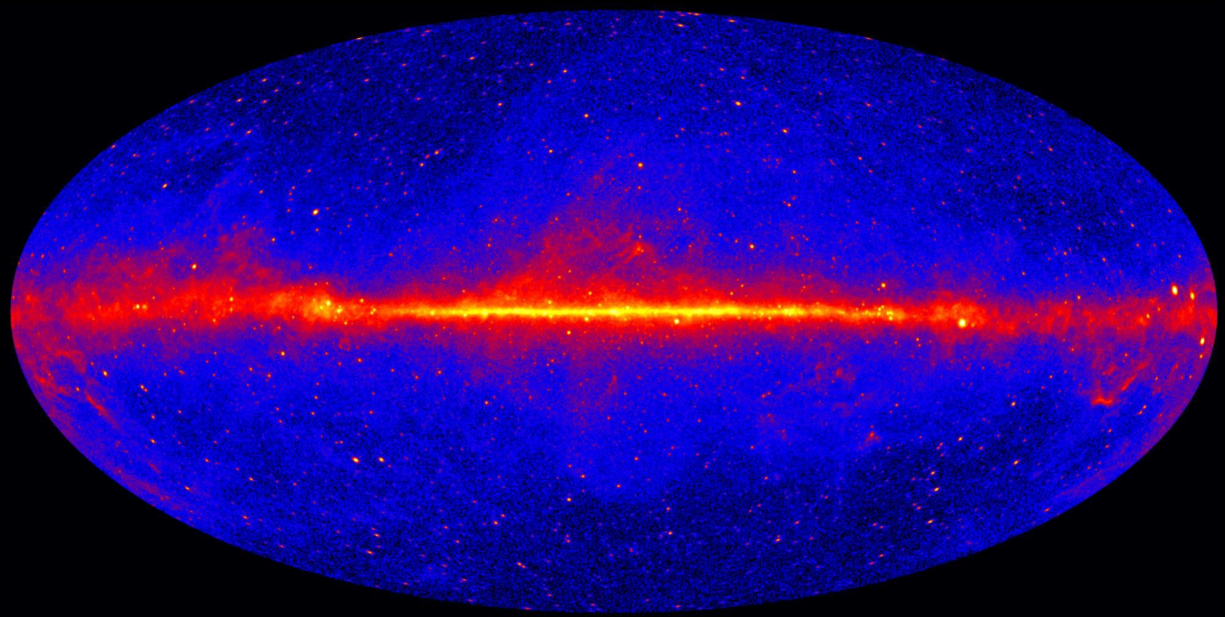
Complementarity of gamma-ray instruments

- Space-based detectors - continuous full-sky coverage in GeV

- Ground-based detectors have TeV sensitivity
  - Current Imaging Atmospheric Cherenkov Telescopes (IACTs) have excellent energy and angle resolutions, but FoV of 0.003 sr and duty cycle of 10%
  - Particle detectors have an aperture > 2 sr and duty cycle of 90% but angular resolution of ~0.6° (@ 1 TeV)



The 4FGL-DR4 catalog



arXiv:2307.12546

7194 sources detected in 14 years (546 more than DR3)
34% are unassociated
Largest source population : AGNs with 1490 BL Lacs, 1624 Blazar candidates, 820 FSRQs
320 Pulsars
191 SNR & PWNe
82 extended sources (75 extended sources in 4FGL and DR2 : 6 modified, 3 new, 1 point => extended, 3 around pulsars)

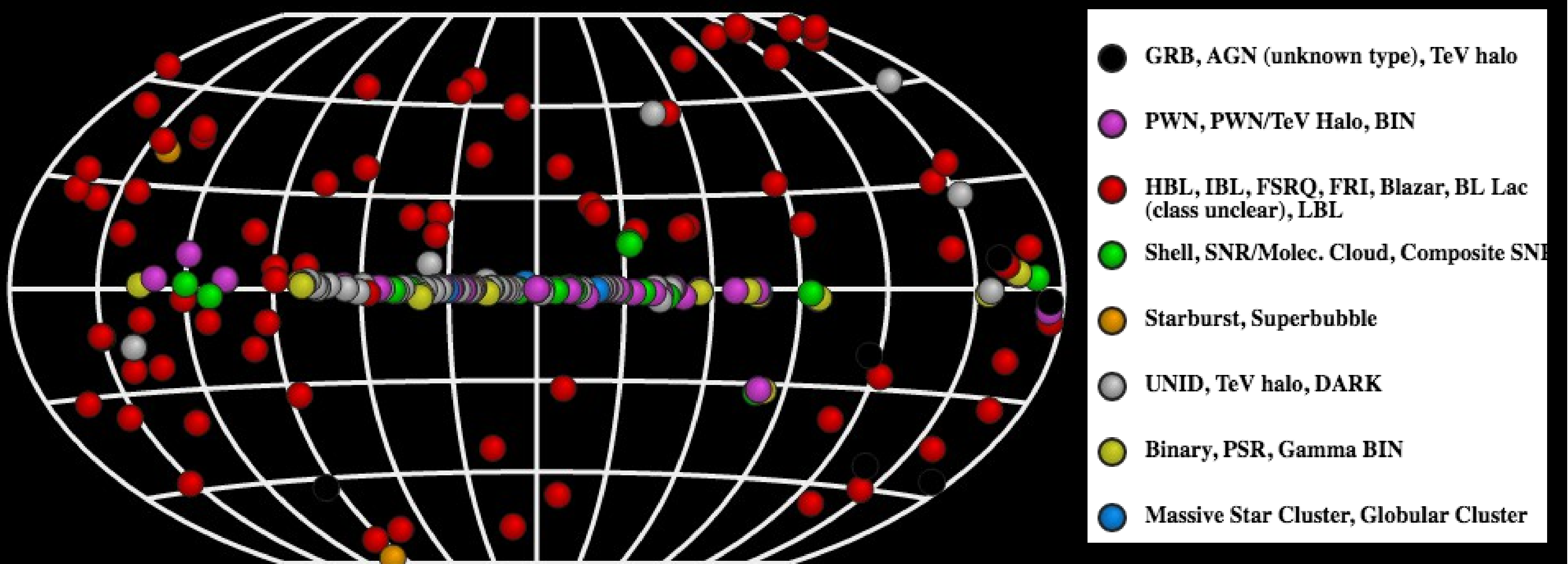
The TeV sky

> 270 sources detected as of mid-2023

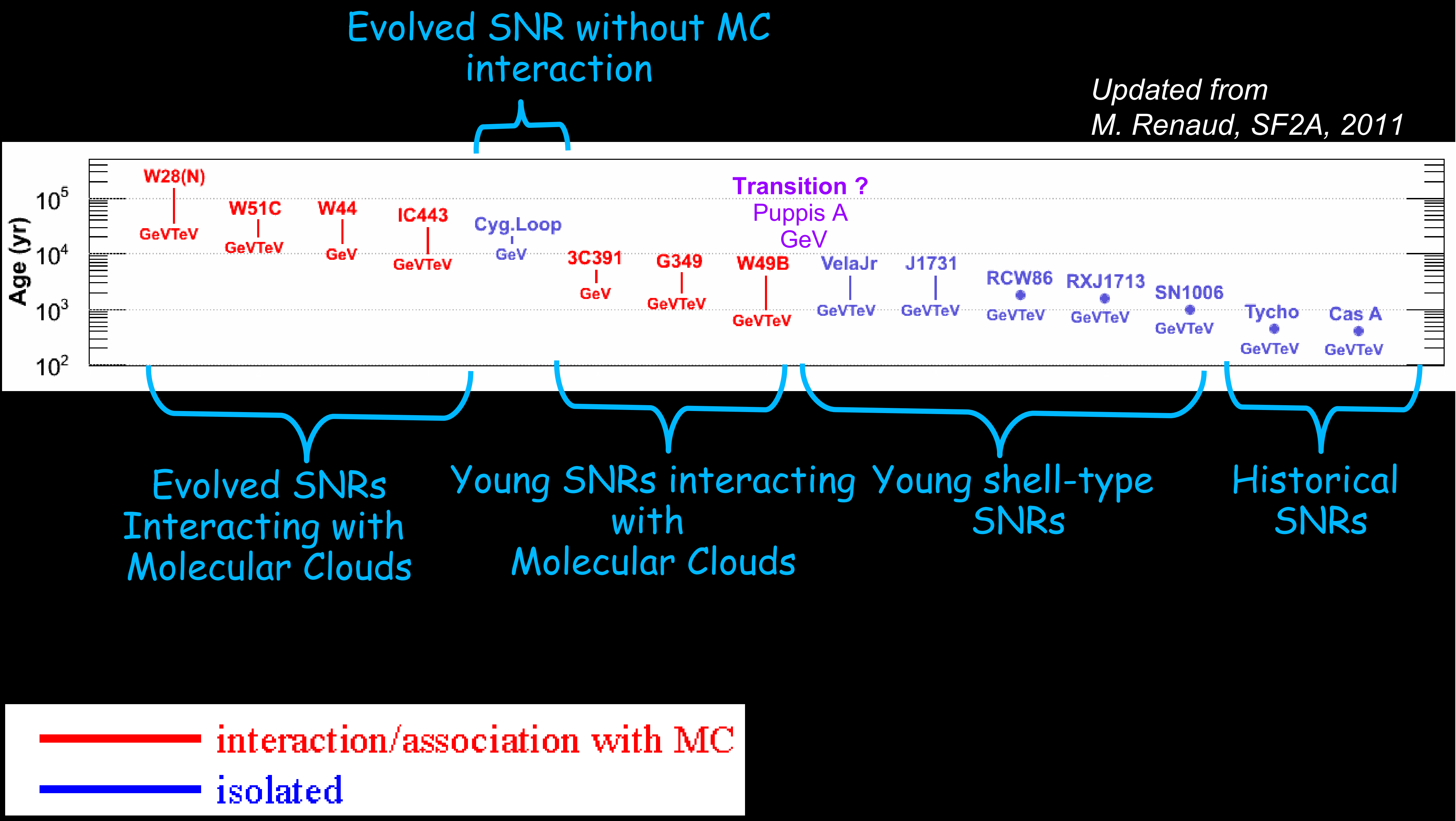
29 being coincident with SNRs (or SNRs interacting with Molecular clouds)

34 TeV sources coincident with PWNe

96 UNIDs : 35% (as for Fermi DR4) !



A large sample of SNRs detected in gamma-rays



Kepler SNR : so hard to catch at GeV/TeV energies !

- Upper-limits reported in LAT SNR catalog (3 yrs of P7 data) F. Acero *et al* 2016 *ApJS* **224** 8
- Upper-limits reported by HESS (13 hours) F. Aharonian et al, 2008, A&A, 488, 219
- Paper by Xiang & Jiang, ApJ, 908, 22 (2021) but:
  - reported TS~21 (~3.8 sigma;12 yrs)
  - no study of the morphology and simple SED modeling

- Re-analysis using Fermi data using the same livetime but different configuration
- Detection with H.E.S.S. using a total of 152 hours of observation (10x more than in 2004-2005)

=> Detection by both instruments !

Acero, MLG, Ballet, A&A 660, A129 (2022)

H.E.S.S. Collab, A&A, 662, A65 (2022)

Table 2. Impact on the source significance of different analysis setups above a 700 MeV energy threshold.

Configuration number	Summed analysis	Bin size (°)	Region size (°)	TS
1	Yes	0.05	15	33.9
2	No	0.05	15	30.6
3	No	0.1	15	23.2
4	No	0.1	20	21.4

Kepler SNR with Fermi

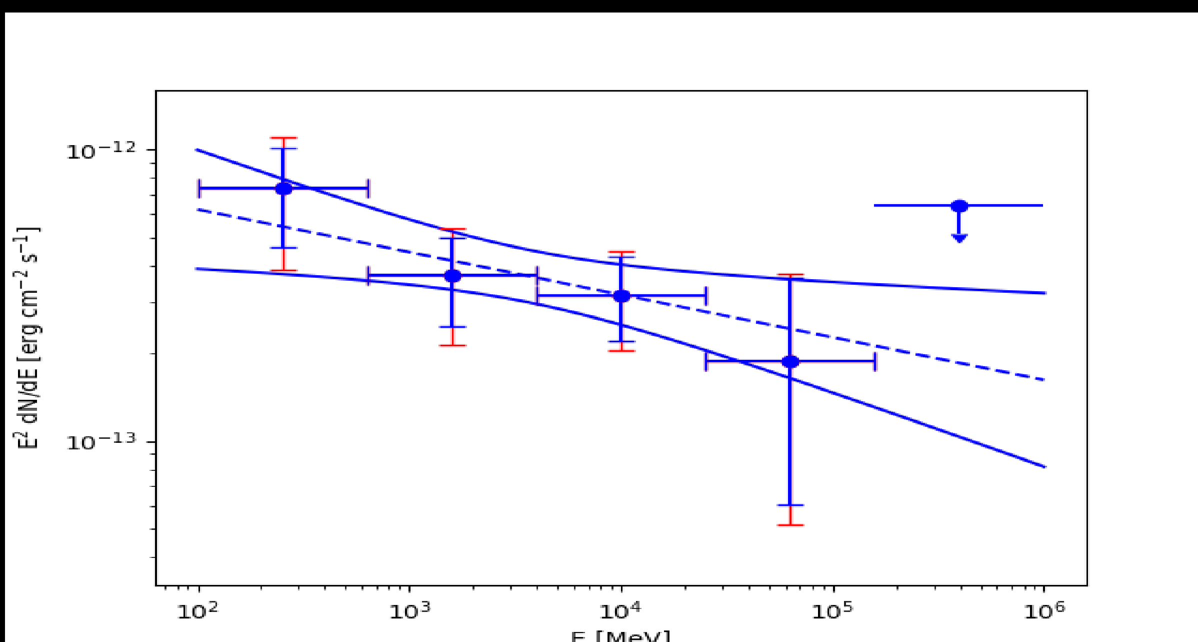
Clear detection (TS=38.3 above 100 MeV)

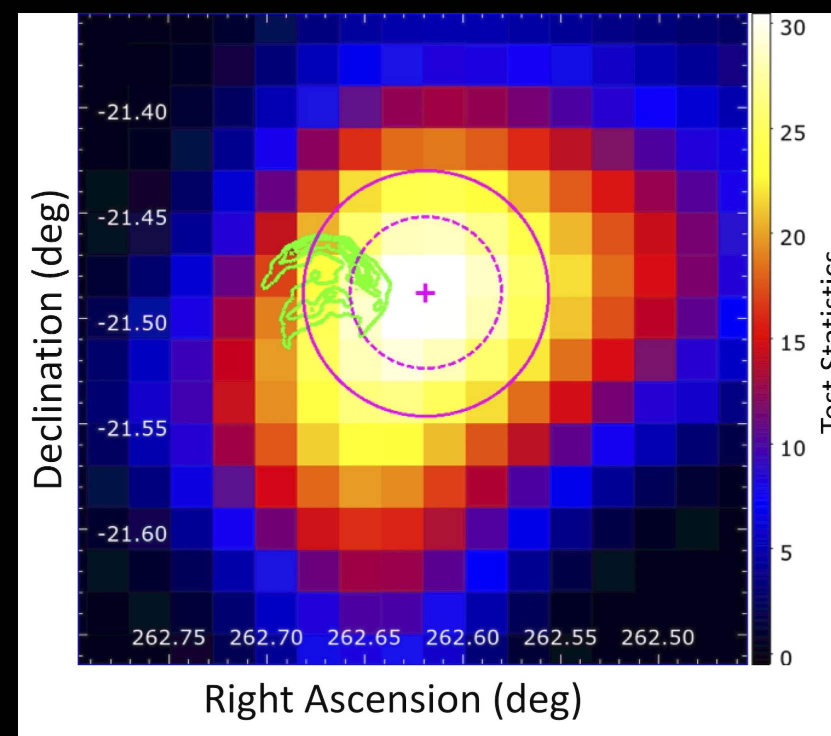
No significant differences between best-fit point-source and MWL templates

Emission not significantly extended

Hard power-law spectrum :

- Index = $2.14 \pm 0.12_{stat} \pm 0.15_{syst}$





Interpretation of our Fermi data (I)

Well measured distance: 5.1 ± 0.8 kpc (Sankrit et al. 2016)

Rationale : Gamma-ray stems from the NW interaction region where density is high (n_0~8 cm^{-3} from optical)

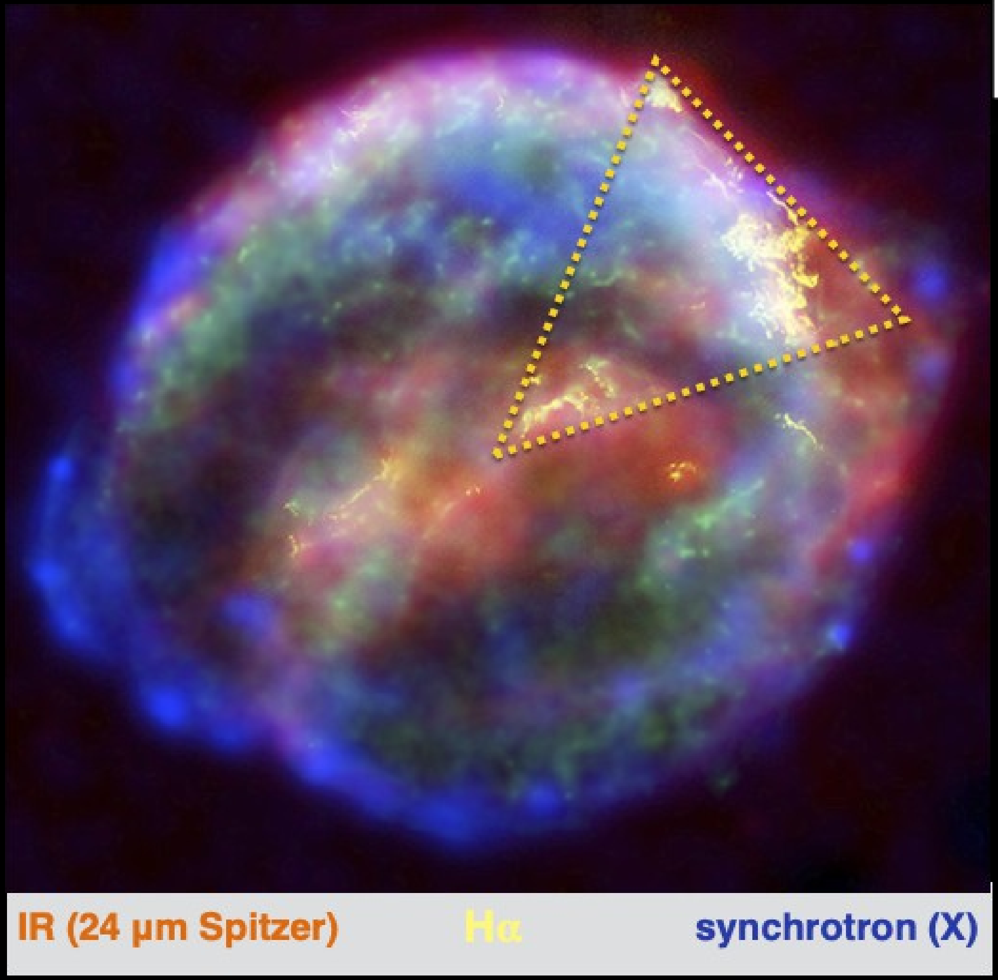
Hadronic emission

Interaction with the CSM with ~8 cm^{-3}
Lower shock speed ~1700 km/s

Synchrotron + IC

Electron emission coming from fast shocks (Southern hemisphere)

V_{shock} ~5000 km/s
n_0~10^{-2} cm^{-3}



Interpretation of our Fermi data (II)

Only 4 degrees of freedom: B field and injection

Most parameters are fixed from theory or literature

$V_{sh,e}$ from Chandra X-ray synchrotron rims motion

$V_{sh,p}$ from Hubble Hα motion

Density from Hα

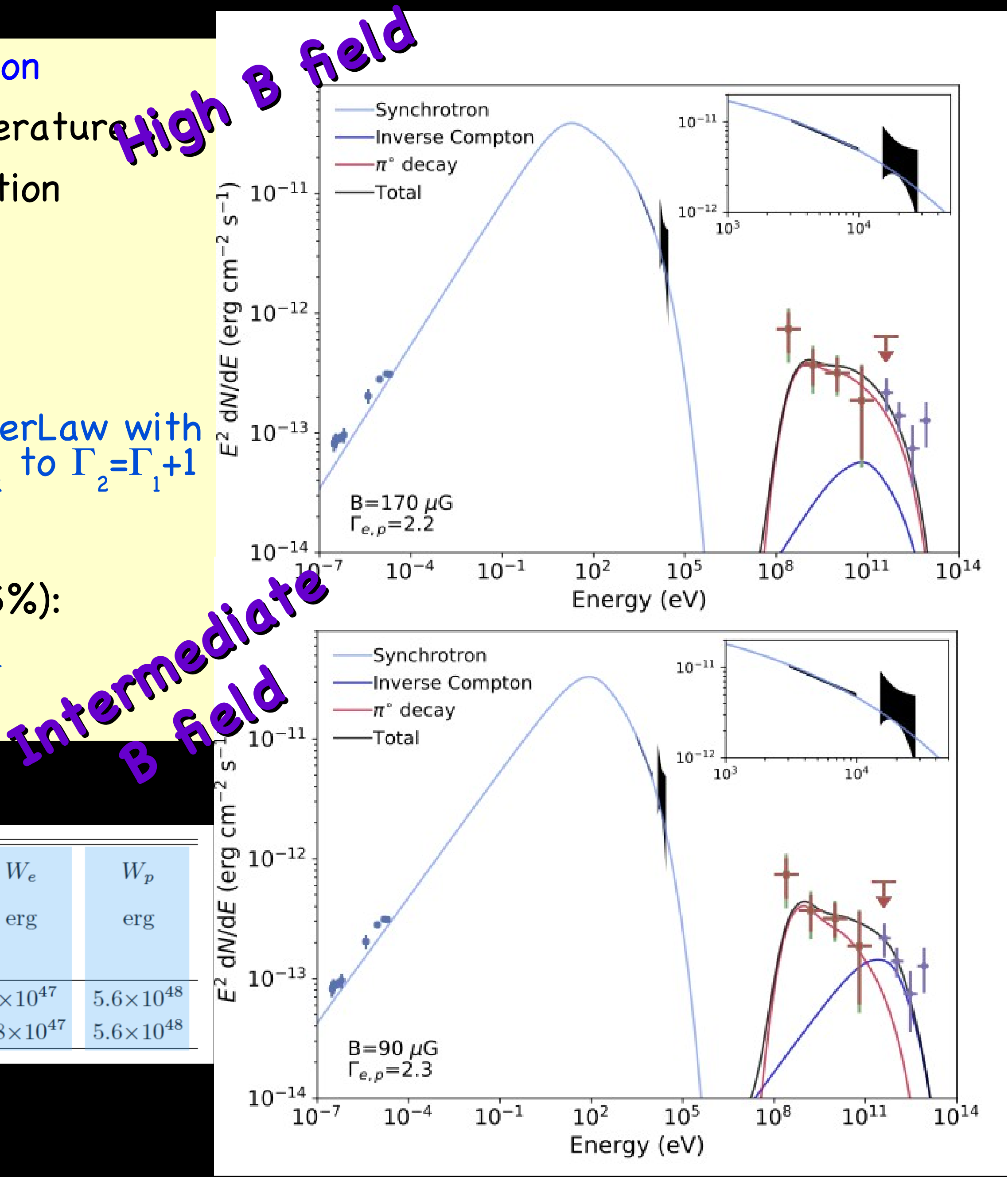
Electrons are cooling limited => $E_{max,e}$ & E_{break}

- Exponentially Cutoff BrokenPowerLaw with a change of slope after E_{break} to $\Gamma_2=\Gamma_1+1$

Proton acceleration is age limited =>$E_{max,p}$

With an opening angle of 45° (filling factor 15%):

- Local proton budget ~ 4% of E_{51}

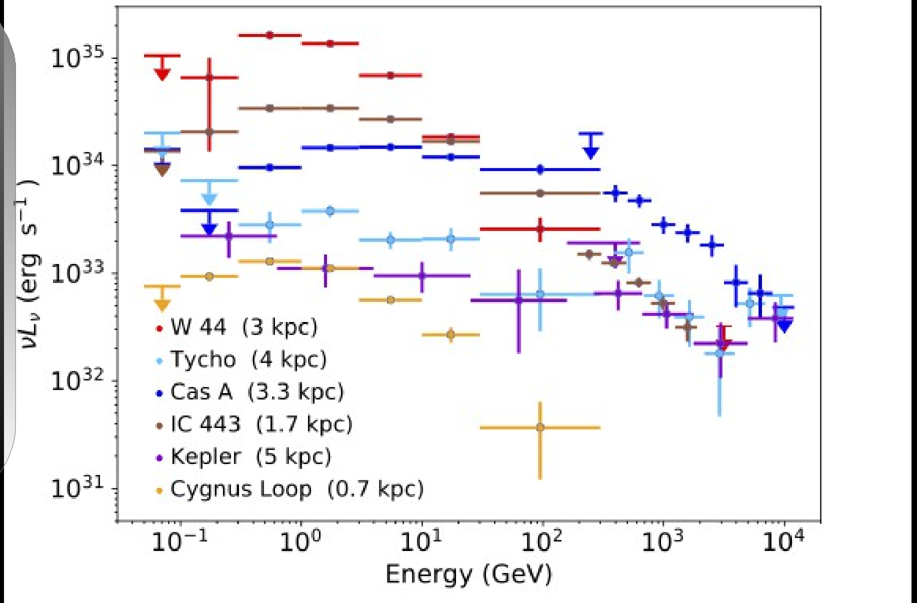


B	n_0	$V_{\rm sh,e}$	$V_{\rm sh,p}$	$\Gamma_{e,1}/\Gamma_{e,2}$	$E_{\rm break,e}$	$E_{\rm max,e}$	Γ_p	$E_{\rm max,p}$	W_e	W_p
μG	cm^{-3}	km s^{-1}	km s^{-1}		TeV	TeV		TeV	erg	erg
170	[8]	[5000]	[1700]	2.2/[3.2]	[1.1]	[18.4]	2.2	[21.2]	1×10^{47}	5.6×10^{48}
90	[8]	[5000]	[1700]	2.3/[3.3]	[3.9]	[25.3]	2.3	[11.2]	2.8×10^{47}	5.6×10^{48}

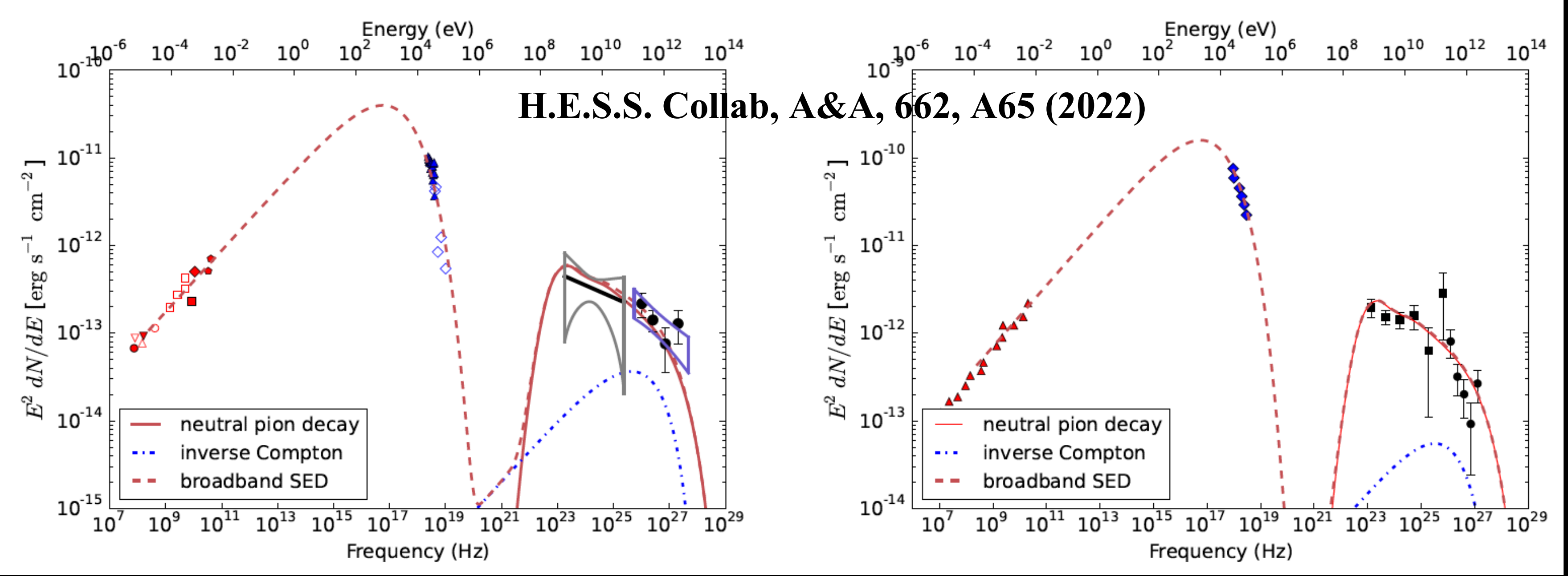
Kepler SNR in a general census

- Very similar with Tycho
- Tycho, Kepler, and Cassiopeia A exhibit a nearly flat spectrum (TeV/GeV=0.2-0.4)
- curvature is stronger for IC 443 (TeV/GeV=0.015), W 44 (TeV/GeV < 2 x 10^{-3})

Acero, MLG, Ballet, A&A 660, A129 (2022)



H.E.S.S. Collab, A&A, 662, A65 (2022)

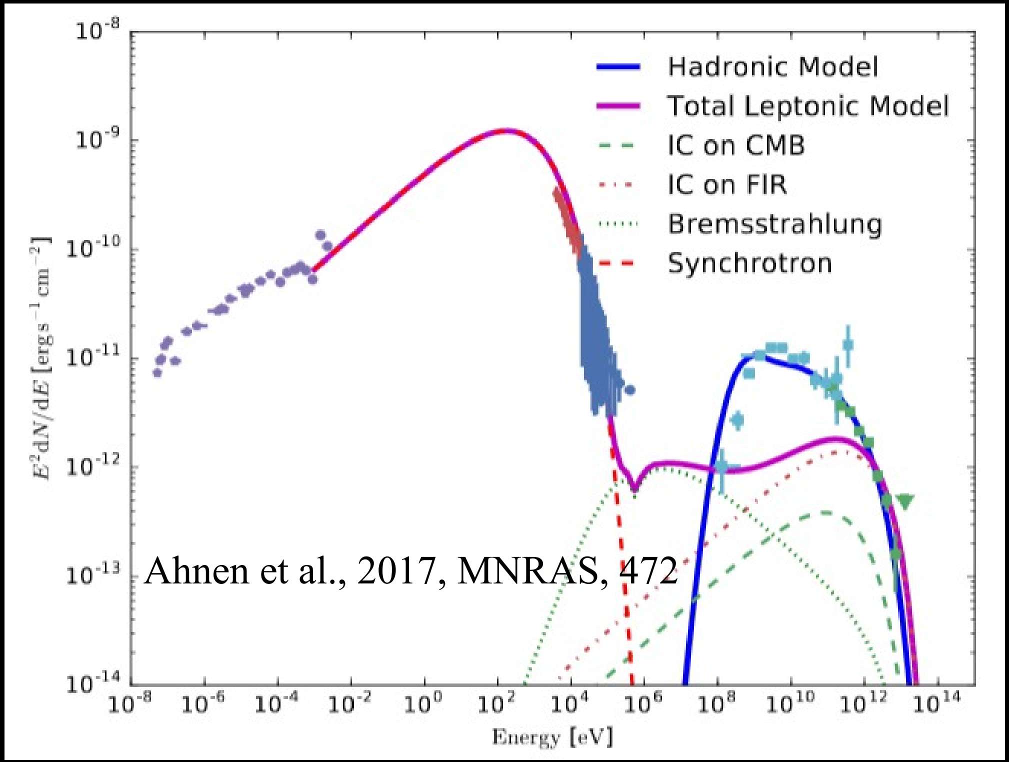


The young SNR Cas A

New Fermi data confirm the pion bump feature
=> Bremsstrahlung and IC ruled out

But detection of a clear turn-off by MAGIC =>
requires a proton population with spectral index 2.2 and cut-off at 12 TeV

Cas A is not contributing to the knee in a significant way....at least currently !



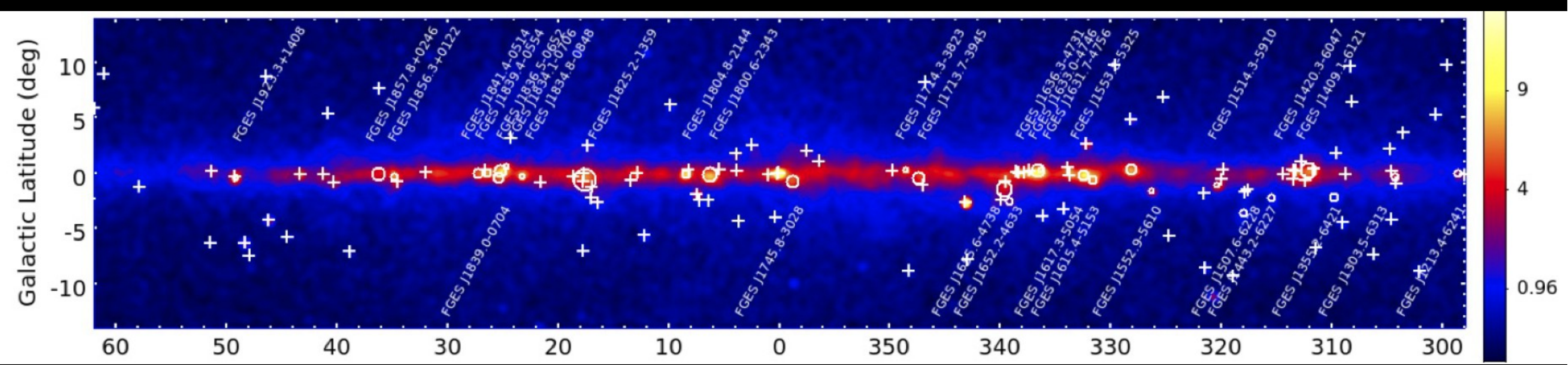
Fermi-LAT Galactic Extended Source Catalog

- 80 months of Pass 8 data; 10 GeV to 2 TeV
- Scan the Galactic plane (±5°) using overlapping regions
- 2independent analysis pipelines as a cross-check
- Test candidates for position, extension, alternative hypotheses

(2 pt. sources vs 1 ext. source) and spectral curvature

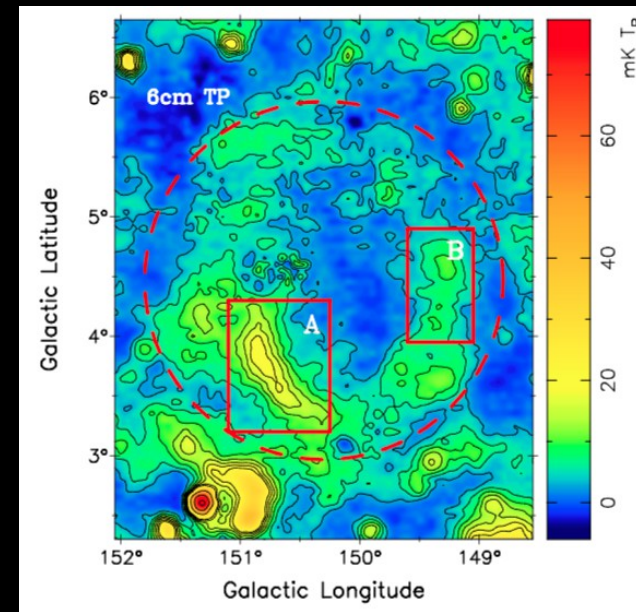
=> 46 extended sources detected

(Ackermann, et al. 2017, ApJ, 843, 2)

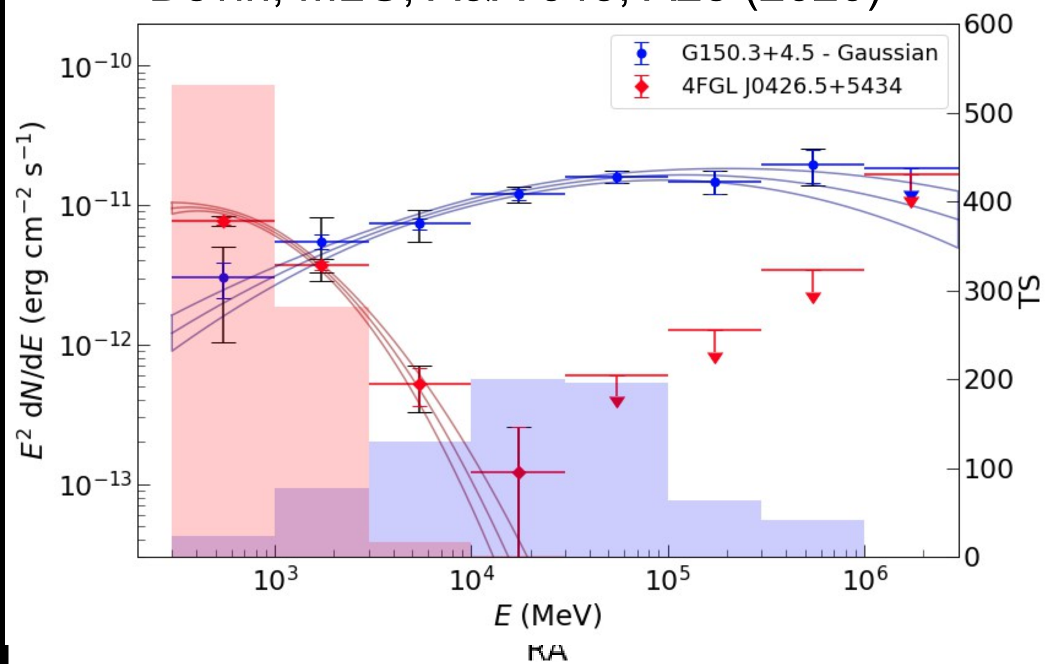


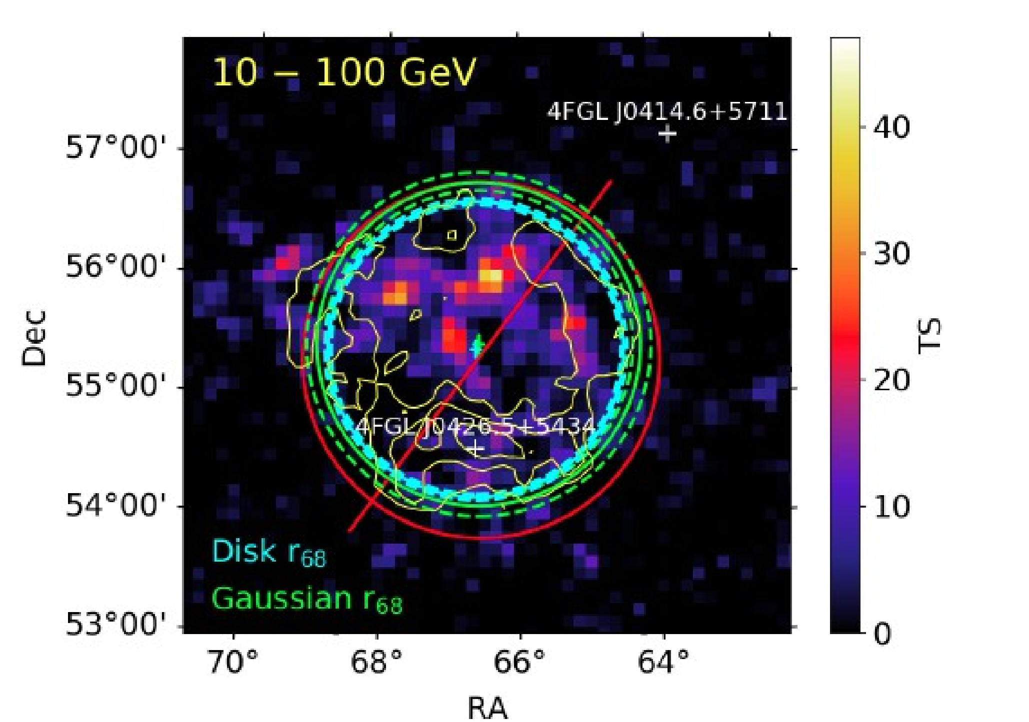
Revealing new SNRs at high energies : SNR G150.3+4.5

- Reported as an SNR using CGPS data (Gerbrandt 2014)
- Urumqi data revealed the total extent of 2.5° (Gao & Han 2014)
- Radio spectral indices variation : -0.4+/- 0.17 (SE) and -0.69 +/- 0.24 (W)



Devin, MLG, A&A 643, A28 (2020)

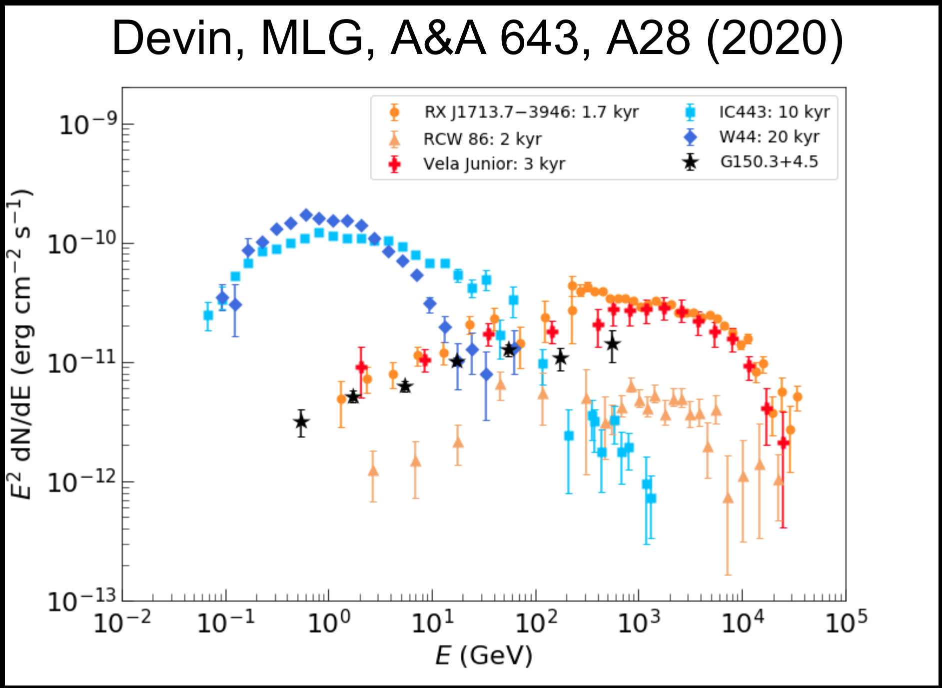


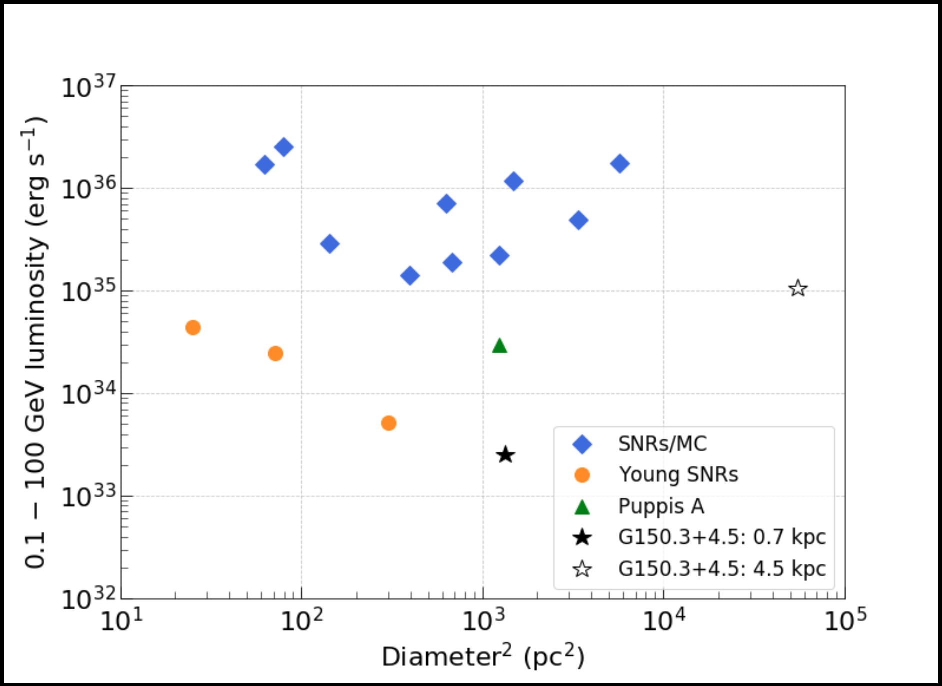


Our Fermi constraints on G150.3+4.5

- G150.3+4.5 is spectrally similar to the dynamically young and shell-type SNRs
- G150.3+4.5 has likely a low luminosity (no hint for an interaction with a molecular cloud)

The hard spectral shape and its likely low luminosity supports the dynamically young and non-interacting scenario => near distance





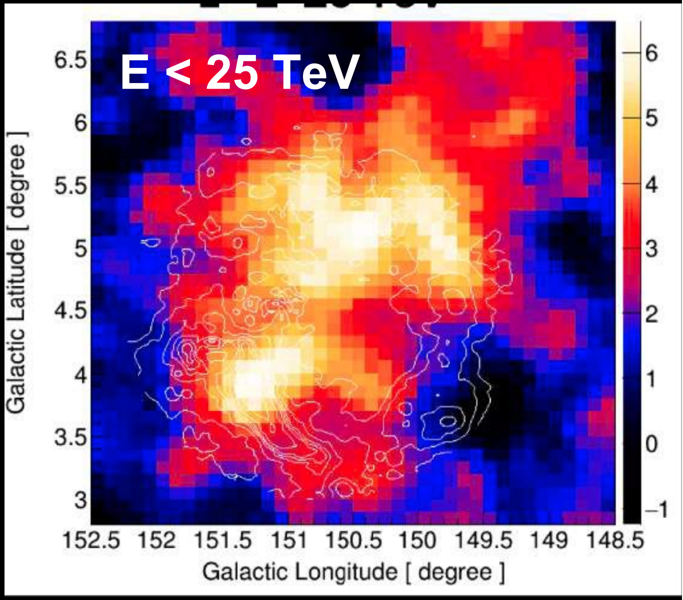
But G150.3+4.5 is now detected by LHAASO !

Zeng (ICRC 2023)

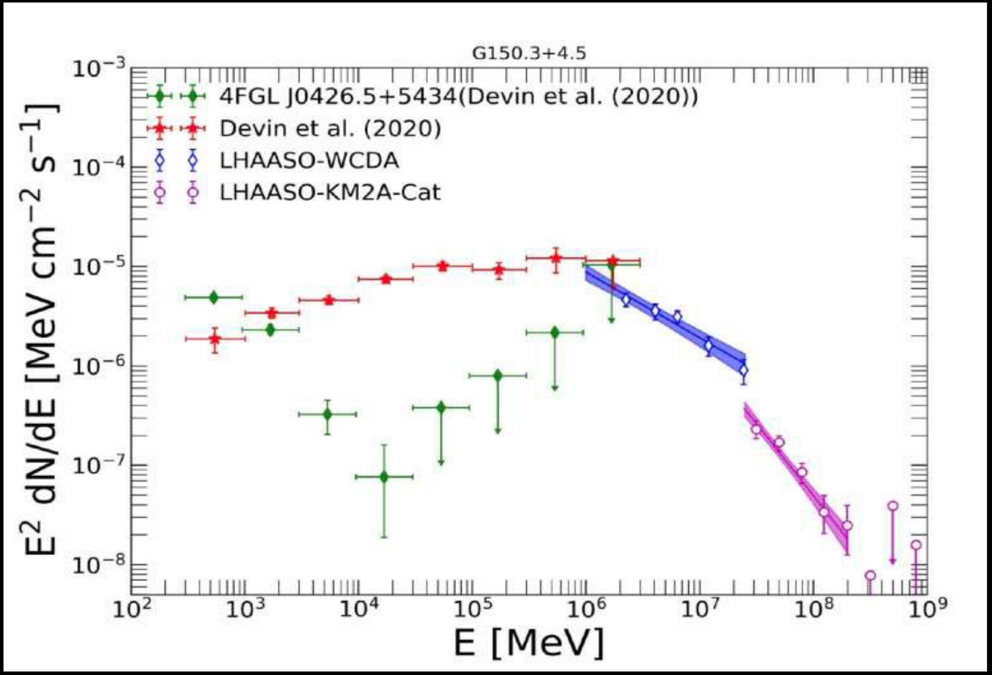
Energy dependent morphology :

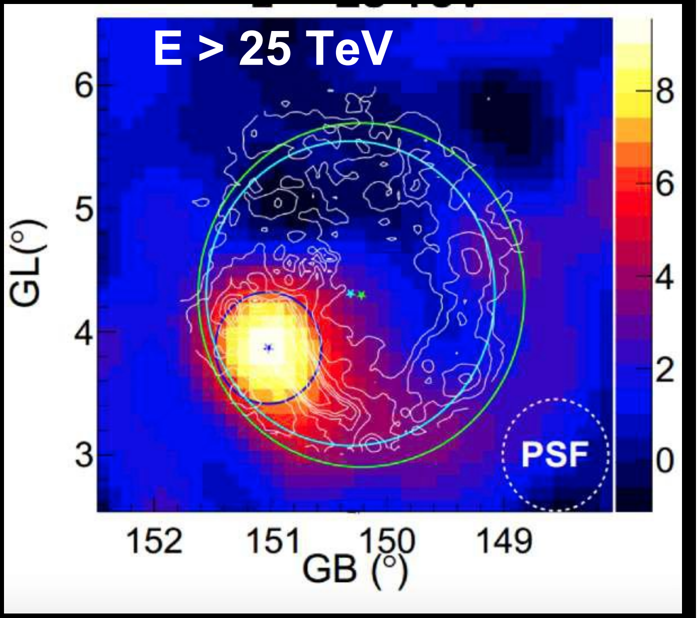
LHAASO-WCDA (E < 25 TeV) : spatial distribution and extension are consistent with that of the radio and the GeV band revealed by Fermi

LHAASO-KM2A (E > 25 TeV) : extended source (0.3°) spatially coincident with 4FGL J0426.5+5434



2 different sources (SNR + PWN) or MC cloud interaction ?



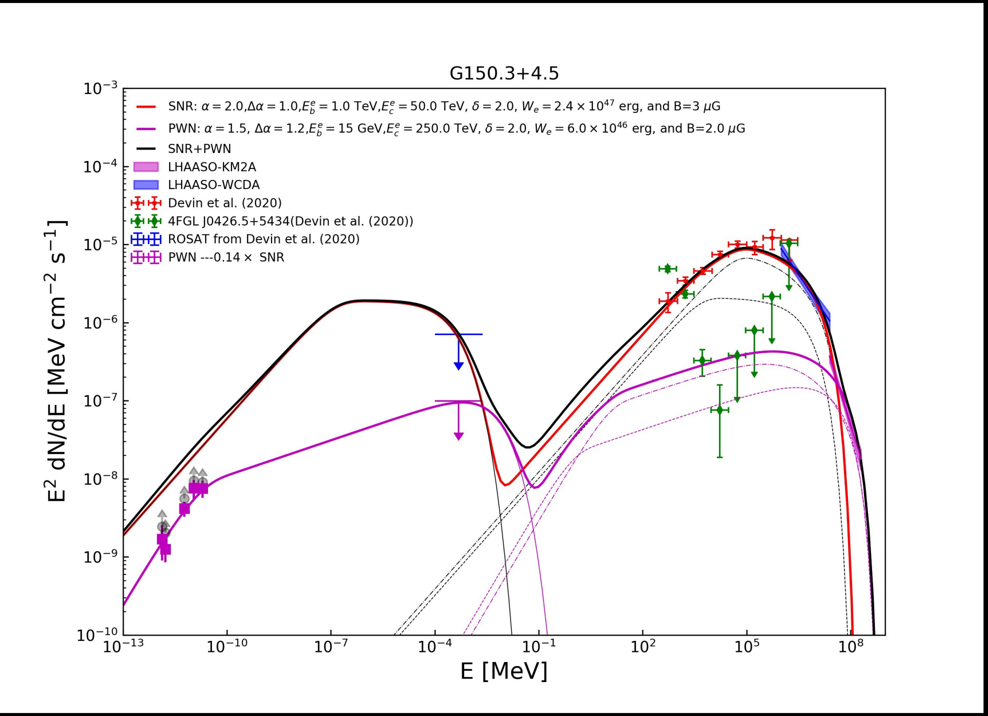


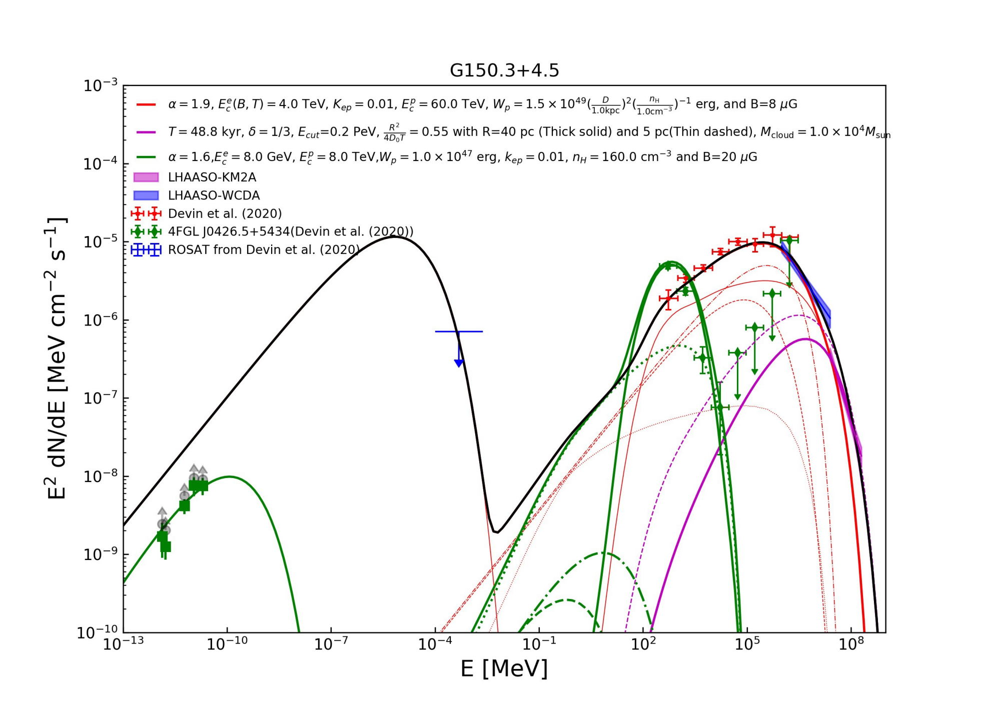
Constraints on G150.3+4.5 from LHAASO

2 scenarii proposed by Zeng (2023)

- SNR + PWN : favoured by radio spectral index variation

- SNR + MC : 3 populations : particles trapped in the SNR + escaped high energy ions + shock colliding with MC : SNR is then supposed to be radiative (48 kyrs) : contradiction with the hard GeV index





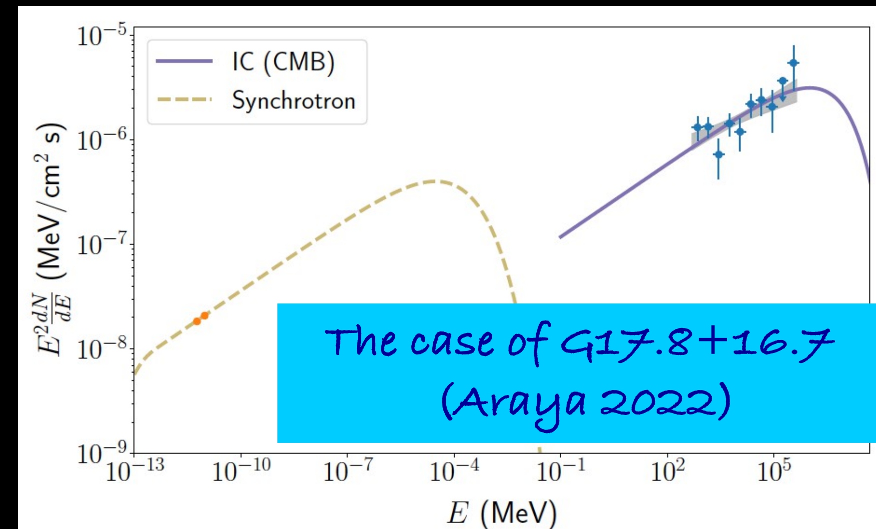
Fermi-LAT detections of radio-dim SNRs

Recent detections of extended sources outside the Galactic Plane :

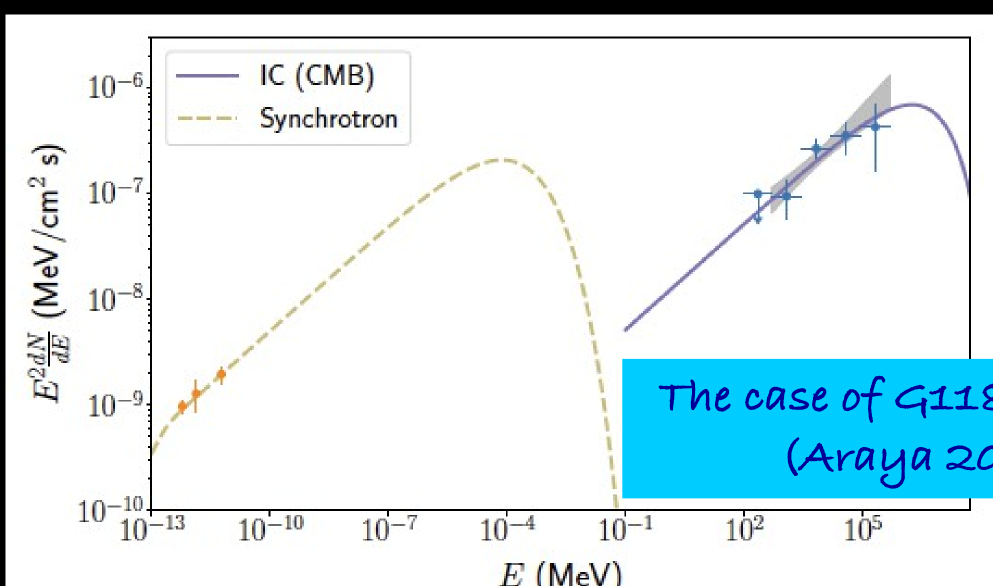
- G279.0+1.1 (Araya 2020)
- G150.3+4.5 (Devin et al. 2020)
- G17.8+16.7 (Araya et al. 2022)
- G118.4+37.0 (Araya 2023)

Radio & gamma-ray extent are comparable

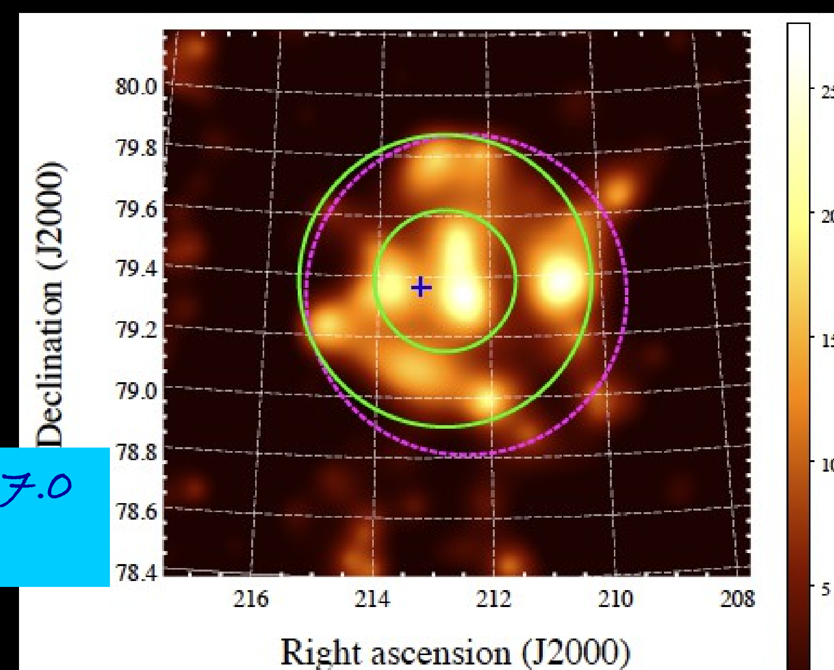
Hard gamma-ray spectra & Low luminosity at radio energies



The case of G17.8+16.7 (Araya 2022)



The case of G118.4+37.0 (Araya 2023)

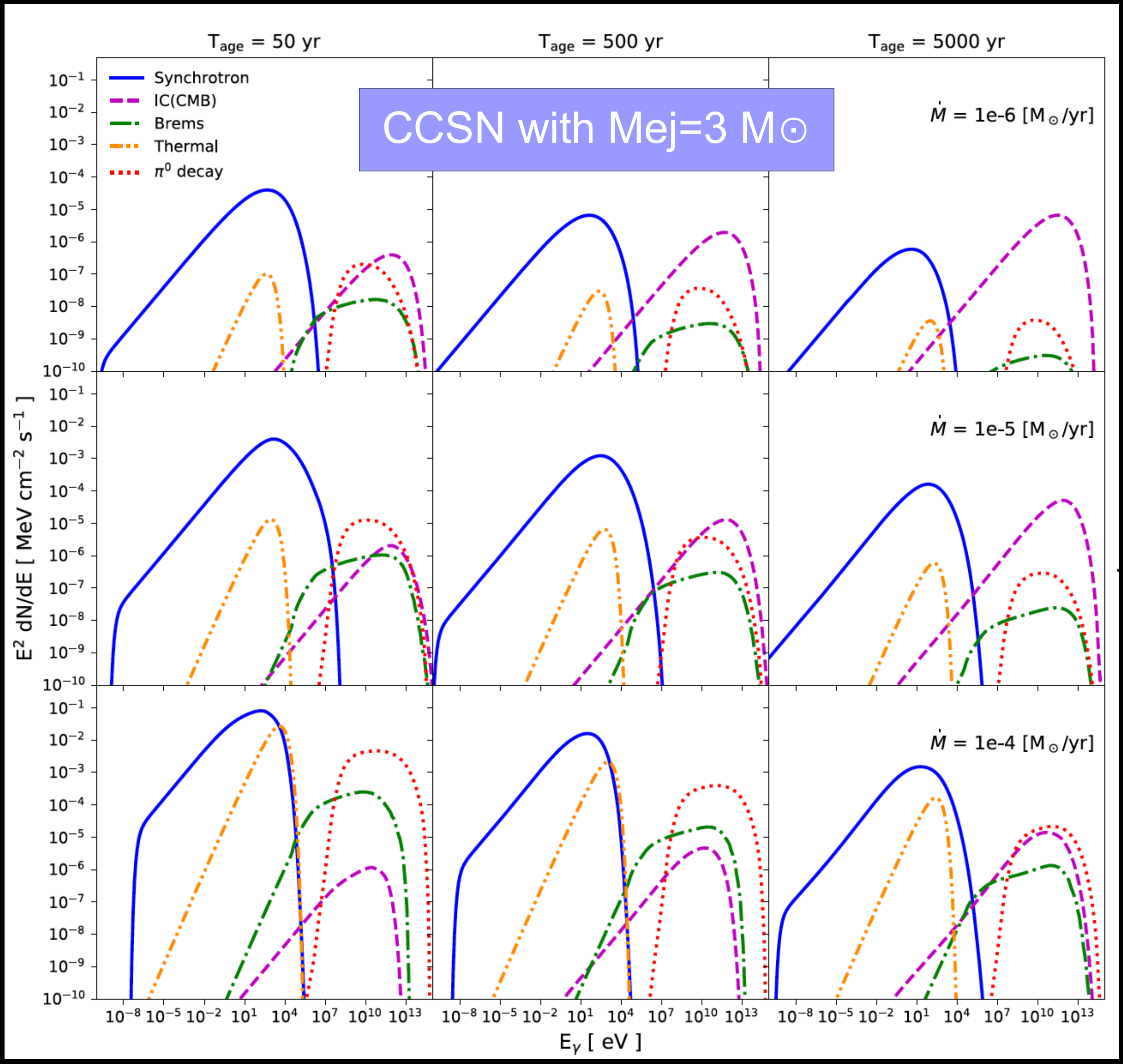


Population of kyr-old SNRs evolving in low density circumstellar environment

(Yasuda & Lee 2019)

- CSM created by stellar wind of massive star prior to collapse
- CSM provides dense target in the early phase
- Then decrease as r^{-2} => Brems and pp decrease
- At late times :
  - very low synchrotron fluxes (compared to most known SNRs)
  - SEDs are dominated by IC emission

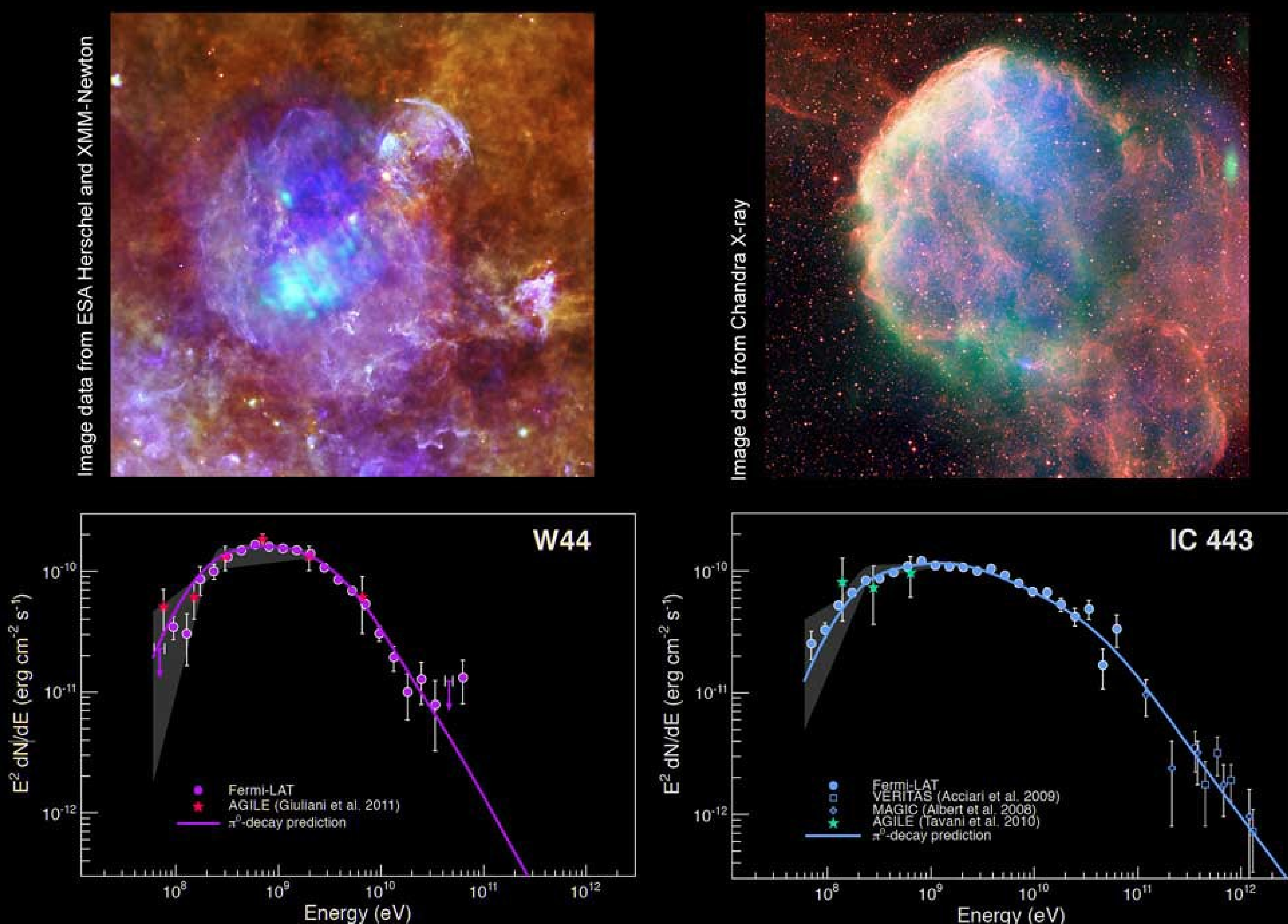
=> Good targets for Fermi & TeV instruments



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



Looking for low energy spectral breaks

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

Interesting new candidates

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

More details in Ackermann et al. 2017, ApJ, 843, 139

Population study

Among these 56 candidates :

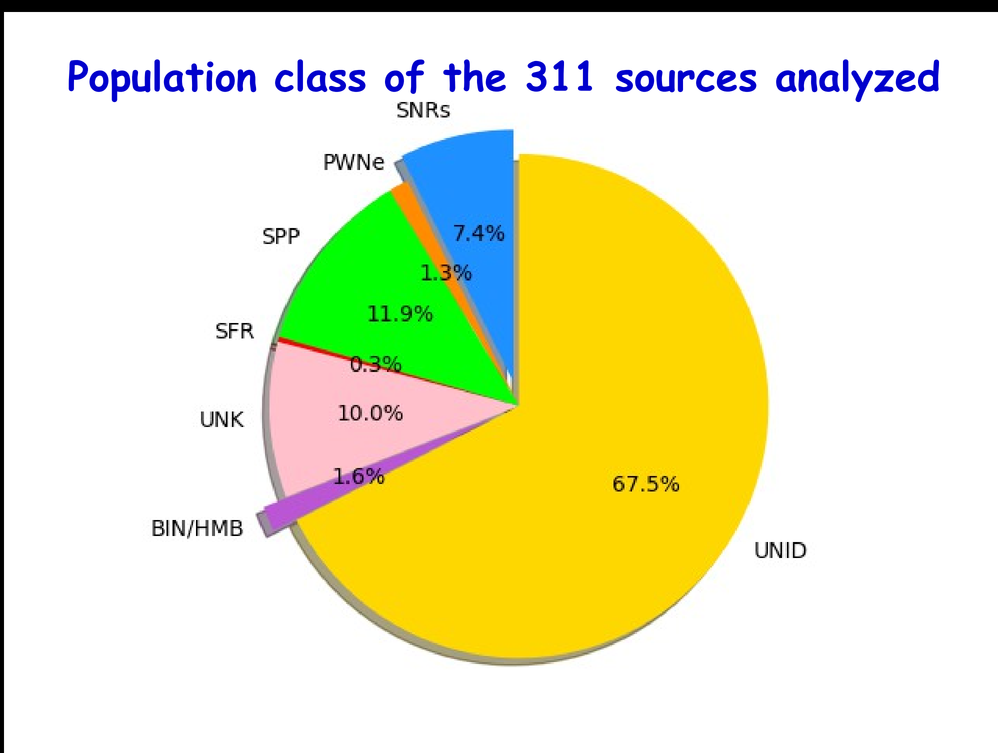
10 sources are firm SNR identifications

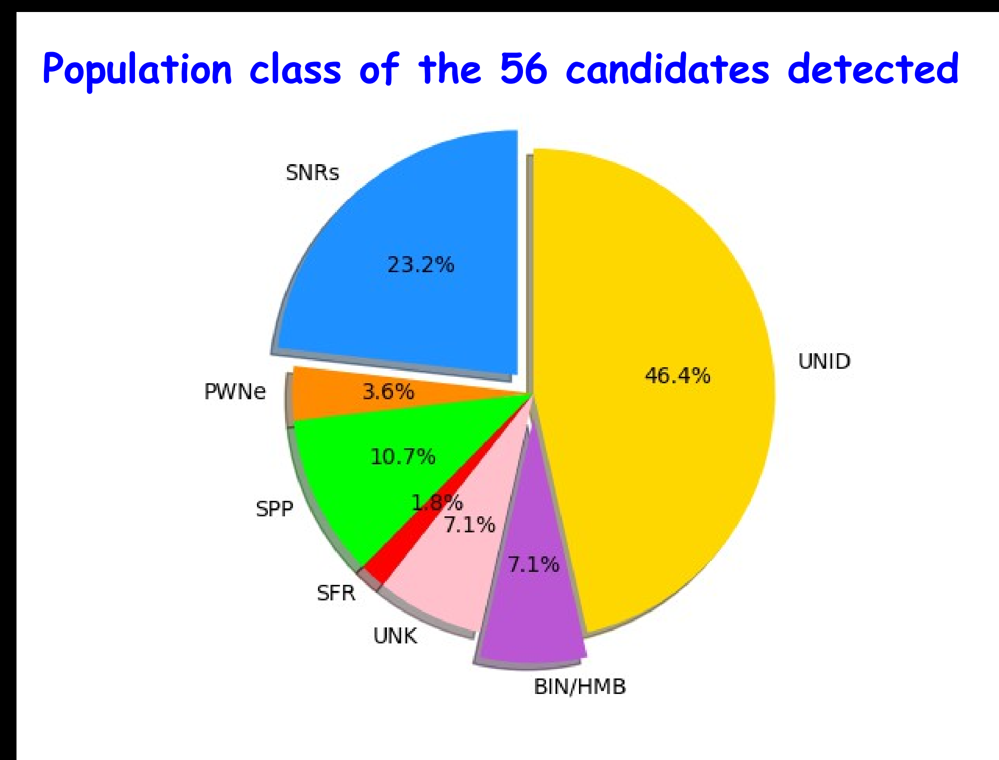
3 are associated with SNRs

6 are SPP (SNRs or PWNe candidates)

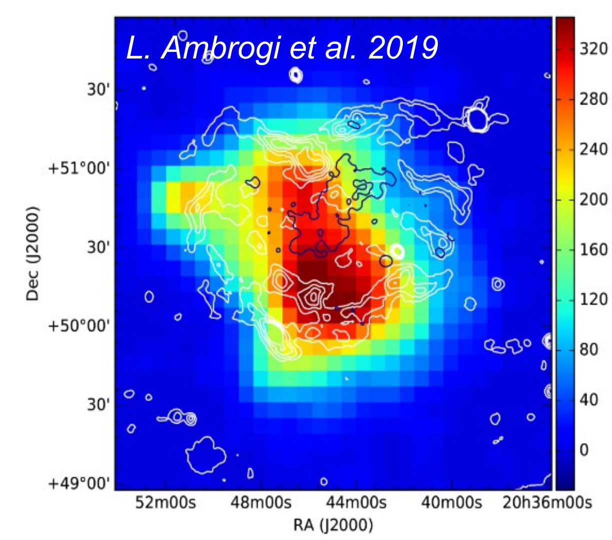
This makes SNRs the dominant class of sources showing spectral breaks in this analysis

Despite their small fractions, binaries also seem to contribute significantly





Proton-Proton interaction in SNR HB21



Similar to IC 443 and W44, HB 21 is also a mixed morphology SNR

Age : few tens of thousands years

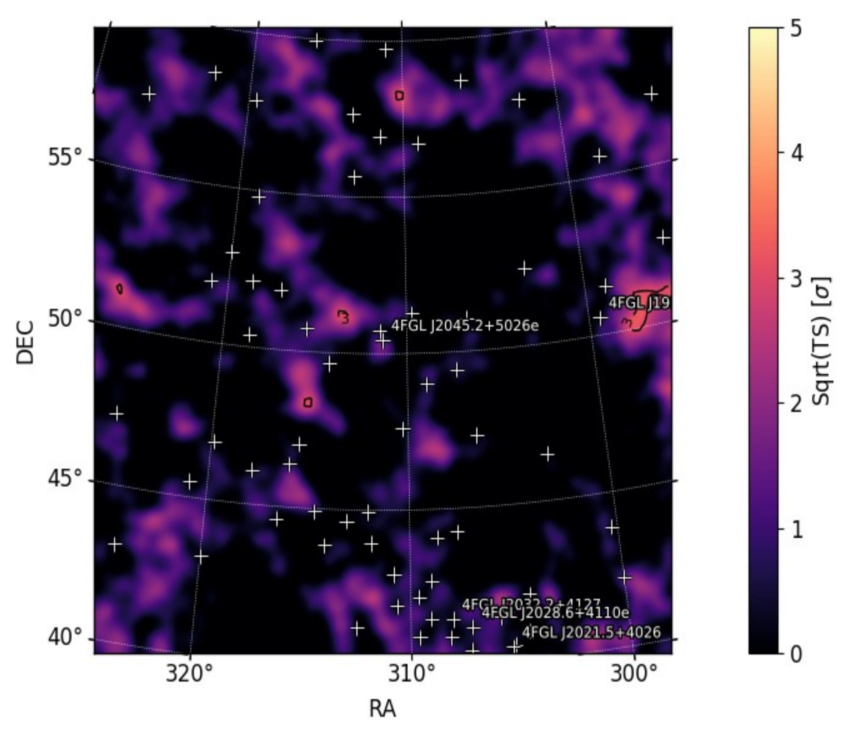
(Koo& Heiles 1991; Leahy & Aschenbach 1996)

Distance : 0.8 kpc (Tatematsu et al. 1990; Koo et al. 2001)

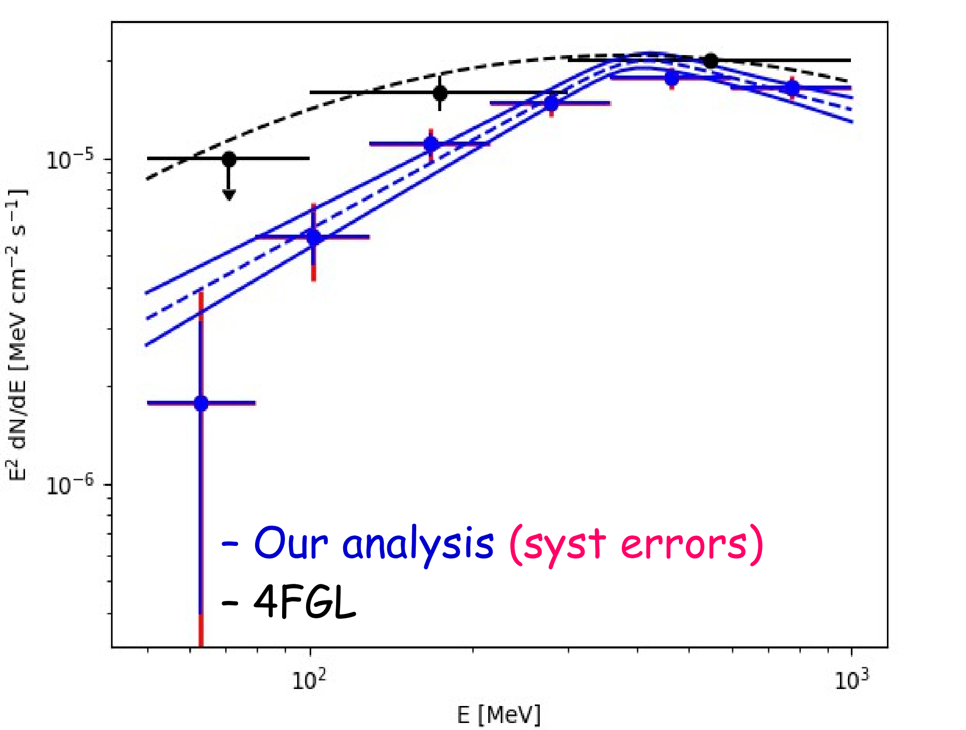
Fermi-LAT low energy turn over was already detected by L. Ambrogi et al. 2019

Very significant break in our analysis : $\Delta TS_{LogP-PL} = 42$; $\Delta TS_{SBPL-PL} = 42$; $\Delta TS_{SBPL2-PL} = 34$

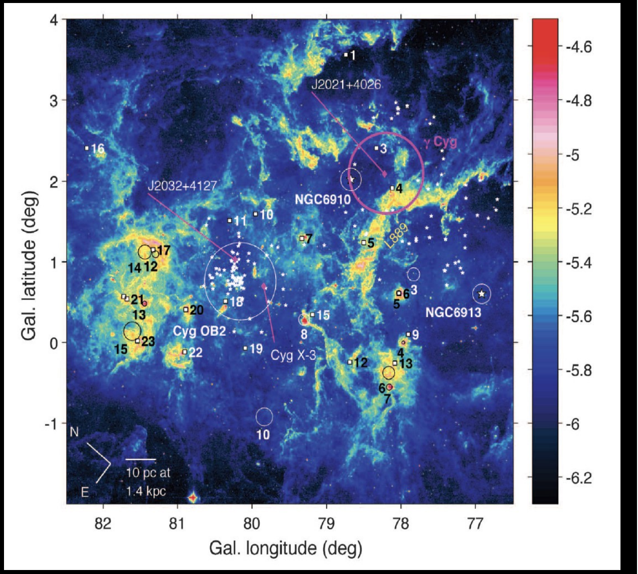
Residual TS map



Spectral Energy Distribution



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*

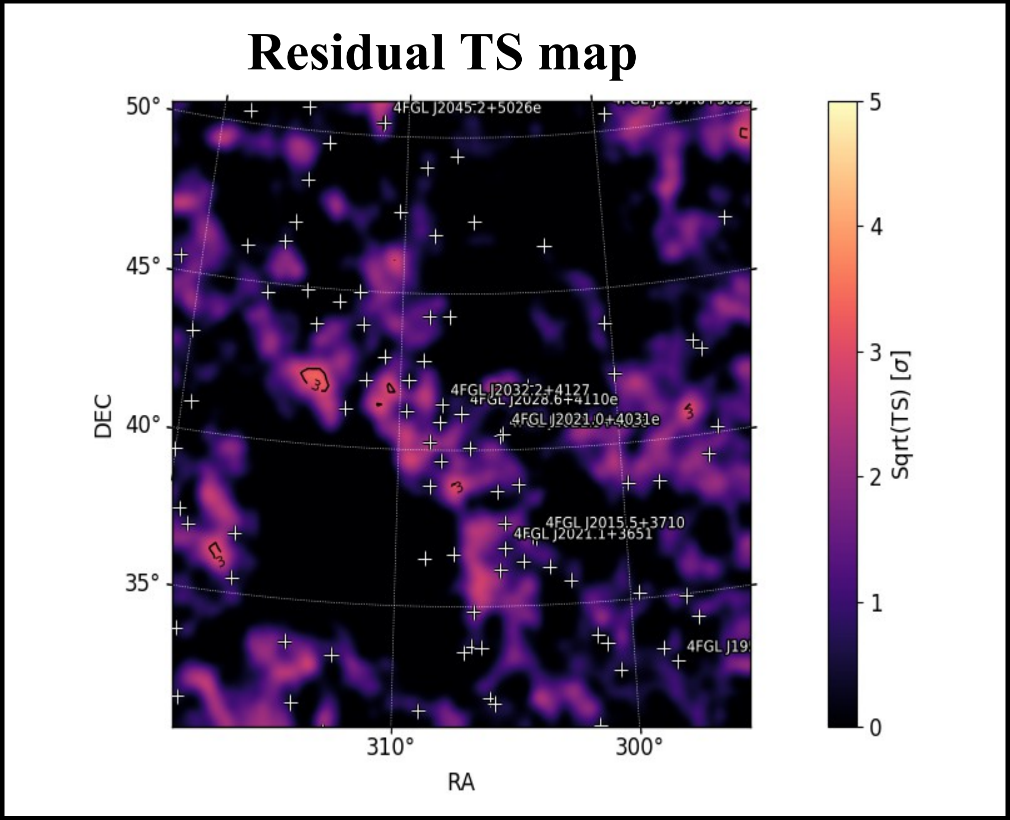
VHE detection of a counterpart HAWC J2030+409 *Abeysekara et al. 2021*

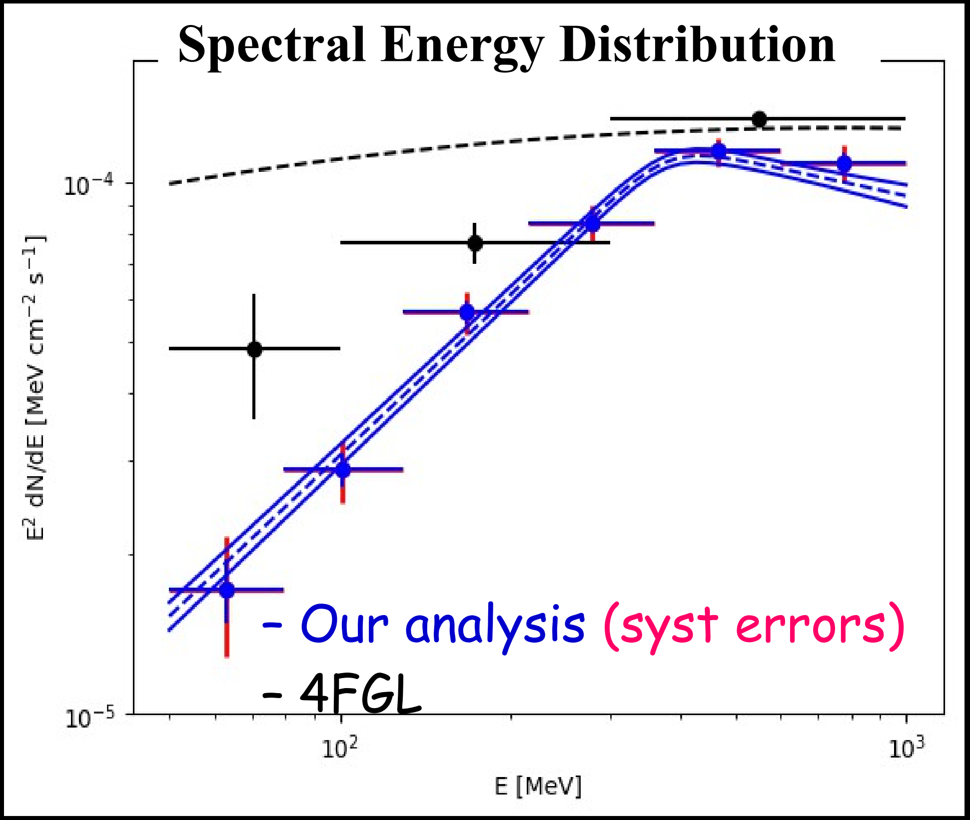
LAT+HAWC emissions likely due to hadronic interactions

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 :

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

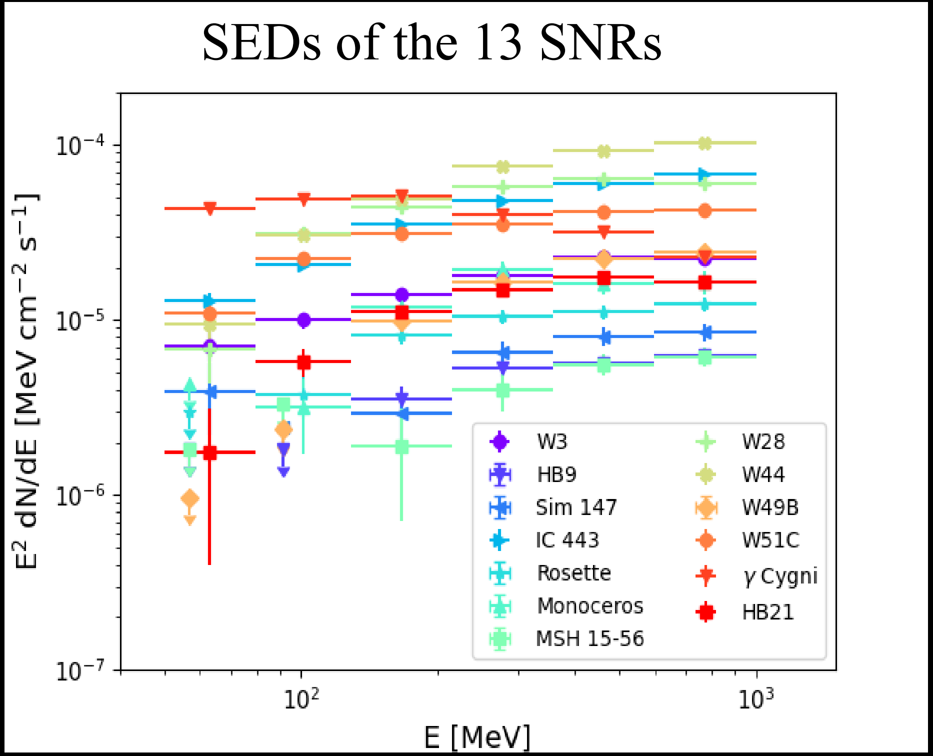


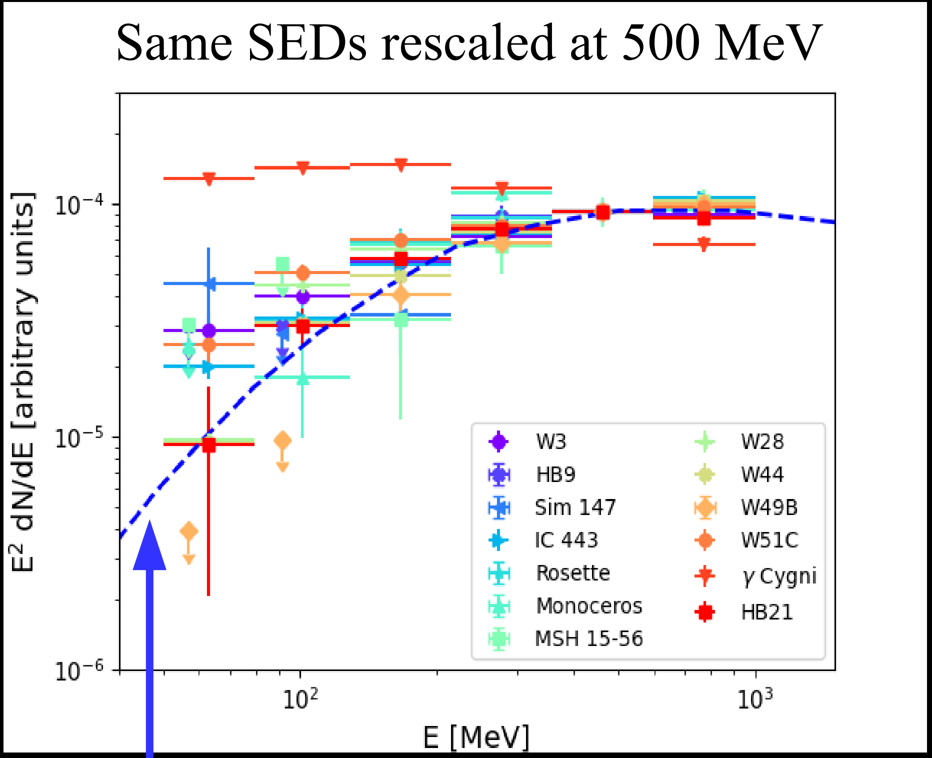


SNRs with significant breaks

12 SNRs follow the gamma-ray emission expected for a proton spectrum with index=2.4
=> hadronic emission favoured

Only exception is gamma Cygni
=> probable contamination by the bright pulsar PSR J2021+4026





Gamma-ray emission expected for a proton spectrum with index=2.4

Prospects with CTA : the Galactic Plane Survey

Building a realistic model :

- **Known sources**
  - TeV catalogues compilation (gammacat)
  - Fermi-LAT 3FHL
  - extrapolating Fermi-LAT pulsars
  - 2HAWC

Diffuse emission :

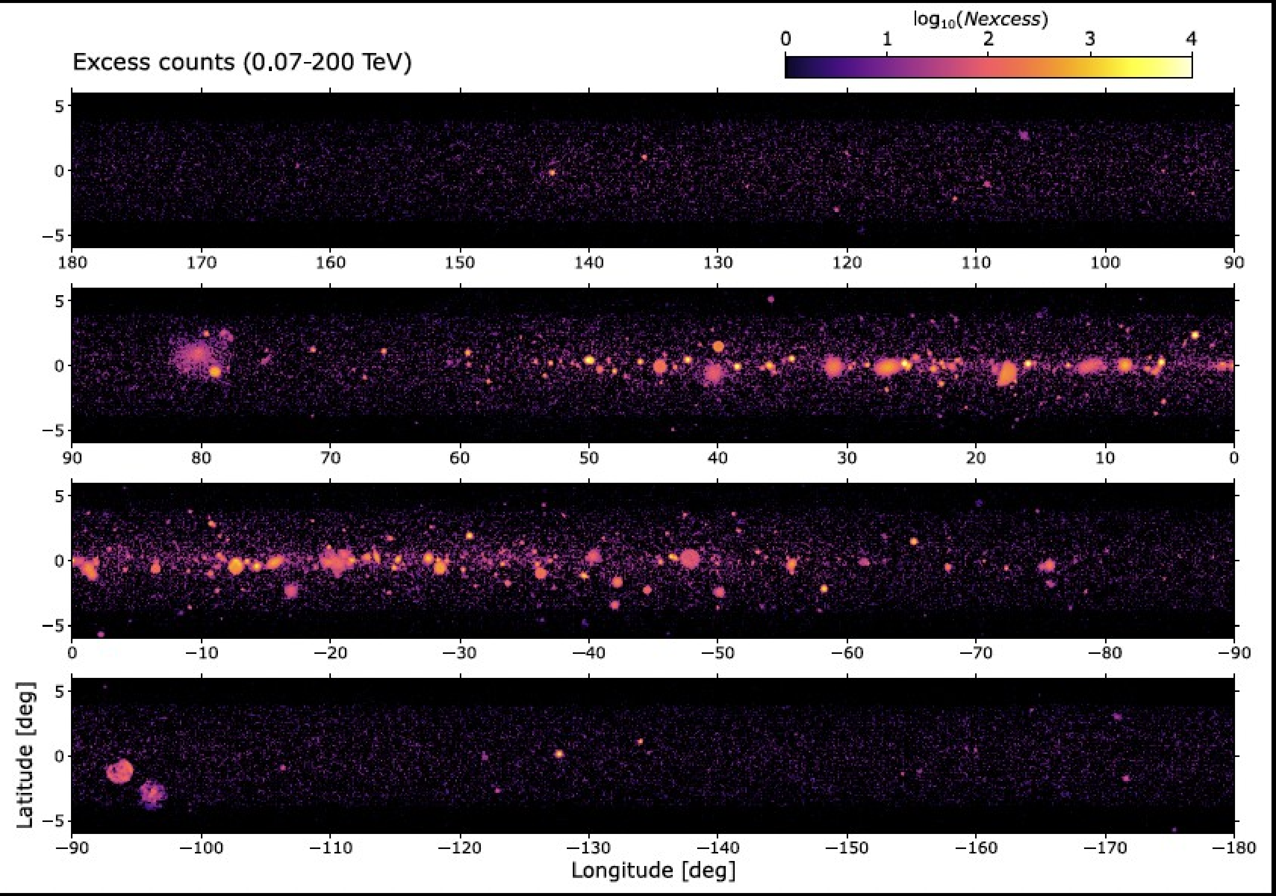
- Fermi bubbles
- Galactic ridge
- Interstellar emission using DRAGON CR code

Synthetic population of:

- SNRs (shell-like and interacting)
- PWNe
- Binaries

Sky model publicly available here

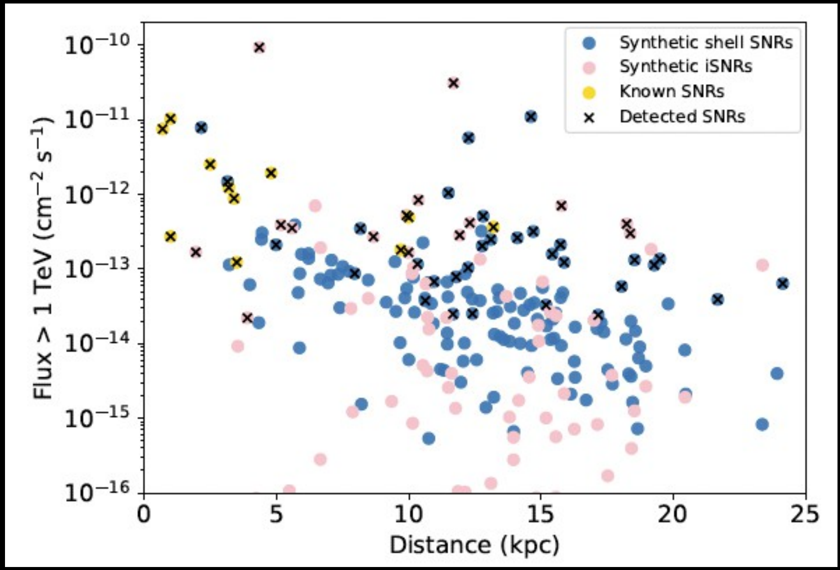
CTA baseline configuration
1620h of observations in 10 years
10h-30h exposure in the plane



Prospects for SNRs

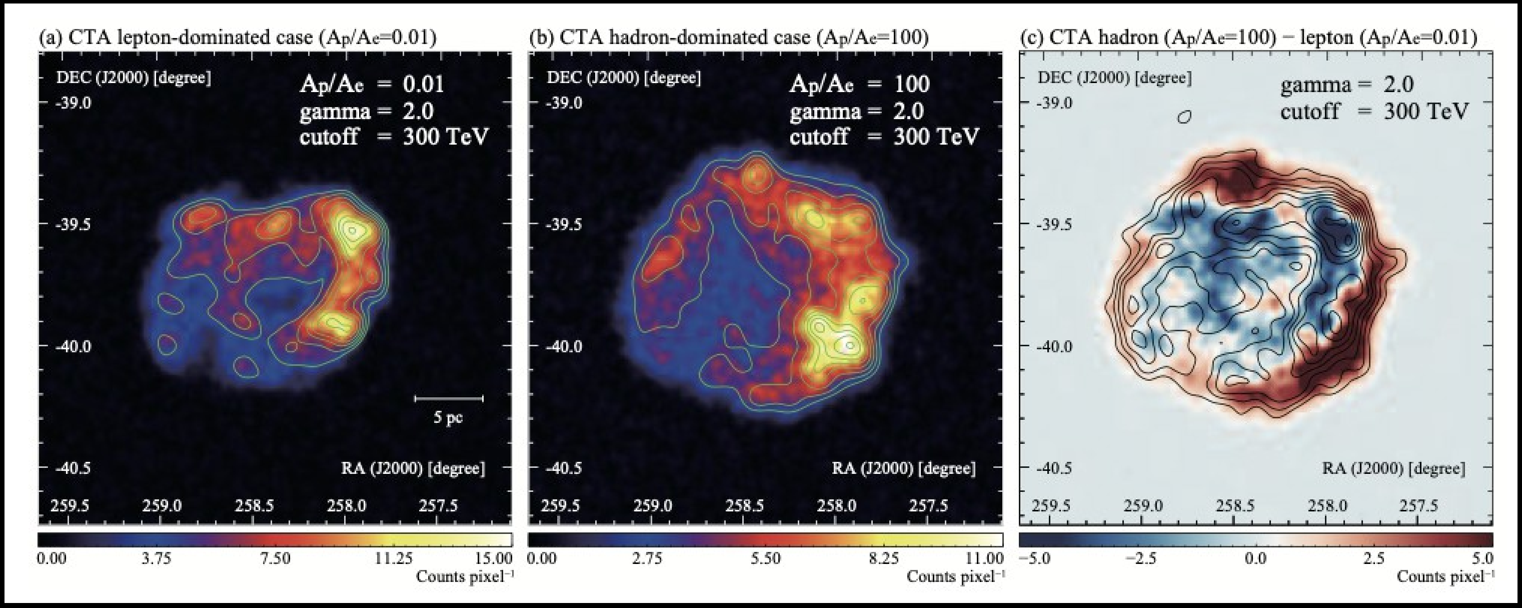
- 31 shell + 14 interacting new synthetic SNRs
- 19 of which are considered as extended
- 5-10 times better flux sensitivity
- About 20 SNRs at d> 10 kpc
- SNRs up to other side of Galaxy (20kpc!)
- Age range from 0-10 kyrs

CTA consortium, 2023, arXiv:2310.02828



➡ wider distribution of ages will pave the way to a more detailed population study

Excellent performances : 50 hours allow the discrimination of the emission mechanism(s) of the gamma rays (i.e., hadronic vs leptonic, or a mixture of the two) through information provided by their spatial distribution



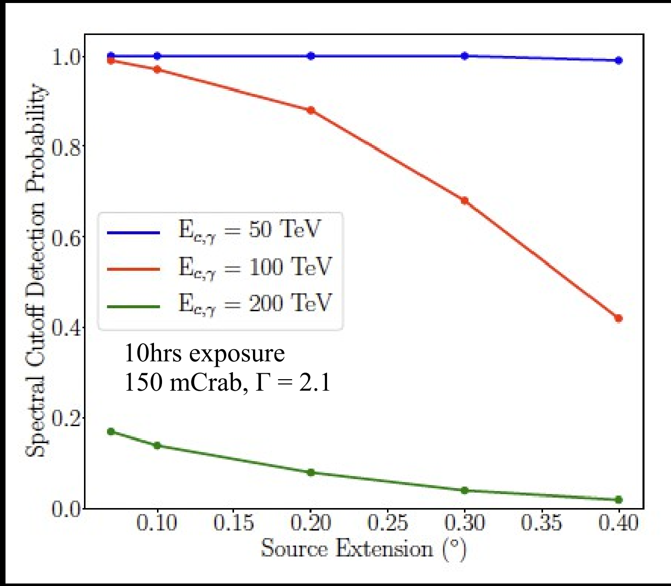
CTA consortium, 2017, ApJ, 840, 74

Identifying PeVatron candidates in the GPS

PeVatron detection and rejection probabilities degrade with increasing source extension

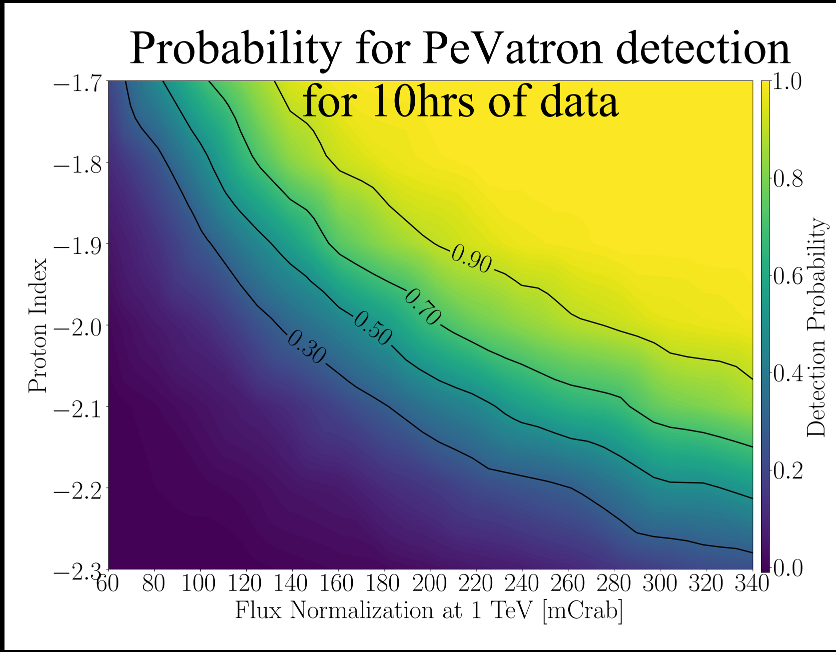
With CTA GPS data (i.e. 10 h of exposure), only point-like PeVatrons with bright γ-ray emission and hard proton spectra are likely to be identified as PeVatrons

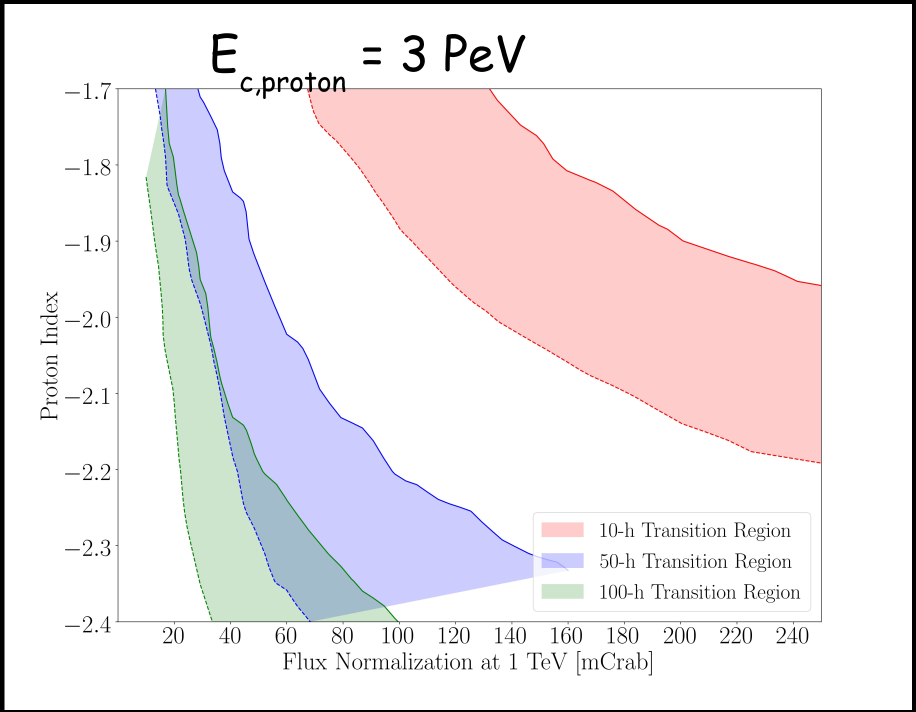
For deep observations with 100 h of CTA data, proton spectral indices $\Gamma p > 2.4$ and flux normalizations larger than 40 mCrab can be tested



=> CTA must rely on deep observations of selected PeVatron candidates

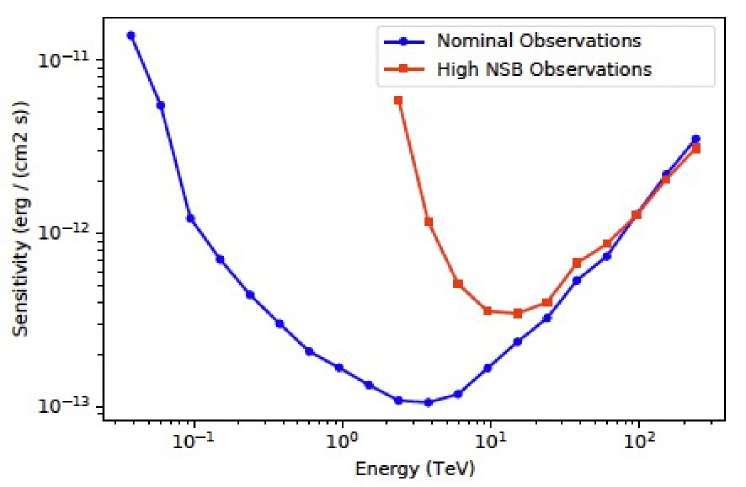
CTA consortium, 2023, Astroparticle Physics, 150





Follow-up of PeVatron candidates with moonlight observations

South CTA site will include a large SST array using silicon photomultipliers => can sustain long periods of exposure to very strong moonlight conditions



Moonlight has little impact on sensitivity for E>20 TeV

Follow-up of candidates during Moon nights ?

10 h of CTA exposure under nominal conditions + 90 h of SST subarray exposure under HNSB = 50 h acquired under nominal conditions

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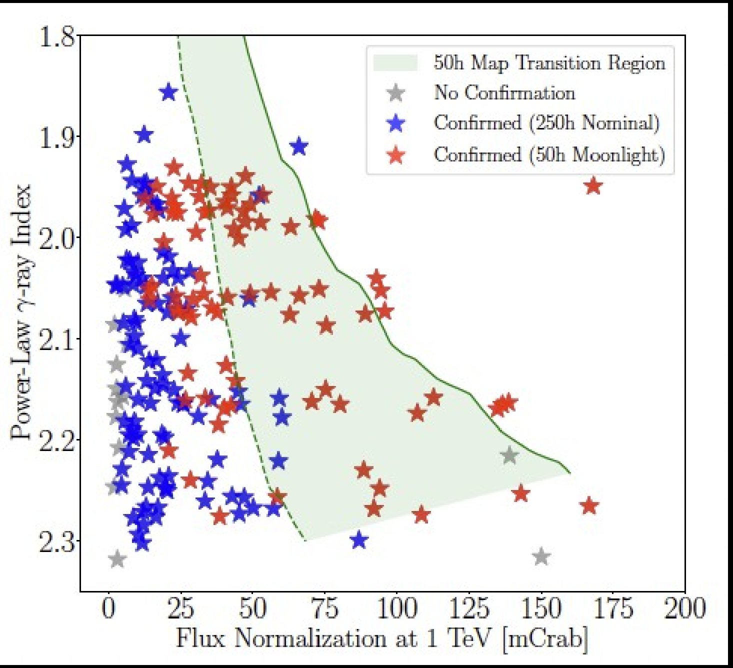
SNRs with Flux > 50 mCrab confirmed with 10 h full array CTA + 40h SST-subarray exposure under moonlight conditions

Total observation time	$\Gamma_p = 2.0$	$\Gamma_p = 2.1$	$\Gamma_p = 2.2$	$\Gamma_p = 2.3$
50 h nominal	$80\%^{+5}_{-6}$	$(62\pm7)\%$	$(46\pm7)\%$	$24\%^{+7}_{-6}$
100 h nominal	$92\%^{+3}_{-5}$	$82\%^{+5}_{-6}$	$64\%^{+6}_{-7}$	$(47\pm7)\%$
250 h nominal	$100\%^{+0}_{-2}$	$96\%^{+2}_{-4}$	$92\%^{+3}_{-5}$	$86\%^{+4}_{-6}$
50 h (10 h nominal NSB + 40 h HNSB)	$68\%^{+6}_{-7}$	$(44\pm7)\%$	$34\%^{+7}_{-6}$	$20\%^{+6}_{-5}$
100 h (10 h nominal NSB + 90 h HNSB)	$88\%^{+4}_{-5}$	$64\%^{+6}_{-7}$	$(50\pm7)\%$	$31\%^{+7}_{-6}$



Conclusions

Large variety of SNRs detected at gamma-ray energies

Protons detected within interacting SNRs and also historical remnants

The environment (dense HI cloud, CO clouds or tenuous ISM) in which the SNR is evolving is a key ingredient

Population of radio-dim SNRs detected with Fermi

TeV instruments provide important constraints on Emax

CTA PeVatron and Galactic plane survey projects are providing exciting results with >400 sources detected in the GPS