Credit Spitzer Cocoon Legacy

Hunting for PeVatrons in the Galaxy

Epiphany Conference 2022, Krakow

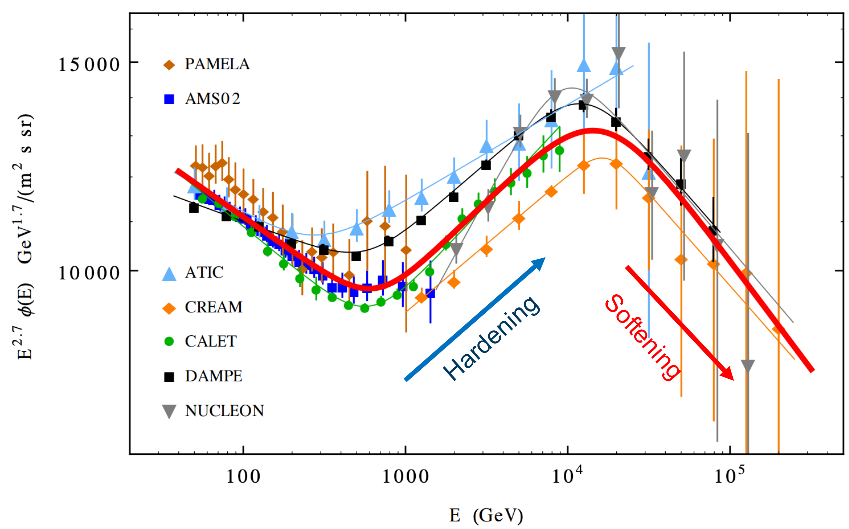
Sabrina Casanova, IFJ-PAN, Krakow

Outline

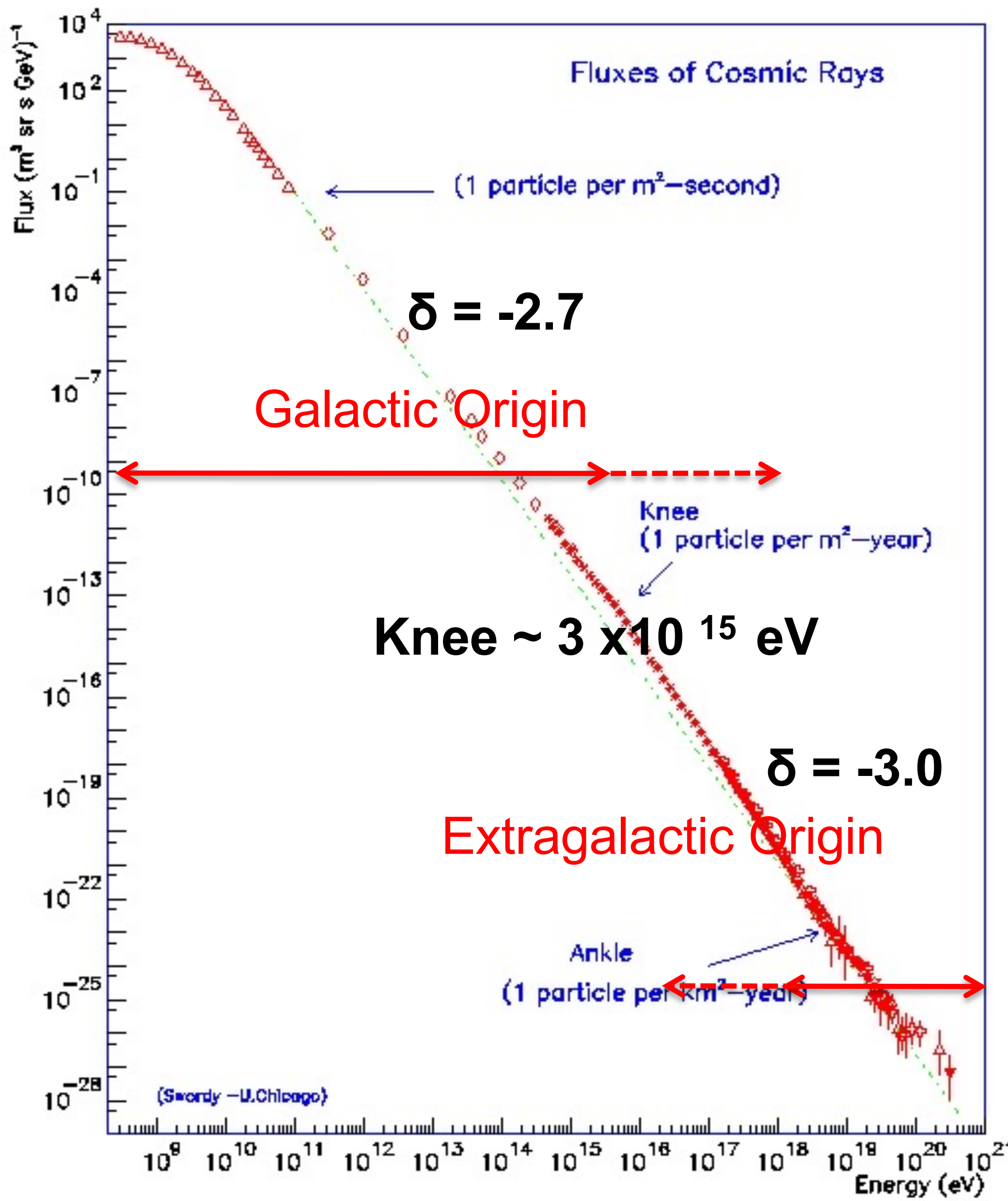
- Hunting Galactic PeVatrons : motivations and method
- PeVatron Candidates
  - Young SNRs
  - Galactic Centre
  - Stellar Clusters
- Surveys with wide FoV detectors
  - Gamma-ray emitters at hundred TeV
  - Testing the SNR paradigm
- Summary and Outlook

Searching for the Galactic PeVatrons

- 90% protons, 9% helium, 1% electrons
- Almost featureless spectrum
- CRs up to the knee are believed to have a Galactic origin
- Galactic accelerators have to inject particles up to at least to the knee at PeV
- The knee for protons at about 400-500 TeV (ARGO Collaboration 2015)



. Cronin, T. Gaisser, S. Swordy, Sci. Amer. 276 (1997) 44.



Relevant tests of candidate PeVatrons

$$CRs(\,1\,PeV\,) + gas \;\rightarrow \pi_0 \;\rightarrow \gamma\gamma\;(\sim 0.1\;PeV)$$

$$CRs + gas \;\rightarrow\; \pi^{-}\pi^{+} \rightarrow\; \nu$$

The candidate PeVatron has its hard spectrum extending up at least several tens of TeV without a break

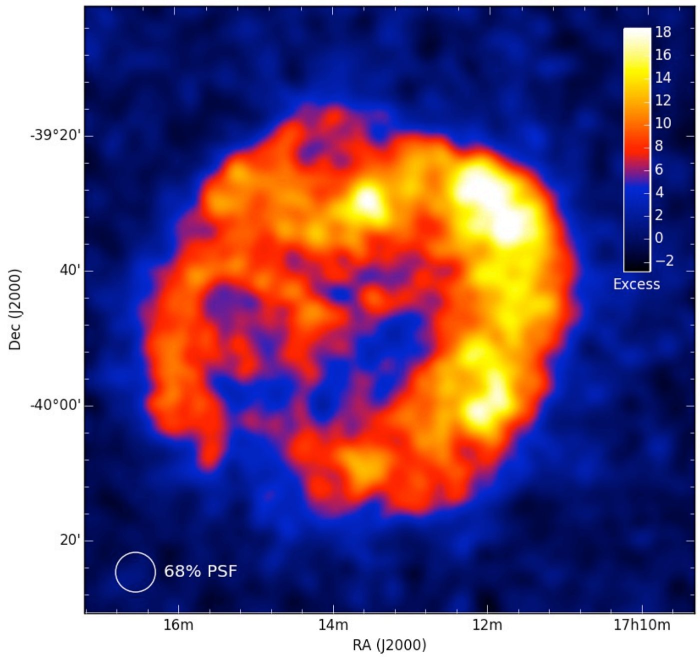
candidate PeVatrons emits hundred TeV γ-rays

The γ radiation is hadronic

Ideally, estimate of energetic input in accelerated particles - $L_{\gamma} \propto W_{p}\, t^{-1} \propto W_{p}\, n$

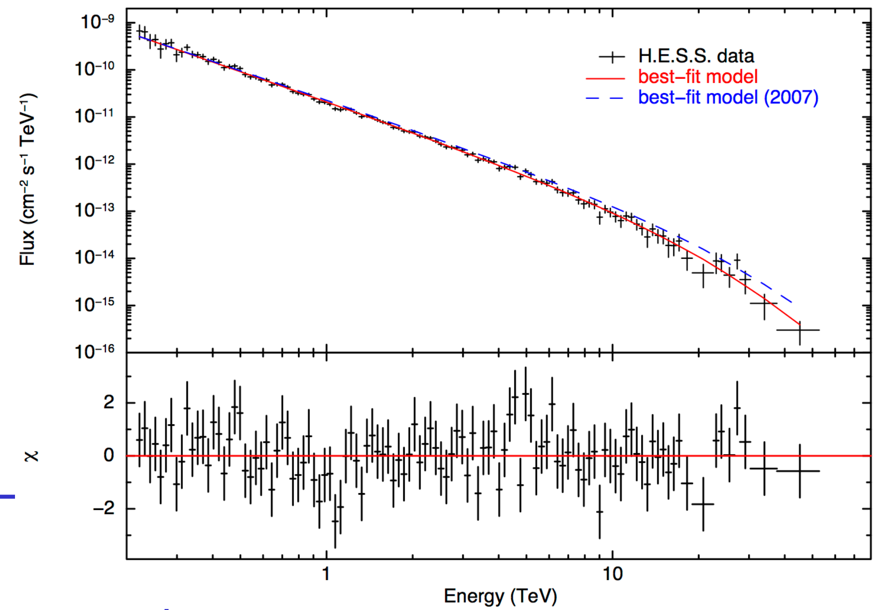
First Suspects : Young SNRs

RXJ1713-3946
HESS Collaboration+16



Theoretically: efficient CR acceleration mechanism

Energetically: energy budget – 10^{51} erg – to sustain the Gal CR population



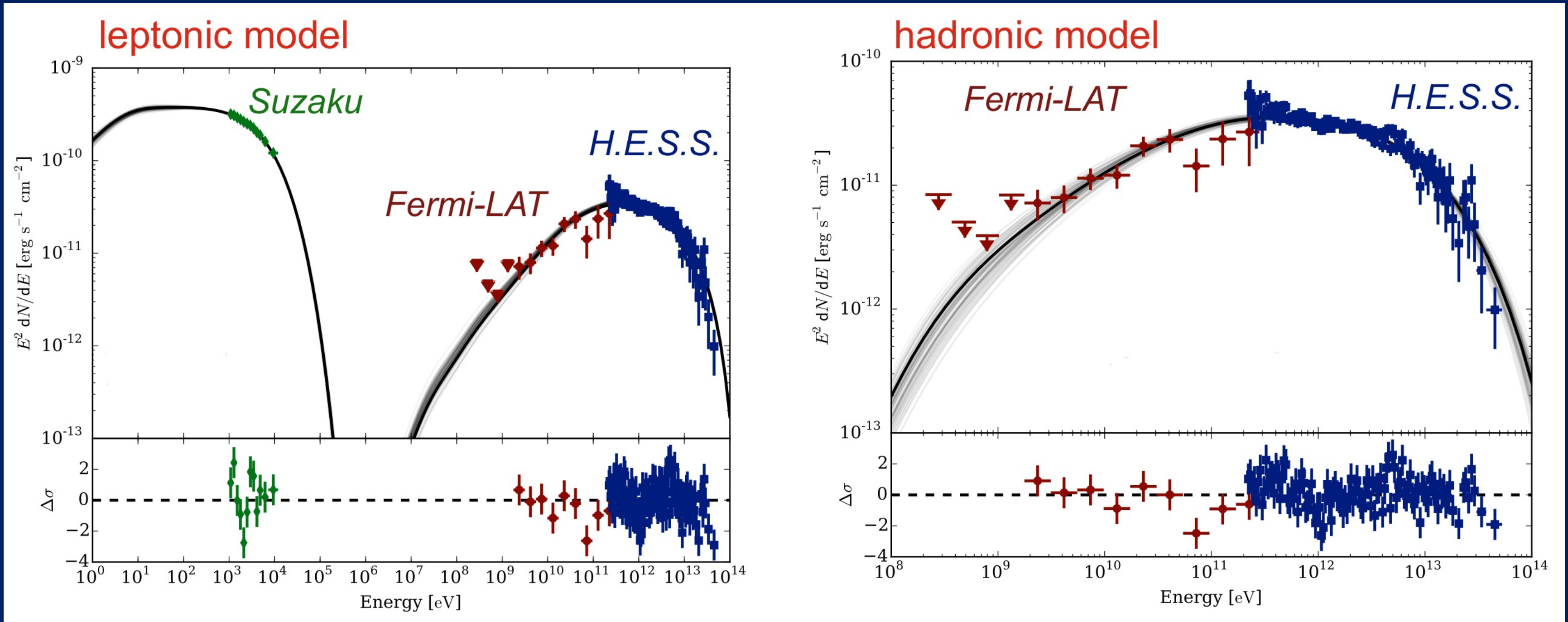
Young (~1.5 kyr) and nearby (~1 kpc) SNR

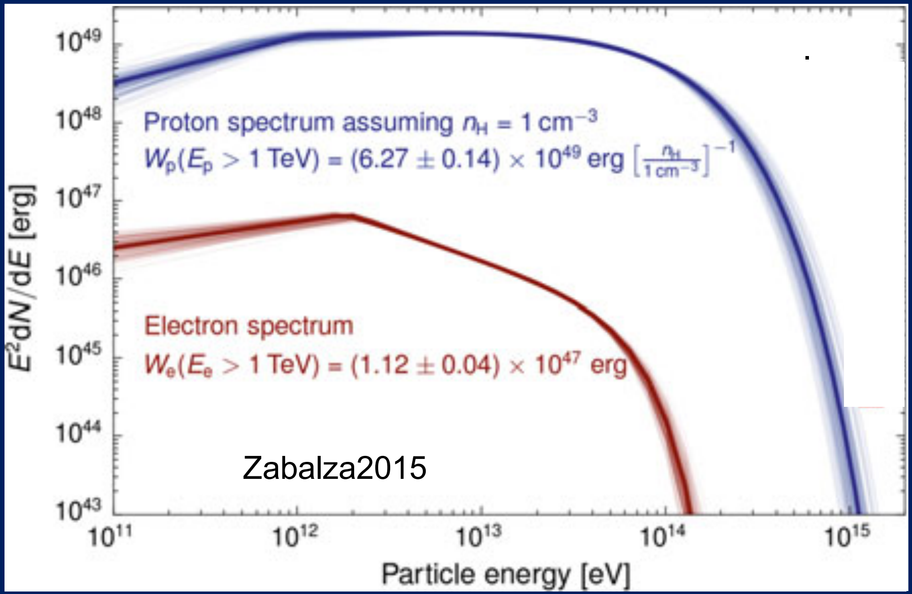
First, and brightest resolved TeV shell

10 years of H.E.S.S. data. (> 27 000 γ's)

Spectrum up to ~50 TeV: cuts off ~ 12 TeV

Hadronic or leptonic ?

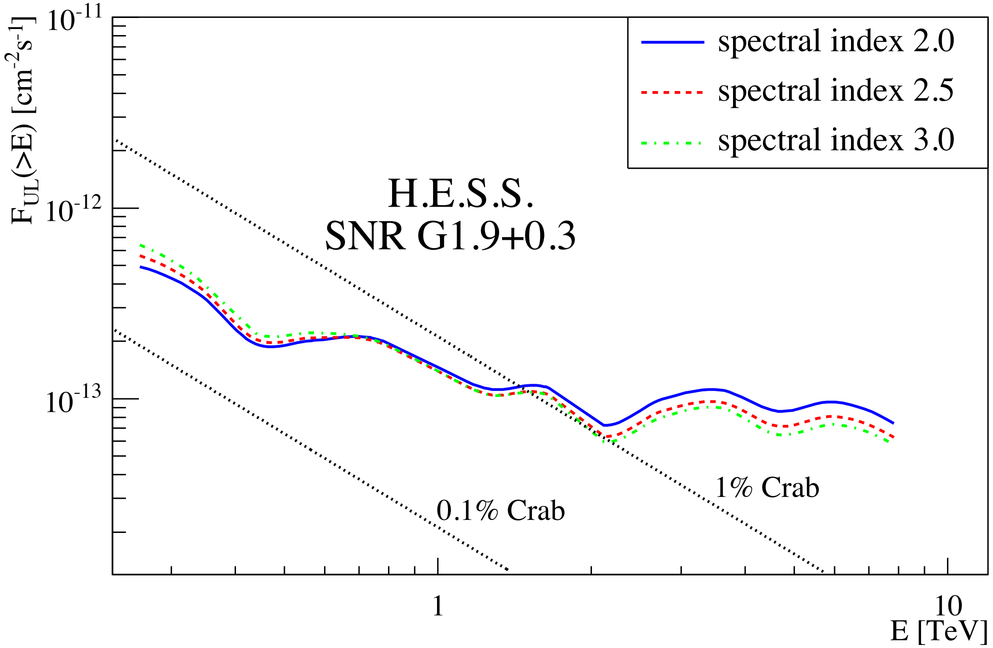


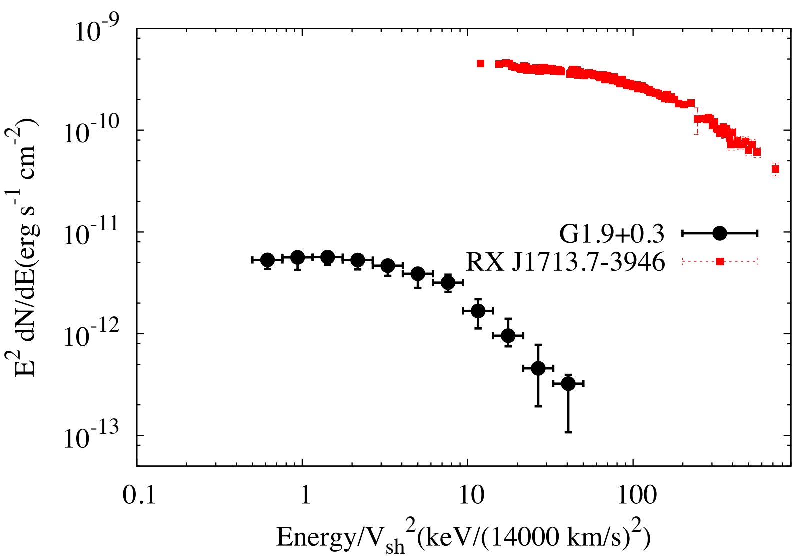


Both hadronic and leptonic can explain the GeV to TeV emission

The content in accelerated hadrons in unknown because of the uncertainty in the estimate of the gas density

The youngest SNR in the Galaxy: G1.9+0.3





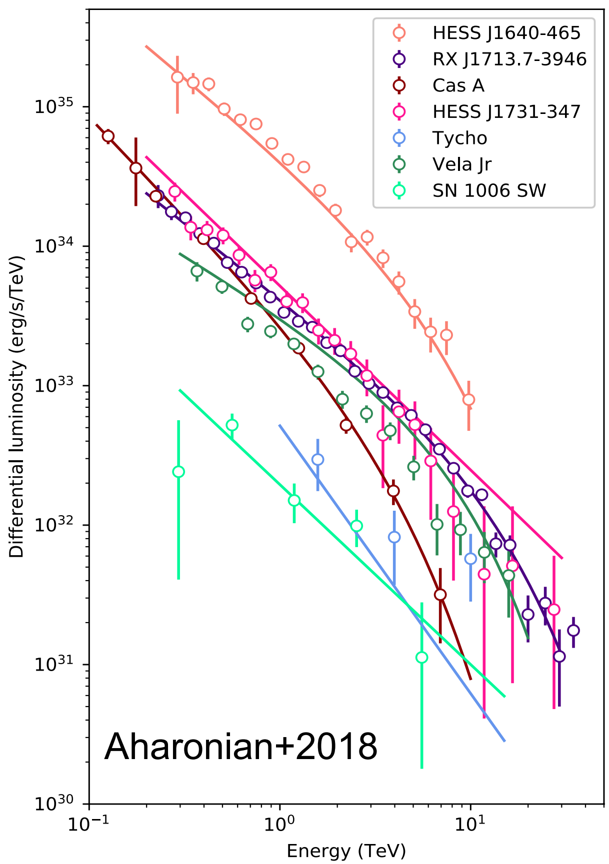
- non thermal dominated youngest SNR
- age~ 150-220 yr
- highest energy protons cannot propagate beyond several pc.
- L_{HESS}(>1 TeV) < 1e32 erg/s -> W_{pp}<10^{45} erg
- Shock speed 14000km/s, Expected in Bohm regime synch peak at 20 keV instead only 1 keV - not efficient accelerator

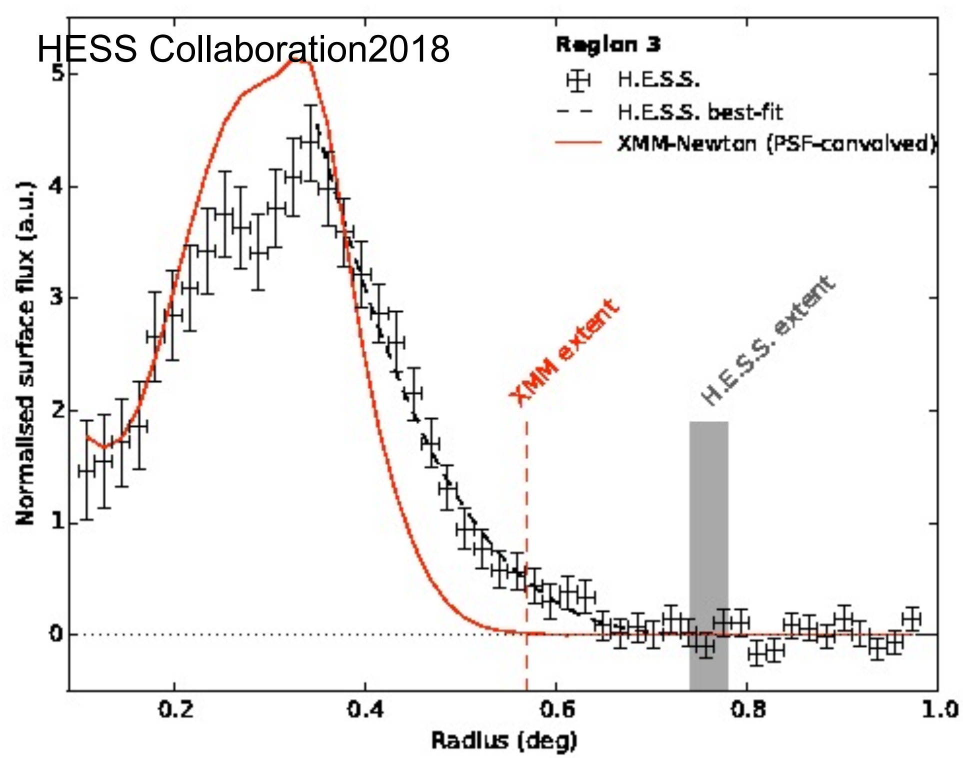
Sun, Yang, Aharonian, 2018

Spectra of young SNRs

- Cutoffs in the spectra of famous young SNRs at few TeVs. Particle acceleration proceeds up to 100 TeV. No indication of particle acceleration proceeding up to the knee

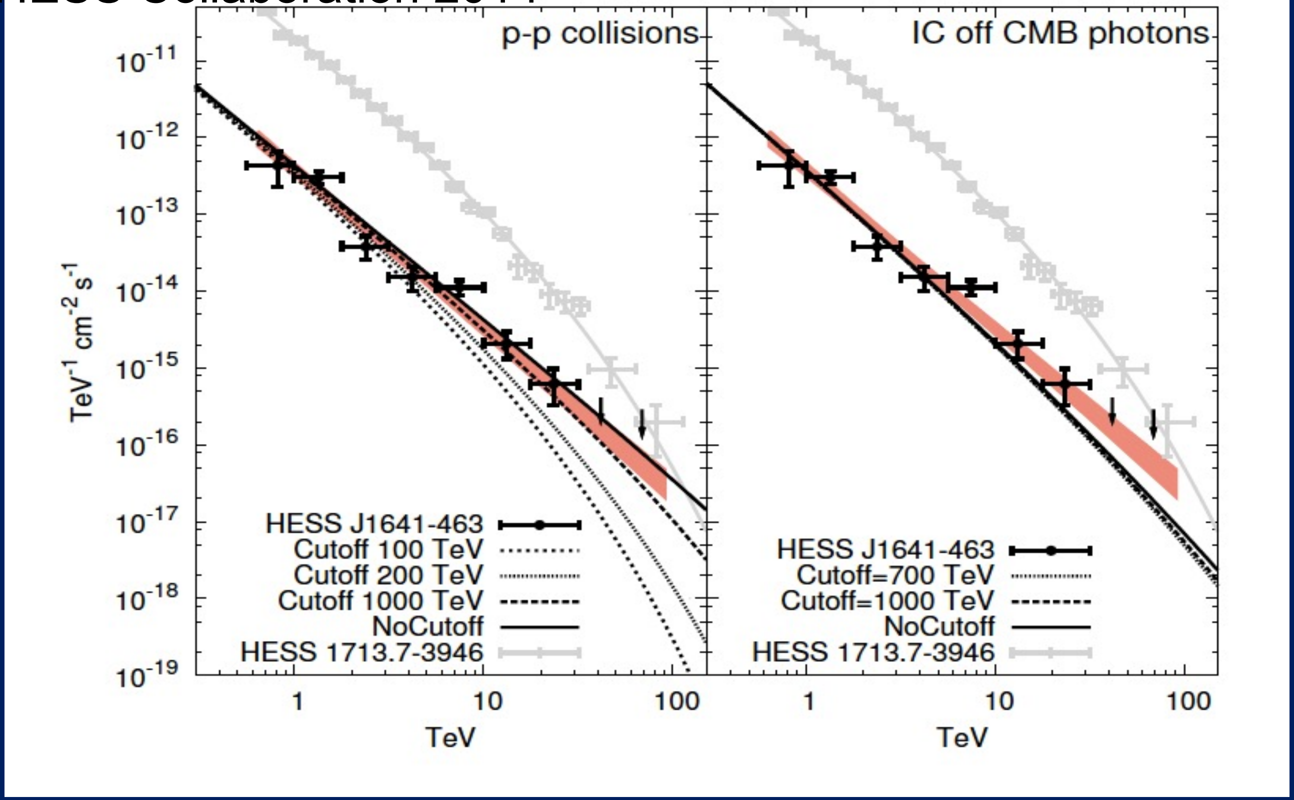
- SNRs thought to act as PeVatrons only during the early phases. Small chance to detect SNRs when they are PeVatrons. Maybe PeVatron gamma-ray signatures from nearby clouds illuminated by runaway CRs

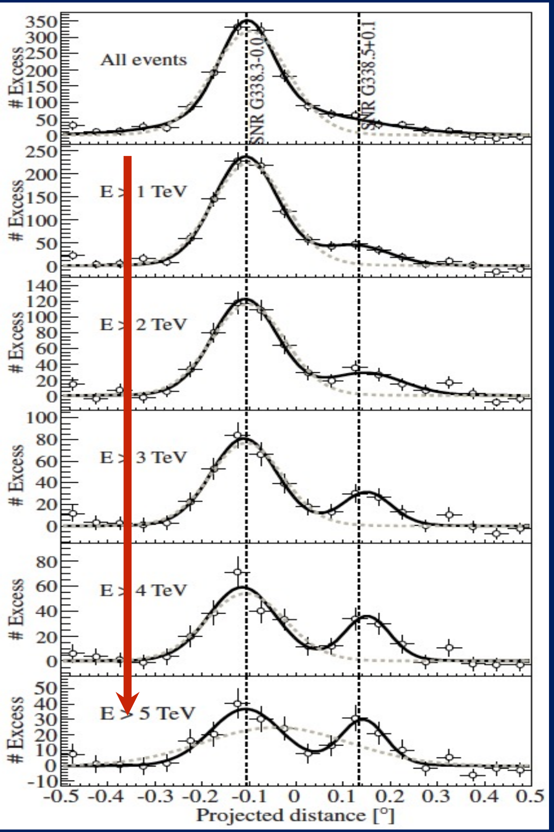


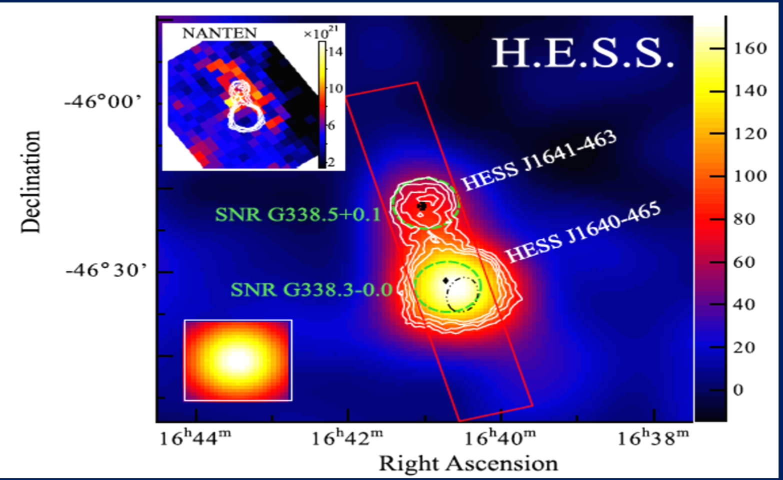


Runaway cosmic rays ?

HESS Collaboration 2014

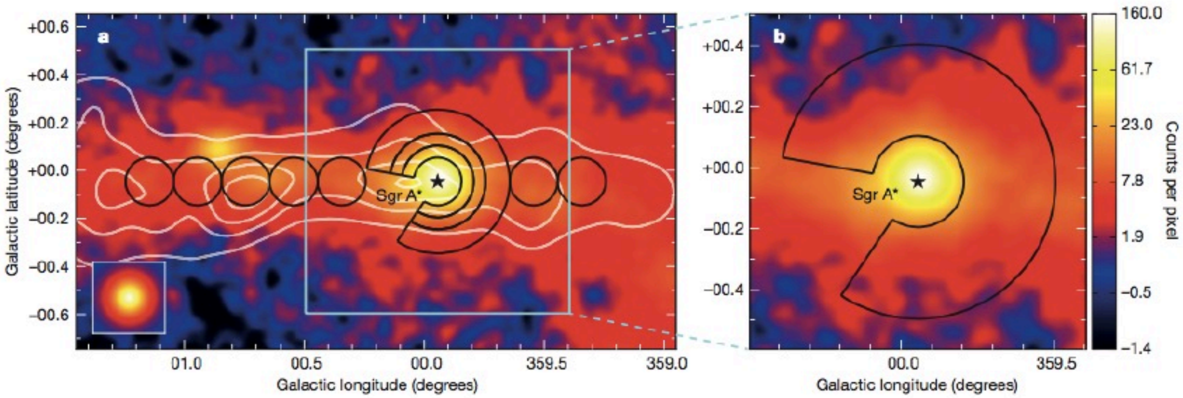






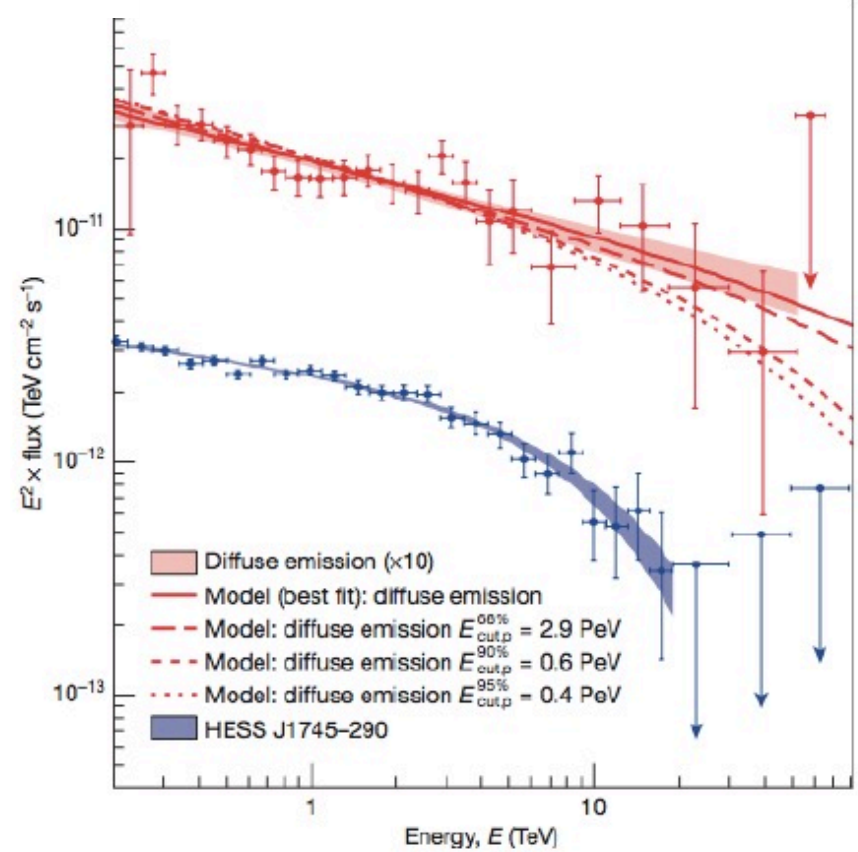
- Very hard spectrum, index 2.07
- No preference for a cutoff
- Data points until 20 TeV
- Lower limit on proton cutoff energy: 100 TeV
- Wp = 10^{50} n^{-1} erg
- Leptonic scenario implies particle spectra up to at least 700 TeV
- Several sources like HESS J1641–463 needed

GC PeVatron : Spectral Studies with H.E.S.S.

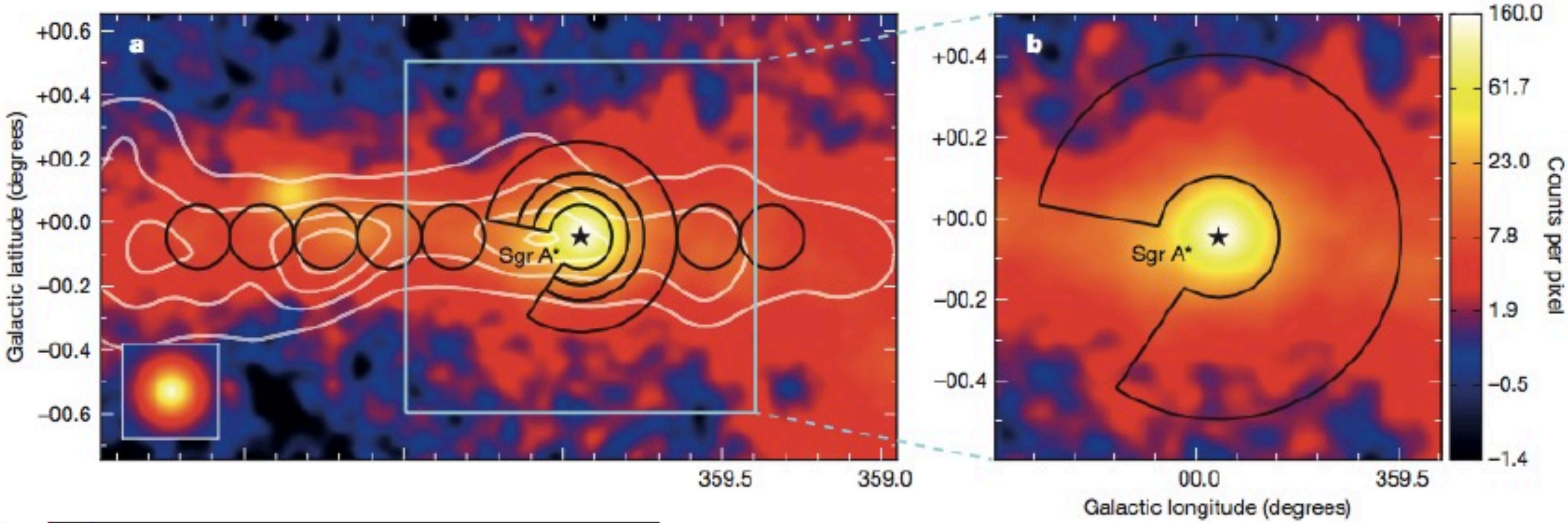


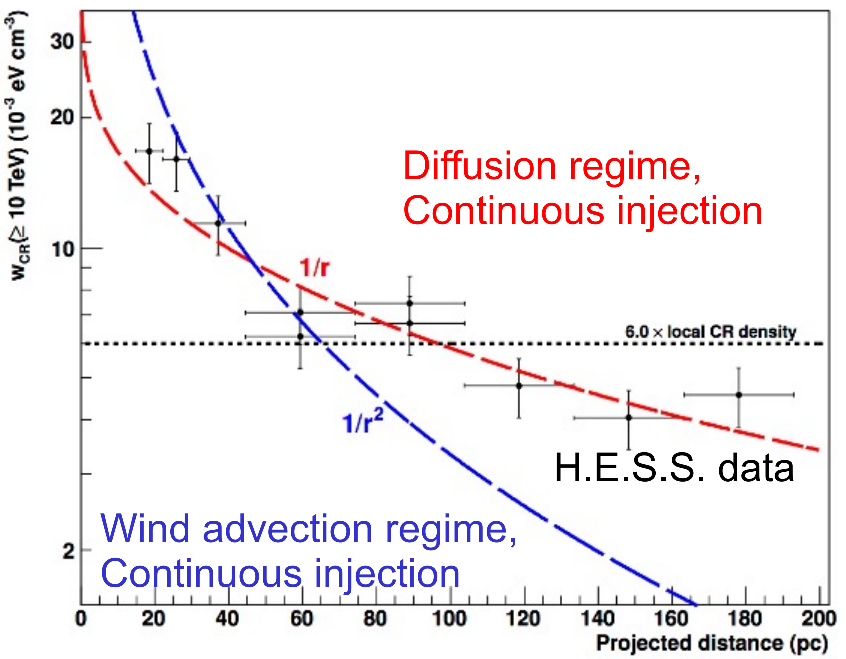
HESS Coll, Nature2016

- Point-like, central source on top of extended (ridge) emission
- Central point source: cut-off @ 10 TeV
- Diffuse emission shows no cut-off well > 10 TeV
- Origin of diffuse emission:
  - Interaction of CR (from central BH) with interstellar medium ?
  - CR acceleration in CMZ (and in particular star forming regions) ?
  - …



GC PeVatron : Morphological studies





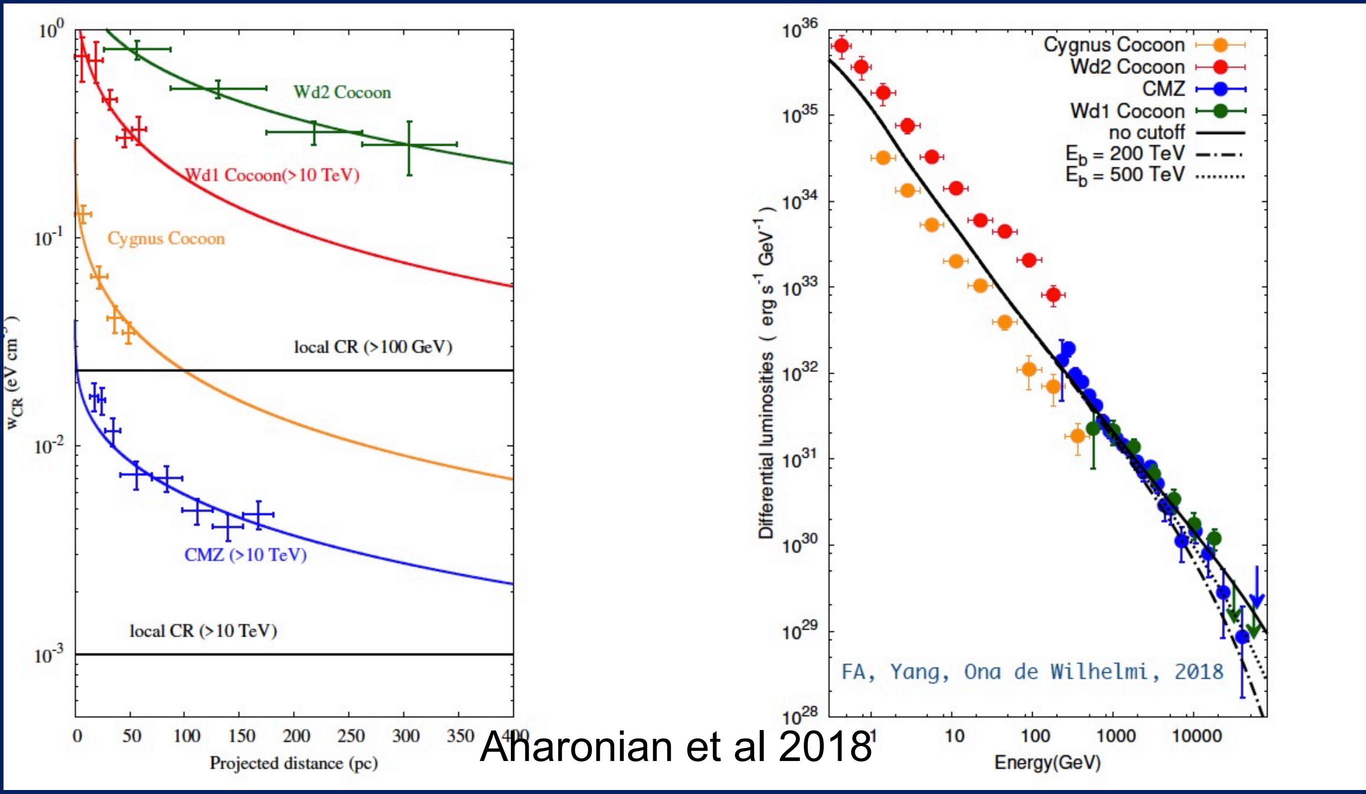
- Emission profile consistent with propagation of protons accelerated continuously from a region < 10 pc from GC
- Current bolometric lum of Sgr A* is 100-1000 times less than required to support CR population. PeVatron more powerful in the past ? Other PeVatrons in the Galaxy ?

Young Stellar Clusters

Extended gamma-ray emissions around young star clusters (50 ~ 200 pc). Gamma-ray luminosity ~ 1e36 erg/s.

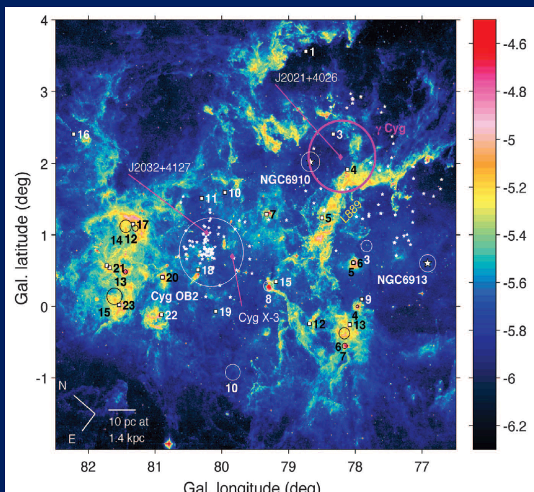
Each source has hard spectrum ~ 2.2, without cutoff

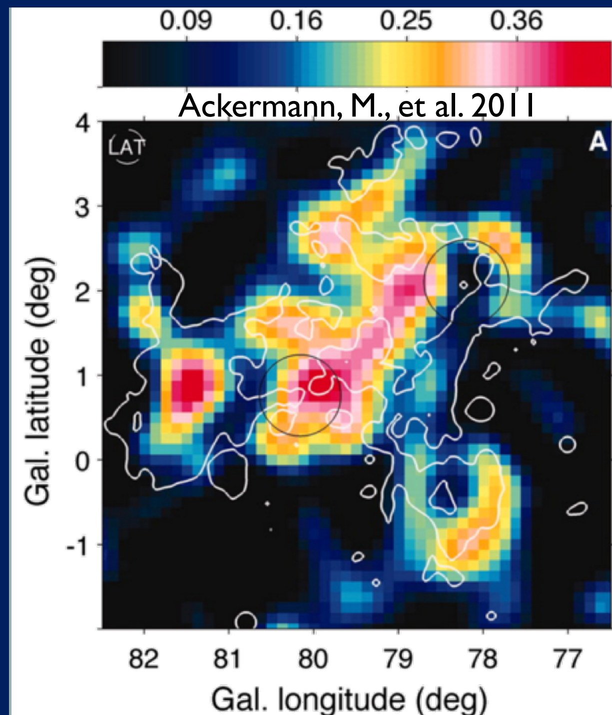
CR distribution derived by gamma-ray profile and gas distributions. 1/r profile implies a continuous injection in the lifetime of clusters



Aharonian et al 2018

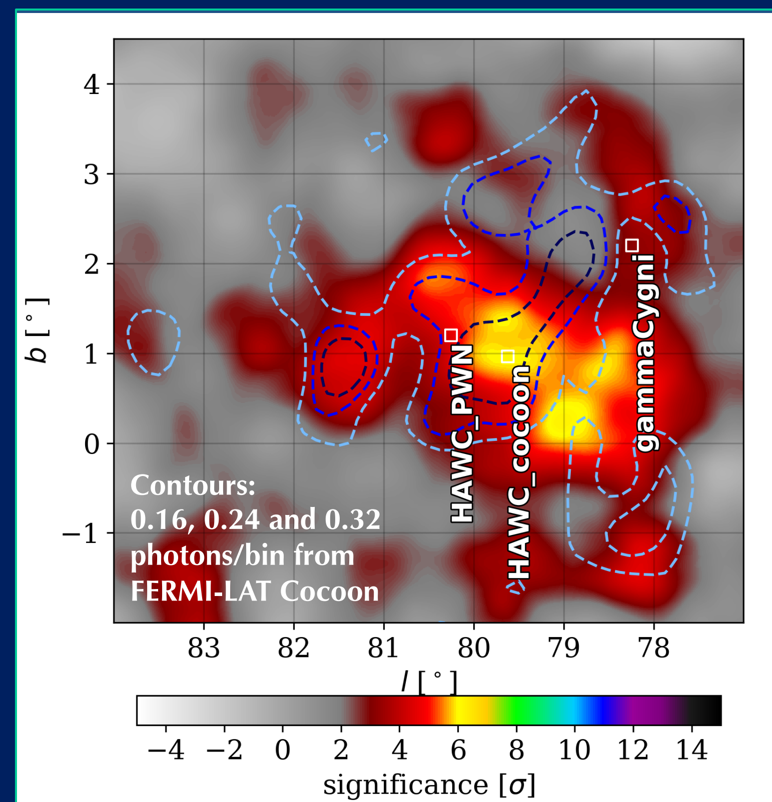
Fermi - Argo -HAWC-LHAASO cocoon





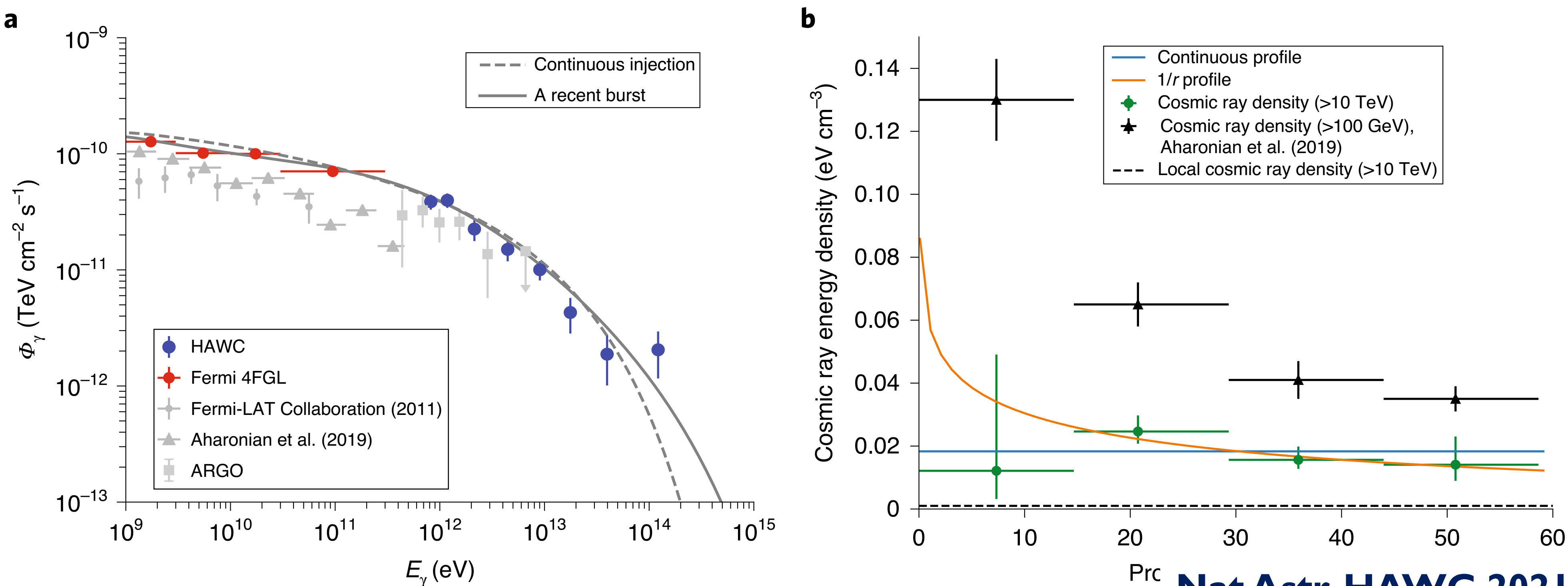
Fermi detected hard and extended emission from Cygnus X, between OB2 and Gamma Cygni SNR

HAWC significance map of the Cygnus Cocoon



HAWC Coll, NatAstr 2021

Cocoon Spectrum and morphology



Nat Astr, HAWC 2021

Unique SFR seen from GeV to PeV energies

Spectral break with respect to Fermi datapoints

CR density > 10 TeV higher than local CR in the whole region

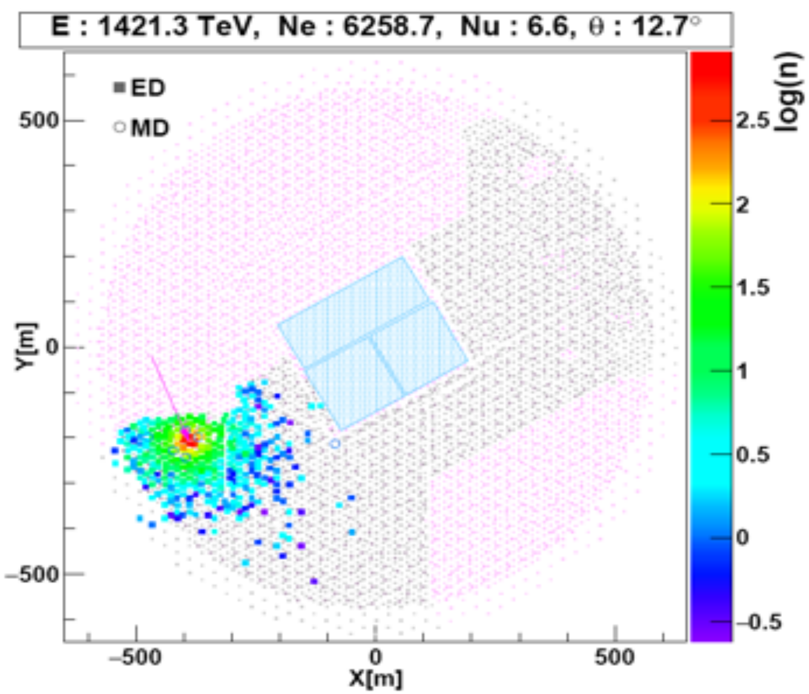
1/r profile would suggest a continous injection. A constant profile would suggest a recent burst event happened less than 0.1 Myr

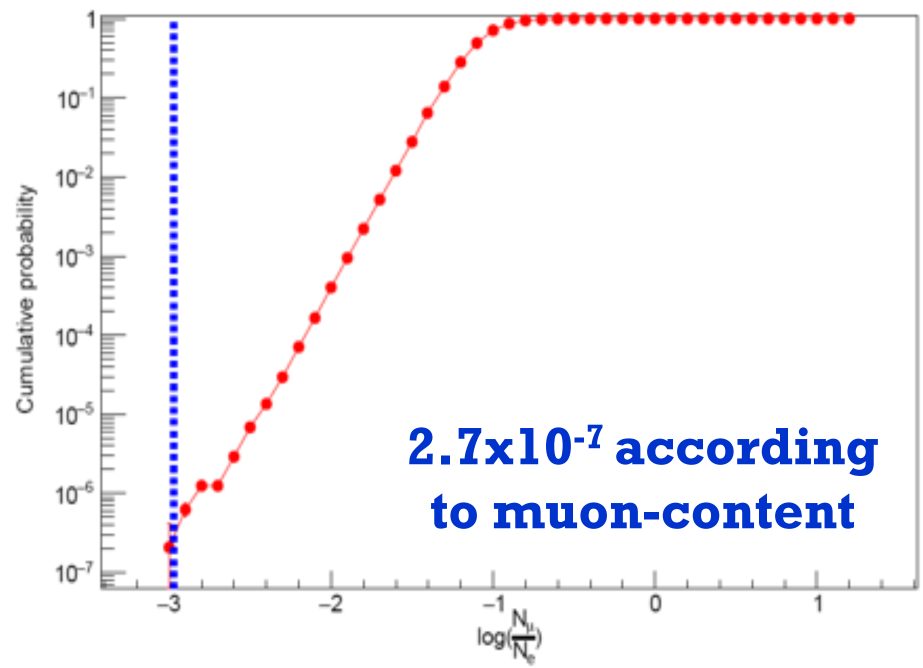
10000 CygOB2 would be required for CRs Galactic population

Highest energy photon

中国科学技术大学 University of Science and Technology of China

- **1.42±0.13 PeV from the Cygnus region**
- **Chance probility due to cosmic ray background 0.028%.**

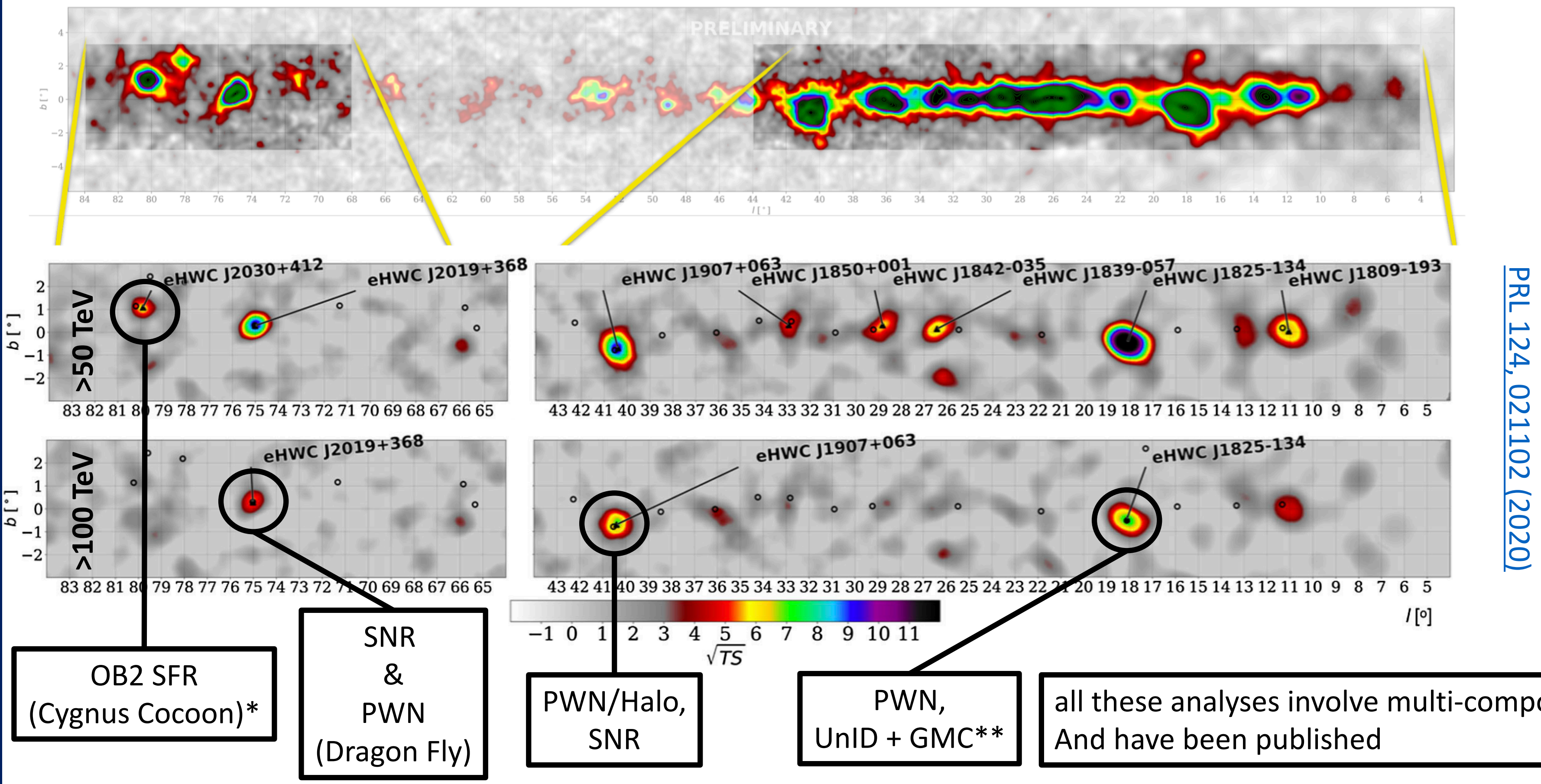




Nature 594:33-36 (2021)

Slide by Ruizhi Yang

HAWC survey for Galactic PeVatrons

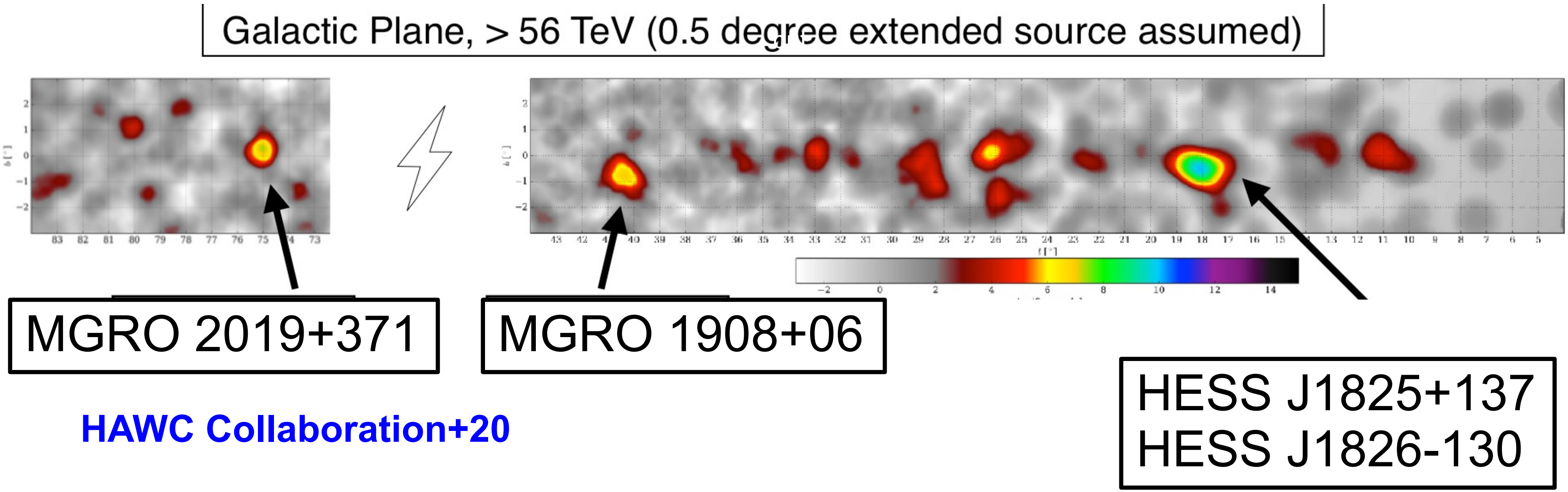


PRL 124, 021102 (2020)

all these analyses involve multi-component fits
And have been published

The Galaxy above 56 TeV

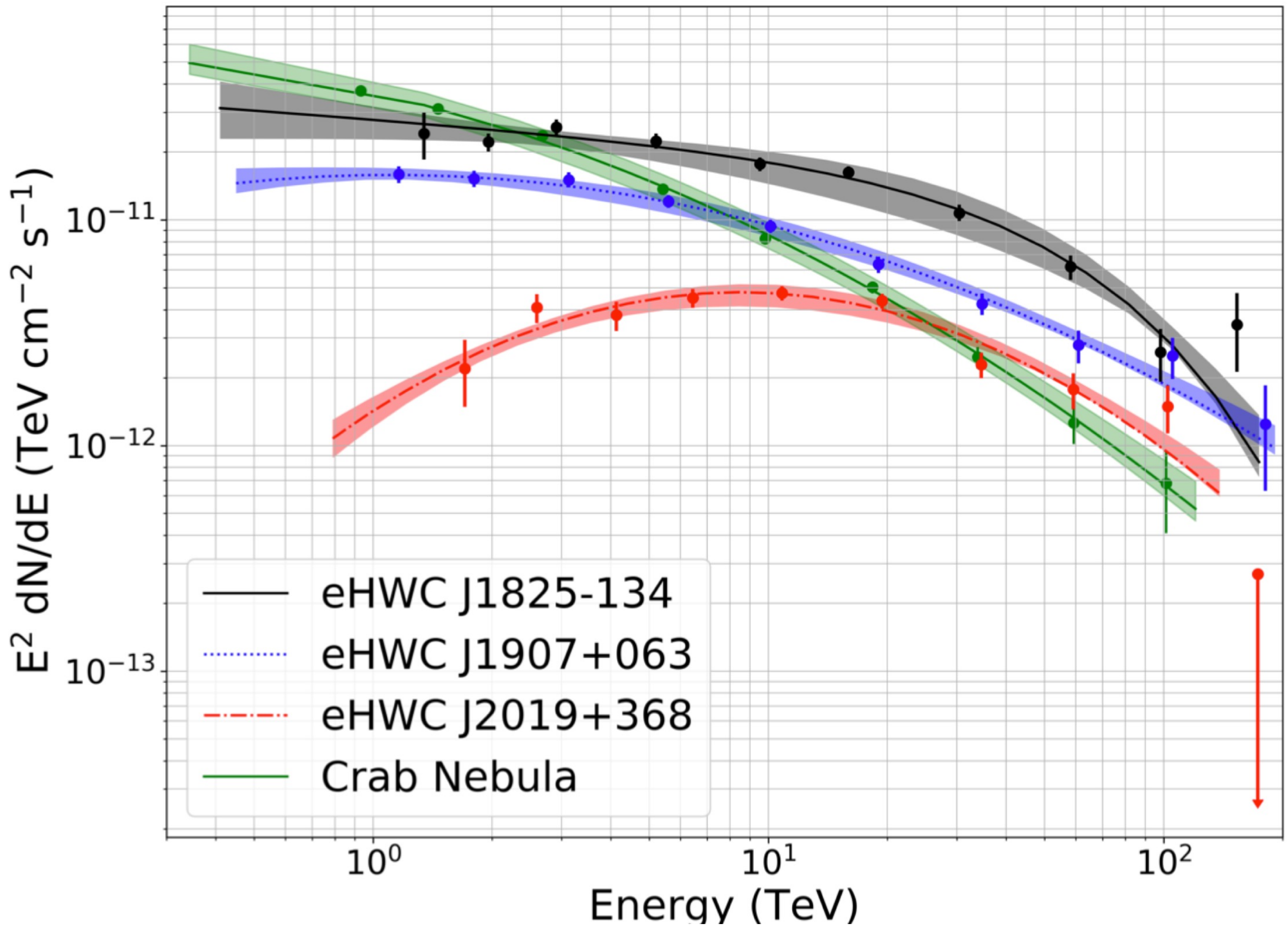
Source name	RA (^{o})	Dec (^{o})	Extension > 56 TeV (^{o})	F (10^{-14} ph cm^{-2} s^{-1})	$\sqrt{TS}$ > 56 TeV	nearest 2HWC source	Distance to 2HWC source(^{o})	$\sqrt{TS}$ > 100 TeV
eHWC J0534+220	83.61 ± 0.02	22.00 ± 0.03	PS	1.2 ± 0.2	12.0	J0534+220	0.02	4.44
eHWC J1809-193	272.46 ± 0.13	-19.34 ± 0.14	0.34 ± 0.13	$2.4^{+0.6}_{-0.5}$	6.97	J1809-190	0.30	4.82
eHWC J1825-134	276.40 ± 0.06	-13.37 ± 0.06	0.36 ± 0.05	4.6 ± 0.5	14.5	J1825-134	0.07	7.33
eHWC J1839-057	279.77 ± 0.12	-5.71 ± 0.10	0.34 ± 0.08	1.5 ± 0.3	7.03	J1837-065	0.96	3.06
eHWC J1842-035	280.72 ± 0.15	-3.51 ± 0.11	0.39 ± 0.09	1.5 ± 0.3	6.63	J1844-032	0.44	2.70
eHWC J1850+001	282.59 ± 0.21	0.14 ± 0.12	0.37 ± 0.16	$1.1^{+0.3}_{-0.2}$	5.31	J1849+001	0.20	3.04
eHWC J1907+063	286.91 ± 0.10	6.32 ± 0.09	0.52 ± 0.09	2.8 ± 0.4	10.4	J1908+063	0.16	7.30
eHWC J2019+368	304.95 ± 0.07	36.78 ± 0.04	0.20 ± 0.05	$1.6^{+0.3}_{-0.2}$	10.2	J2019+367	0.02	4.85
eHWC J2030+412	307.74 ± 0.09	41.23 ± 0.07	0.18 ± 0.06	0.9 ± 0.2	6.43	J2031+415	0.34	3.07



HAWC Collaboration+20

The Galaxy above 100 TeV: Spectra

HAWC Collaboration+20

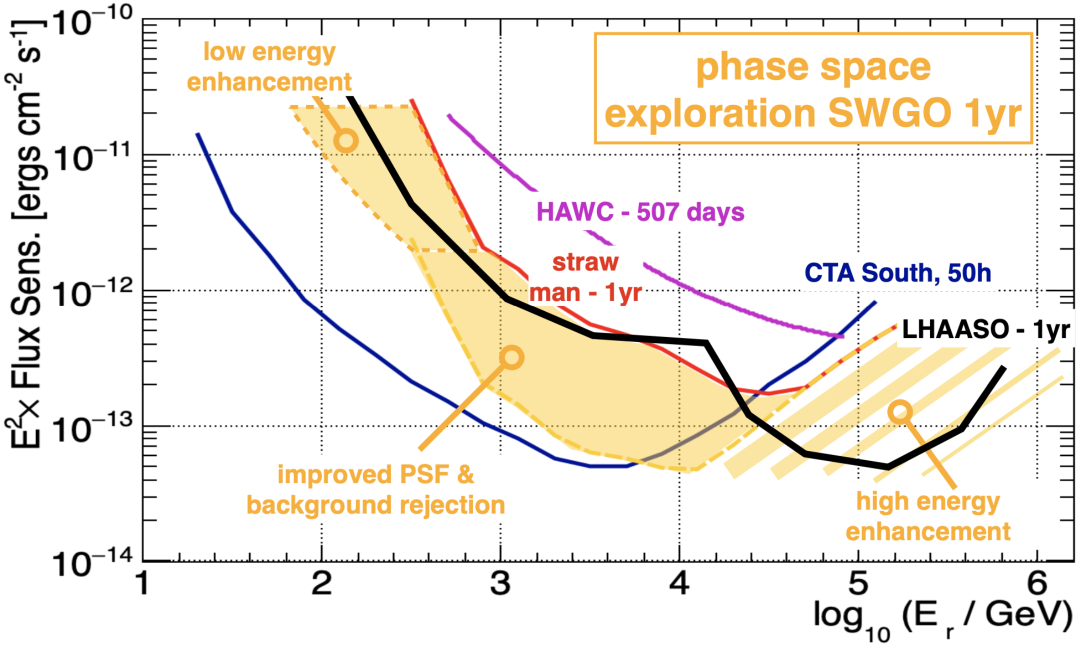


Source	$\sqrt{TS}$	Extension (^{o})	ϕ_0 (10^{-13} TeV cm^2 s)$^{-1}$	α	E_{cut} (TeV)	PL diff
eHWC J1825-134	41.1	0.53 ± 0.02	2.12 ± 0.15	2.12 ± 0.06	61 ± 12	7.4

Source	$\sqrt{TS}$	Extension (^{o})	ϕ_0 (10^{-13} TeV cm^2 s)$^{-1}$	α	β	PL diff
eHWC J1907+063	37.8	0.67 ± 0.03	0.95 ± 0.05	2.46 ± 0.03	0.11 ± 0.02	6.0
eHWC J2019+368	32.2	0.30 ± 0.02	0.45 ± 0.03	2.08 ± 0.06	0.26 ± 0.05	8.2

Extrapolating the number of sources

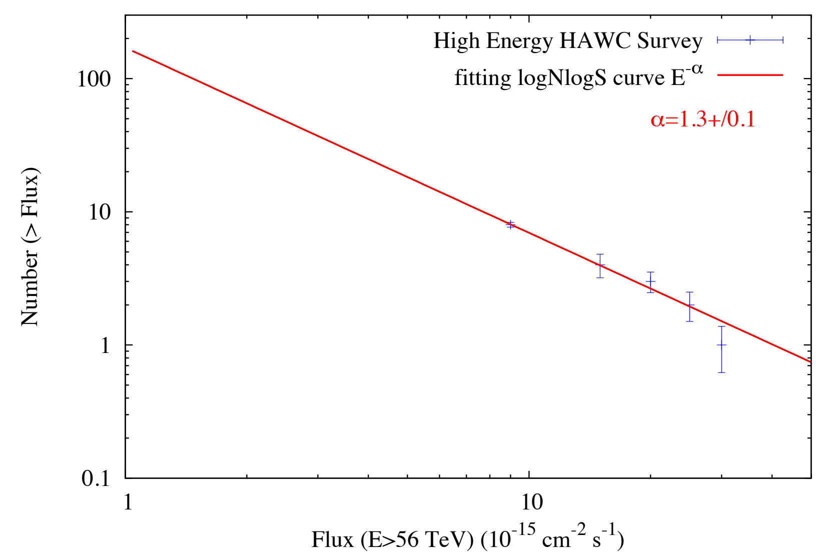
Schoorlemmer, for SWGO Coll 2021



Differential point source sensitivity of several experiments and the phase-space for the design studies for SWGO

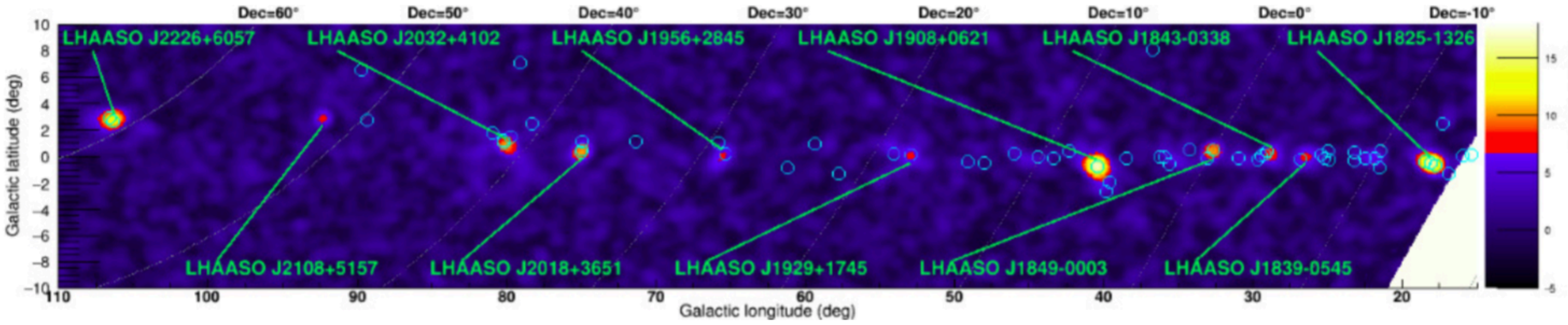
HAWC Collaboration+19

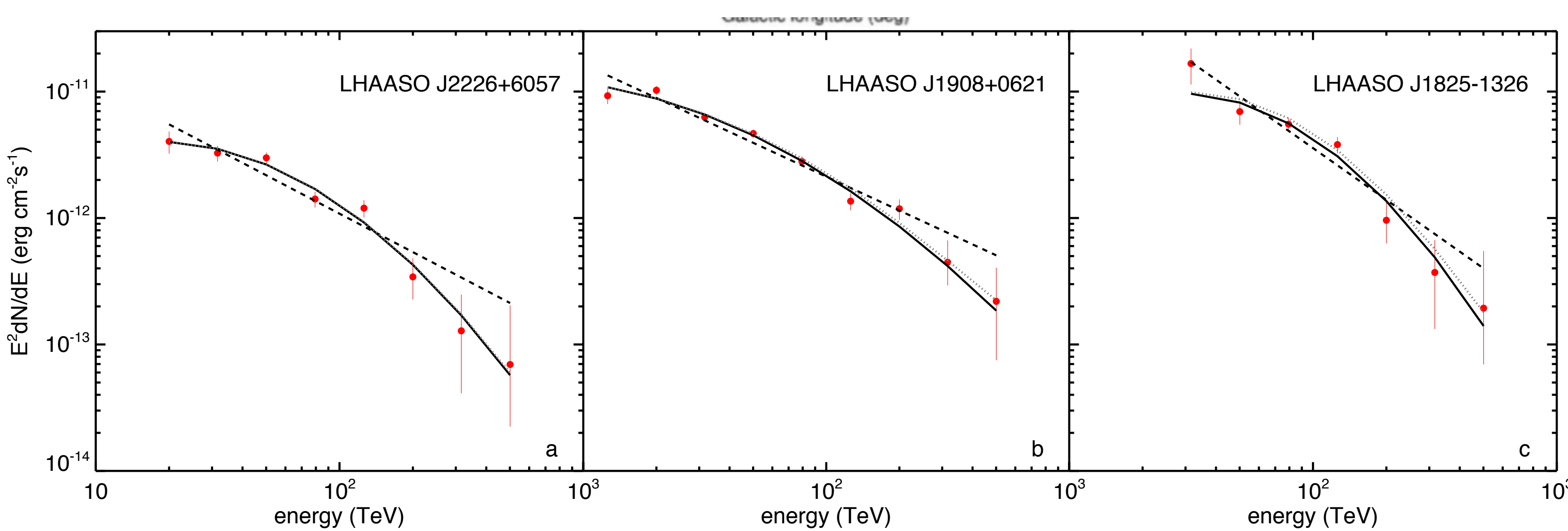
Source	F (10^{-14} ph cm^{-2} s^{-1})	$\sqrt{TS}$ > 56 TeV	$\sqrt{TS}$ > 100 TeV
eHWC J0534+220	$1.5^{+0.3}_{-0.2}$	11.7	4.27
eHWC J1809-193	$2.6^{+0.7}_{-0.6}$	6.76	4.69
eHWC J1825-134	$5.4^{+0.7}_{-0.6}$	14.0	7.35
eHWC J1839-057	$1.7^{+0.4}_{-0.3}$	6.63	3.03
eHWC J1842-035	$1.7^{+0.4}_{-0.3}$	6.06	2.52
eHWC J1850+001	$1.3^{+0.4}_{-0.3}$	5.18	3.09
eHWC J1907+063	$3.4^{+0.5}_{-0.4}$	10.3	7.17
eHWC J2019+368	1.9 ± 0.3	9.86	5.55
eHWC J2030+412	$1.1^{+0.3}_{-0.2}$	6.16	2.96



1 yr LHAASO Survey

LHAASO Coll Nature 2021





1 yr LHAASO Survey

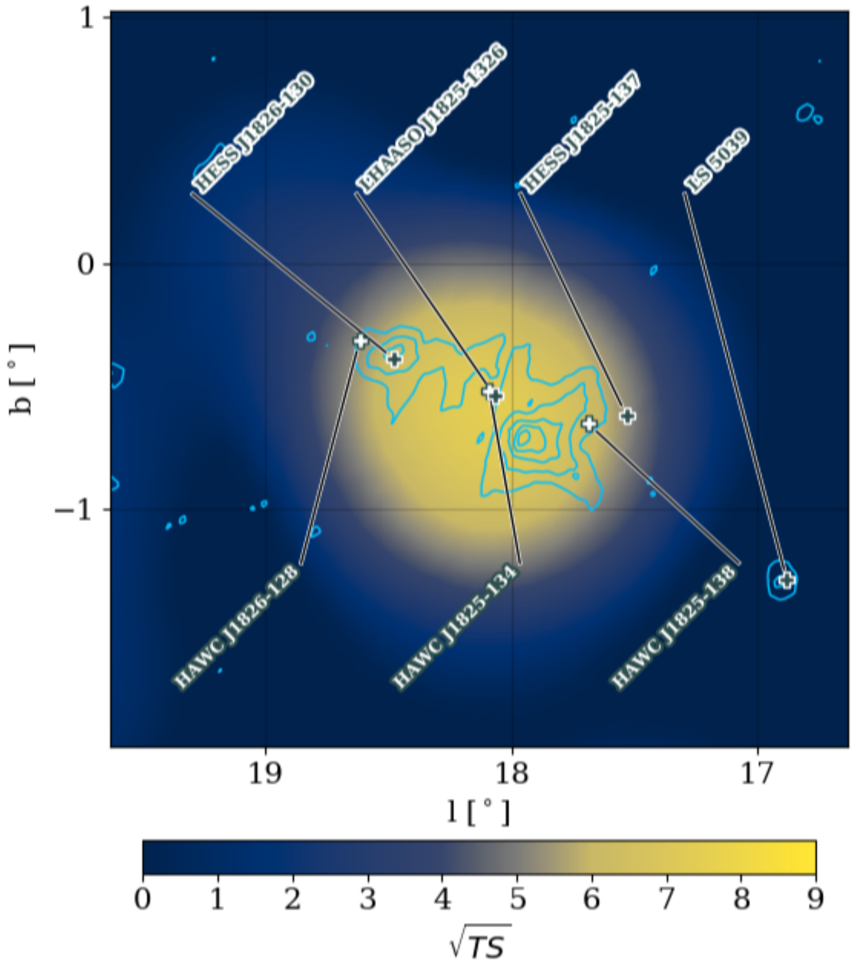
Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 -0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 -0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

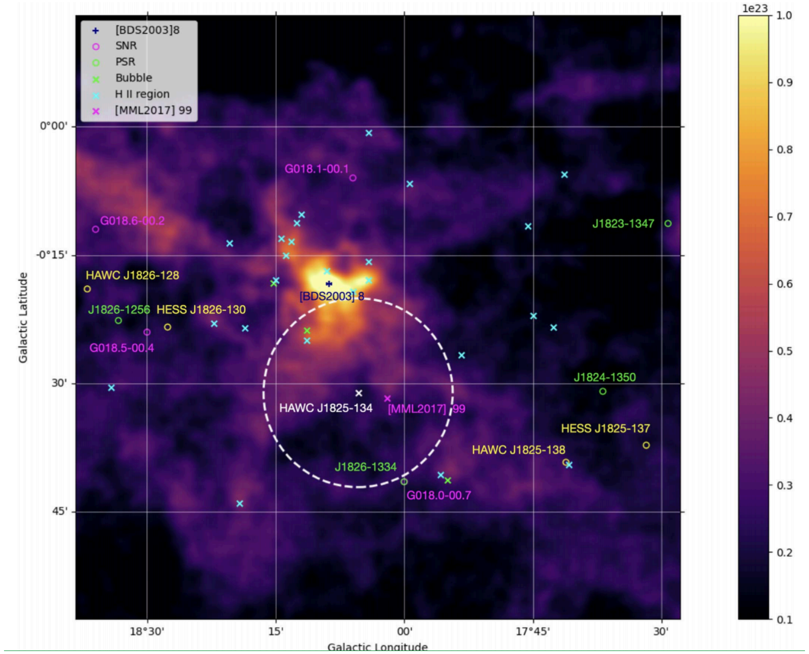
LHAASO Coll Nature 2021

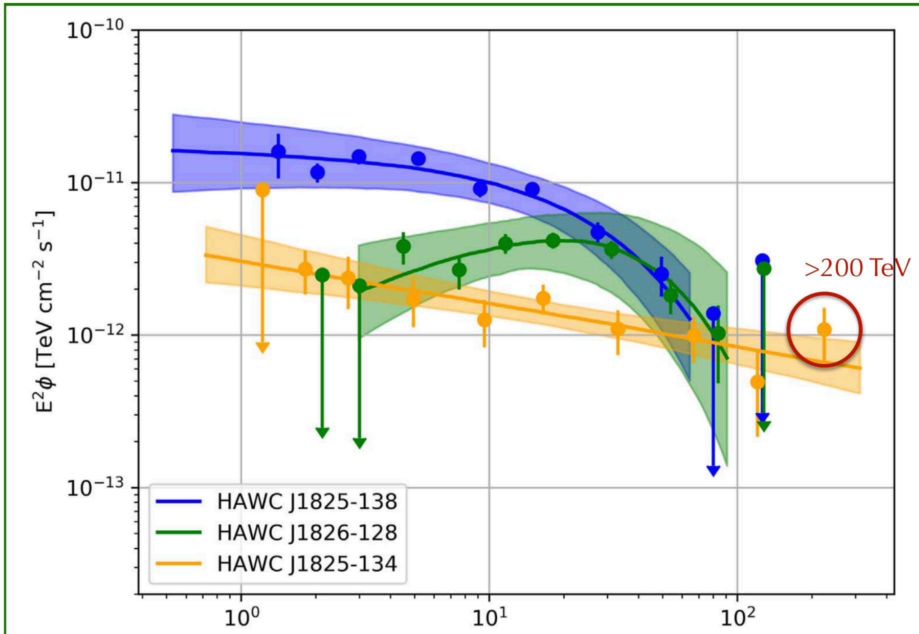
HAWC J1825-134

HAWC Coll ApJL 2021

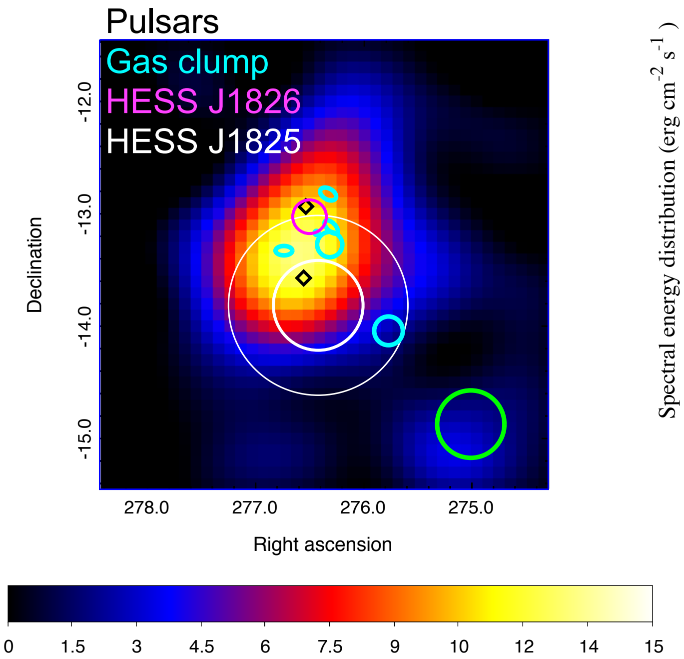


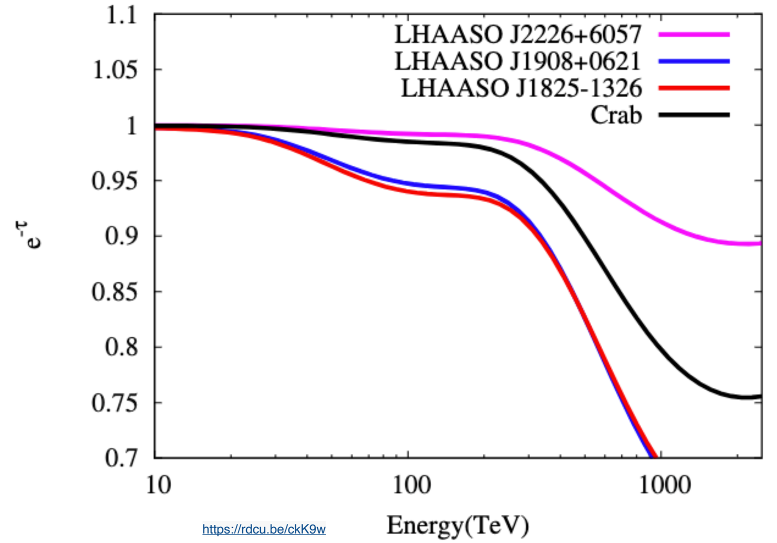
Above 177 TeV

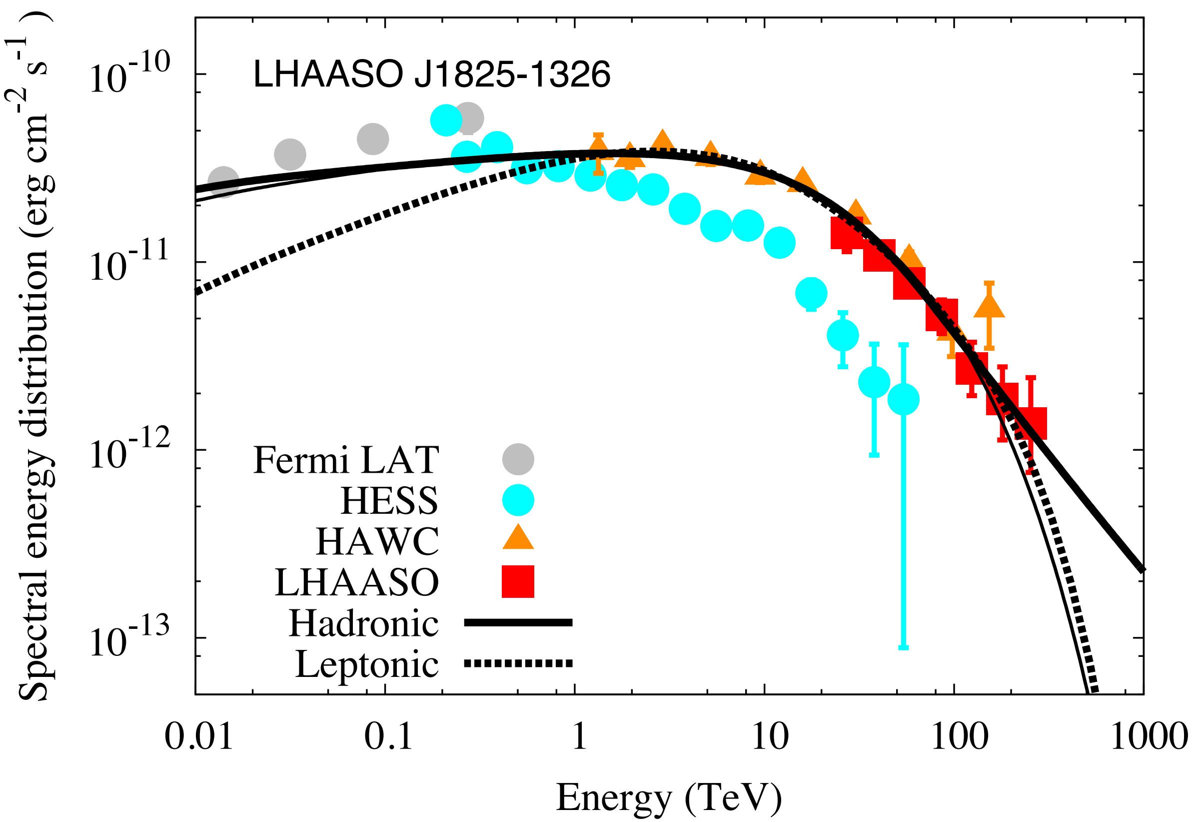




LHAASO J1825-1326

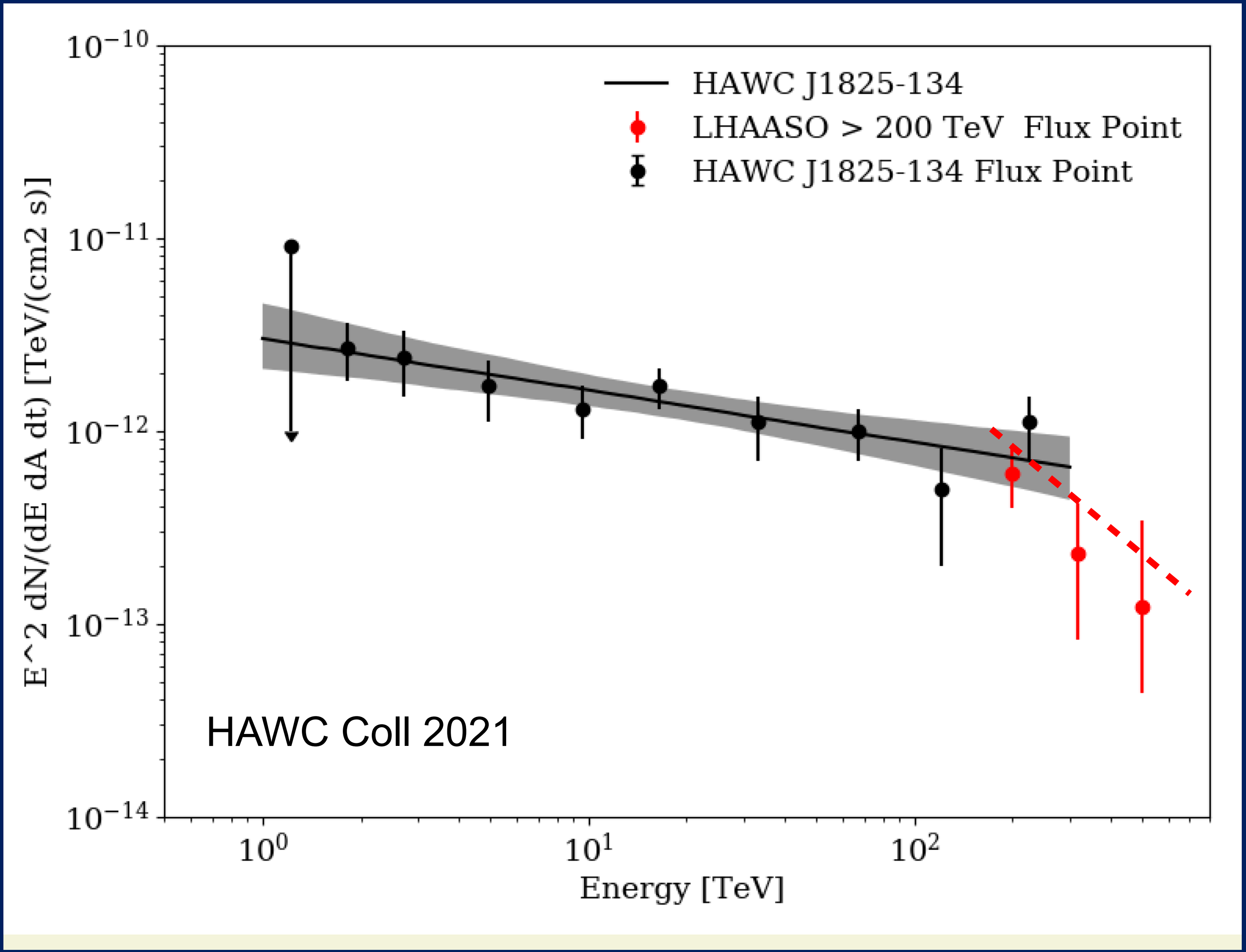






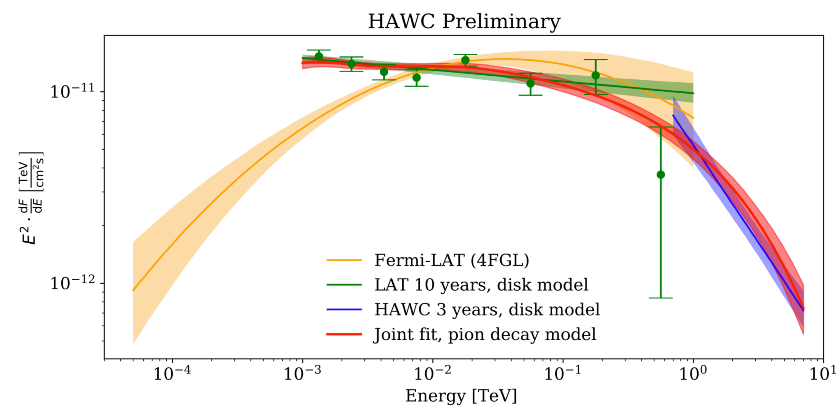
LHAASO Coll Nature 2021

HAWC J1825-134 and LHAASO J1825-136 above 200 TeV



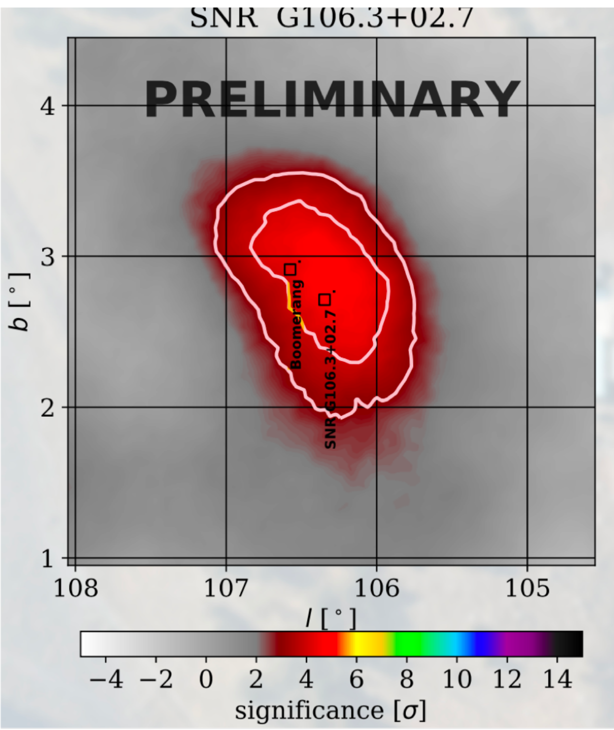
Testing the SNR paradigm

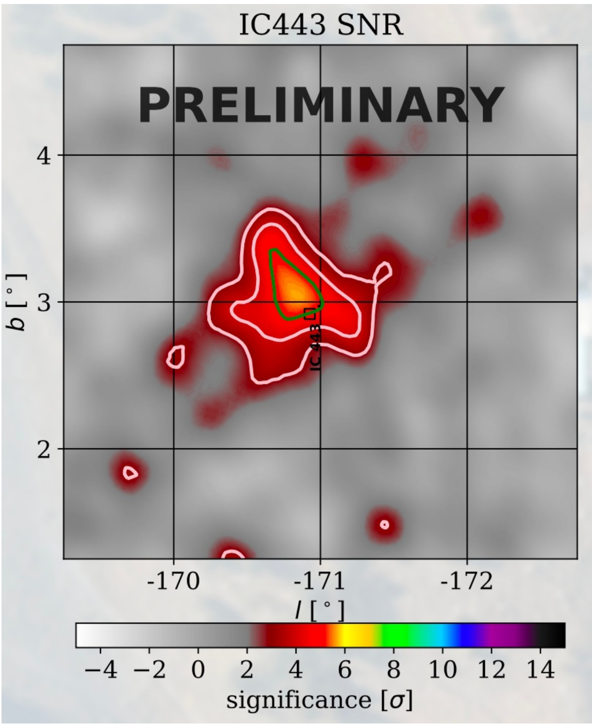
Combined Fermi - HAWC fit to γ Cygni

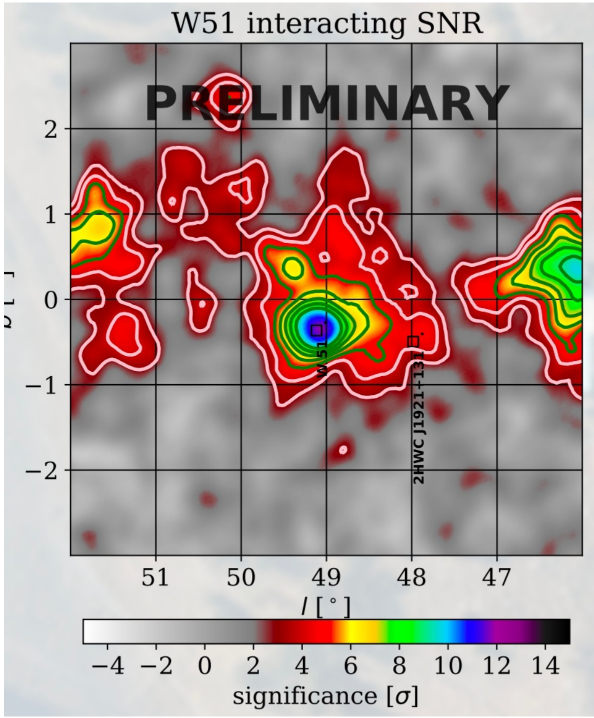


HAWC TeV γ-rays from middle-aged

from γ-Cygni, IC 433, and W51C



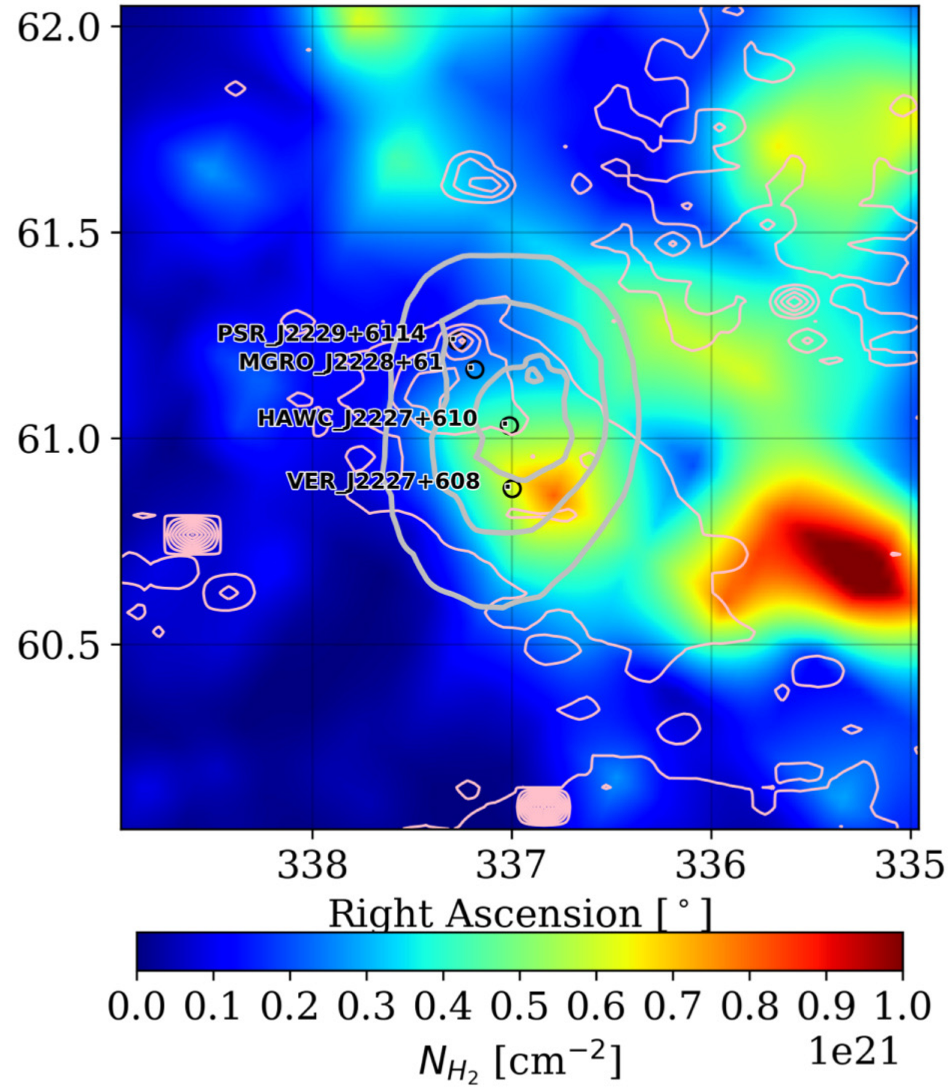




SNR G106.3+2.7: Galactic PeVatron ?

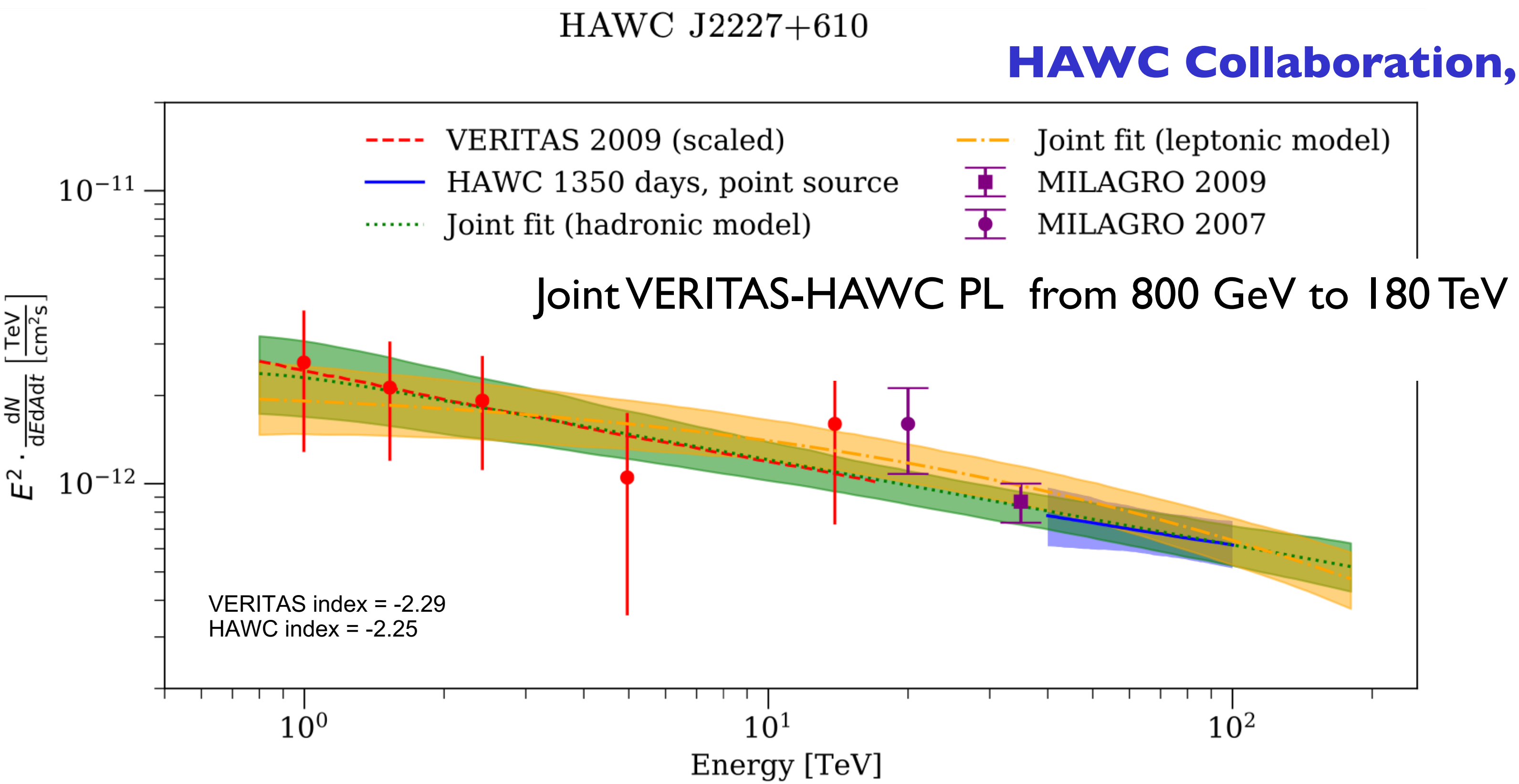
HAWC Collaboration, ApJL 2020

- SNR G106.3+2.7 is a 10kyr comet-shaped radio source at 0.8 kpc
- PSR J2229+6114, seen in radio, X-rays, and gamma rays
- Boomerang Nebula is contained in the remnant
- VERITAS source (energy range 900 GeV – 16 TeV)
- HAWC emission pointlike, morphology compatible with VERITAS source and coincident with a region of high gas density



G106.3+2.7 : a Galactic PeVatron?

HAWC Collaboration, ApJL 2020



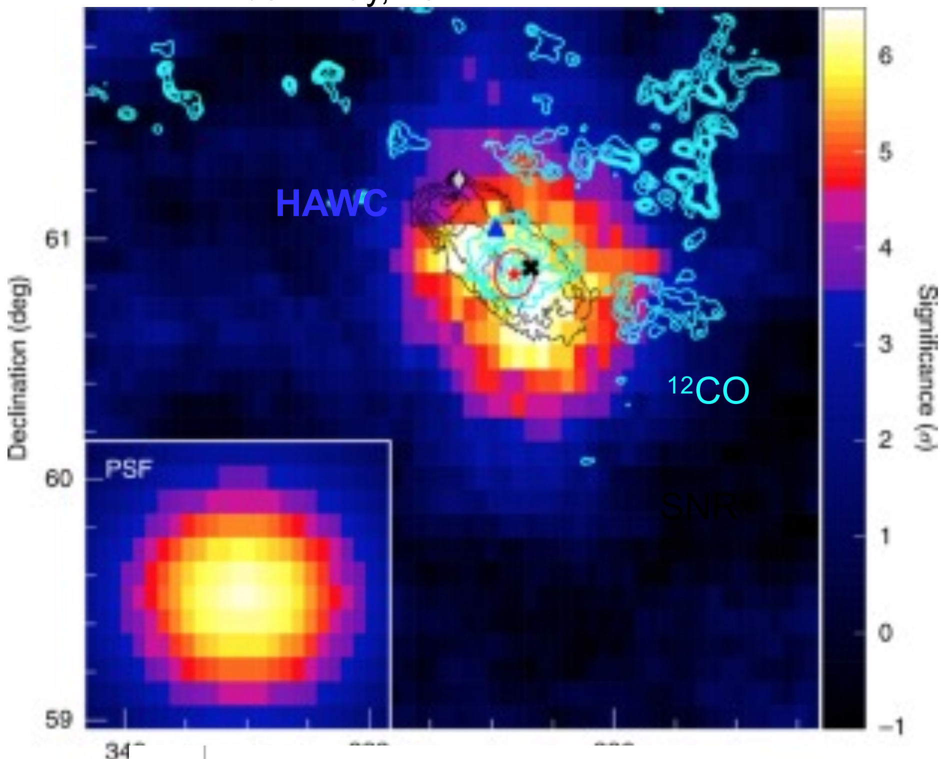
Gamma PL : 2.29, Lower limit on gamma Ecut = 120 TeV

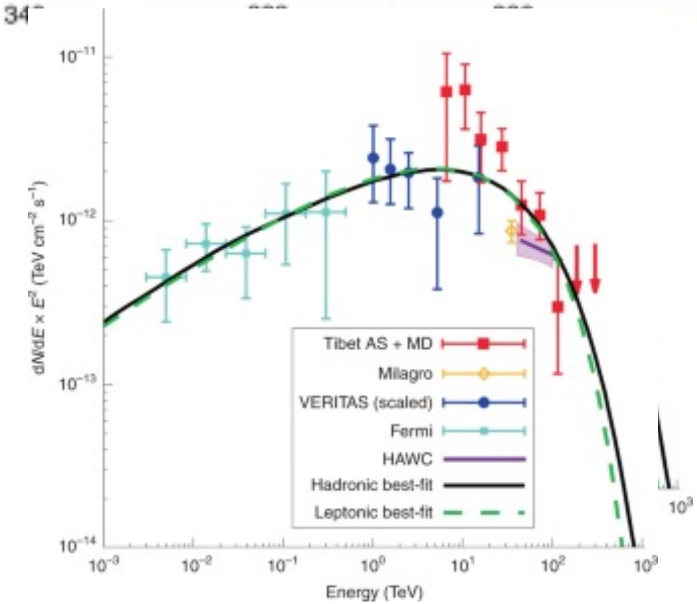
Proton PL : 2.35, Lower limit on proton Ecut = 800 TeV,

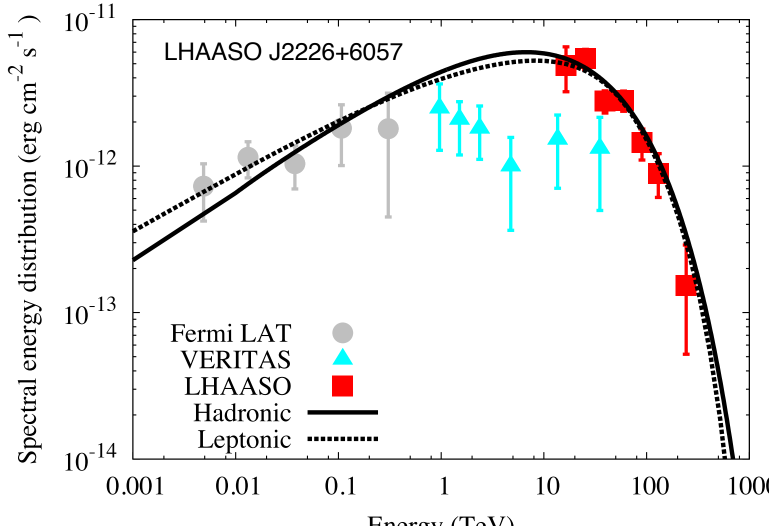
$W_p = 10^{48} (n/50)^{-1}$ erg

G106.3+2.7: a Galactic PeVatron ?

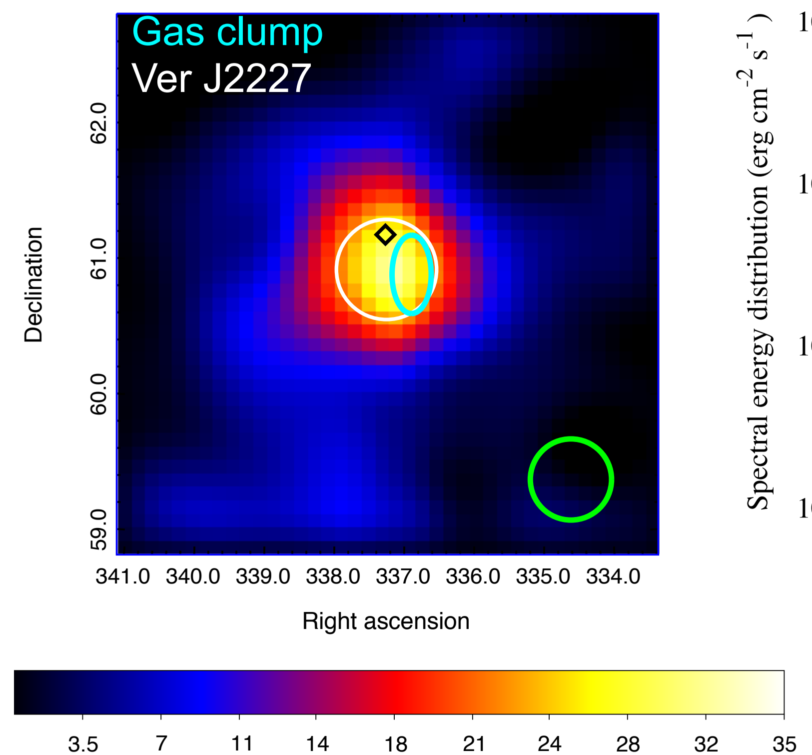
Significance above 10 TeV
Tibet Array, 2021







Pulsar

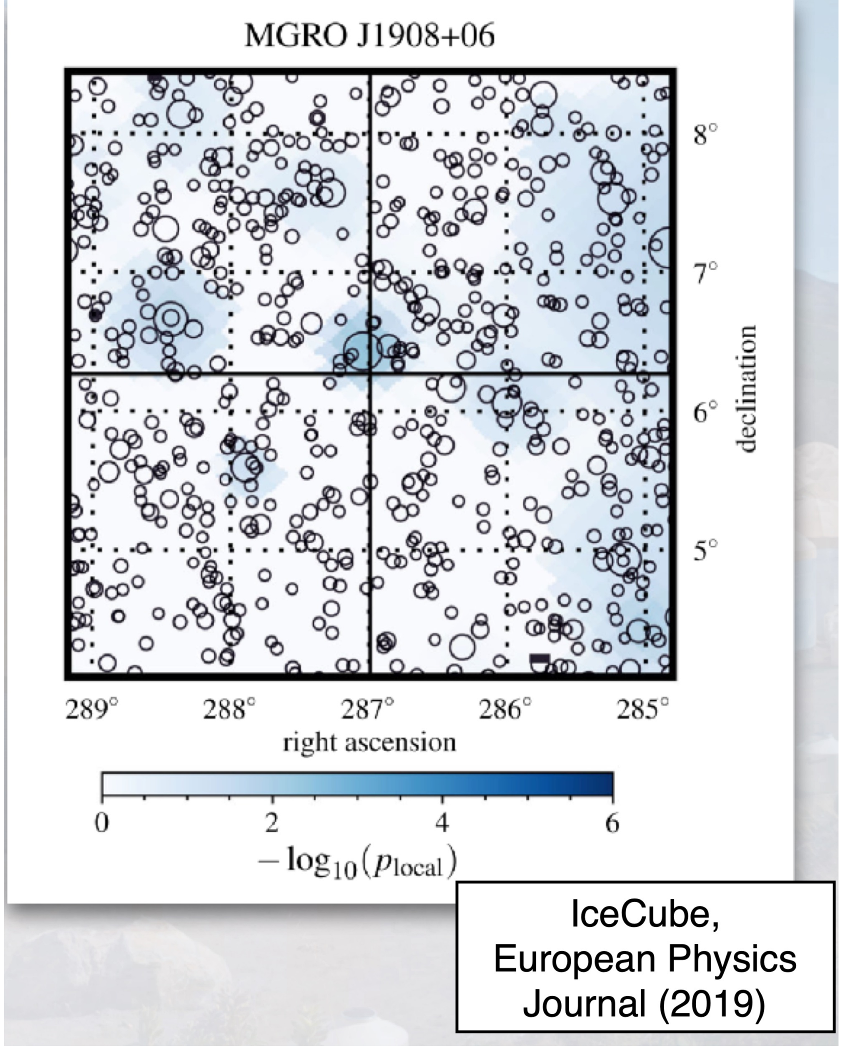


HAWC J1908+06 as neutrino source?

Some HAWC PeV candidates are promising neutrino sources

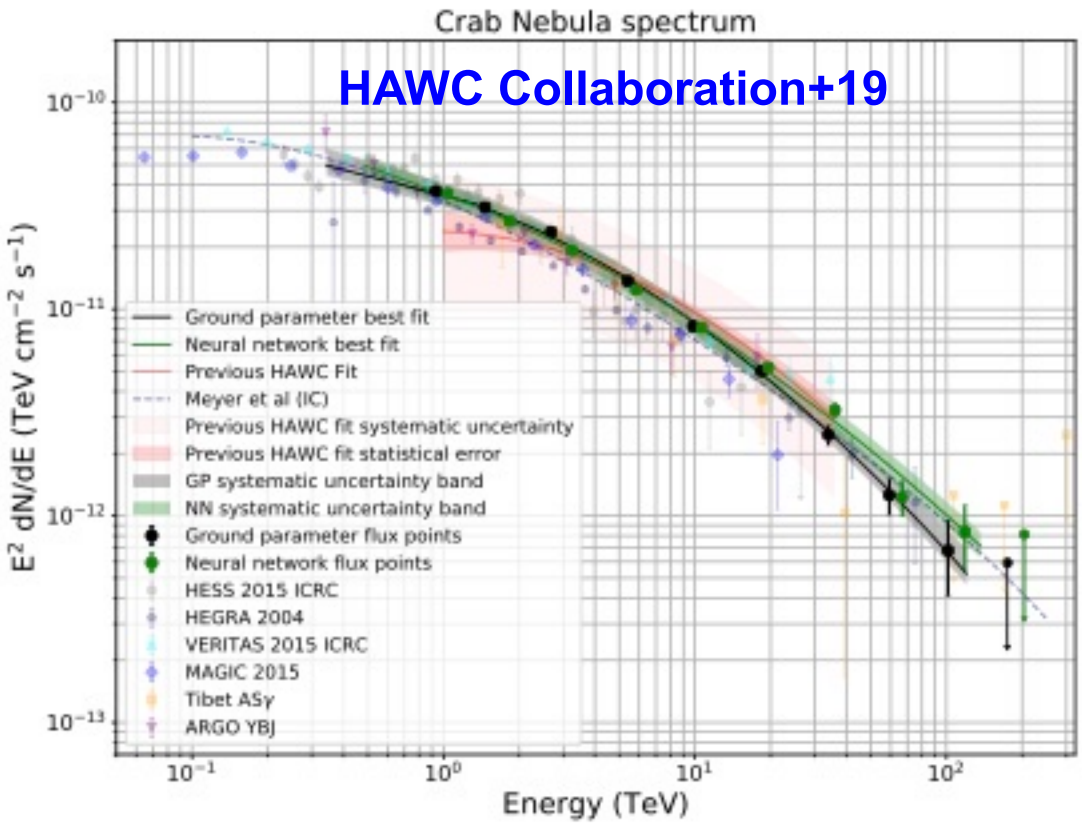
Neutrinos seen in coincidence with a PeVatron candidate would unambiguously indicate hadronic origin

J1908+06 one of best p-values in IceCube point source searches, although still consistent with background-only hypothesis



IceCube, European Physics Journal (2019)

100 TeV photons from the Crab with HAWC



Highest Energies~100 TeV

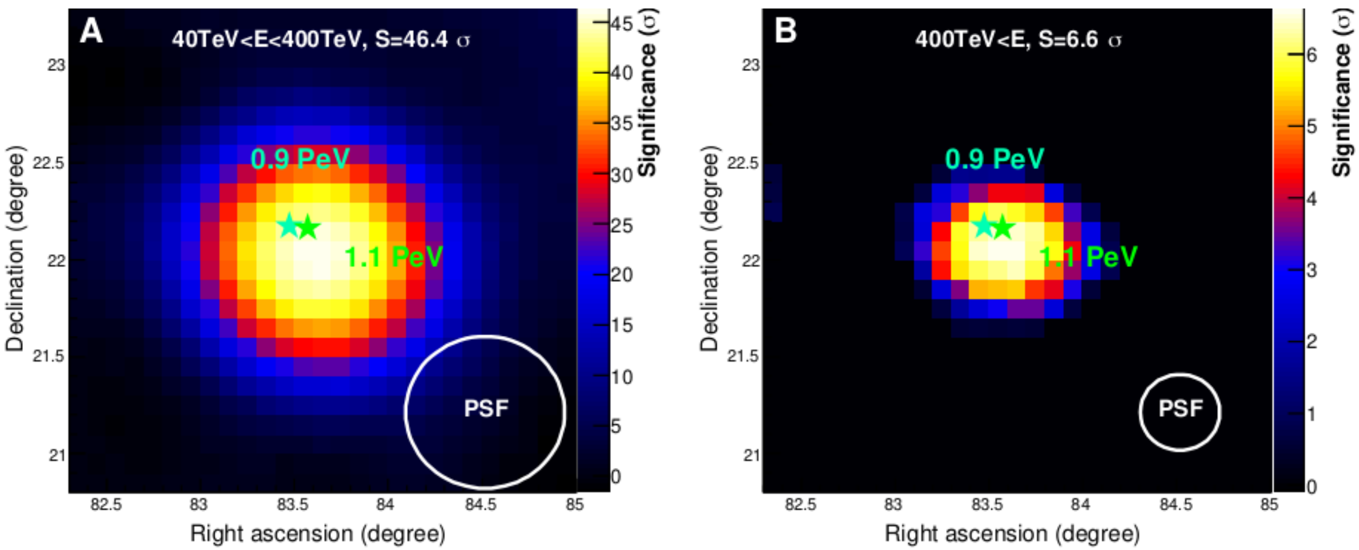
Two independent energy estimation algorithms (grey and green points/bands above)

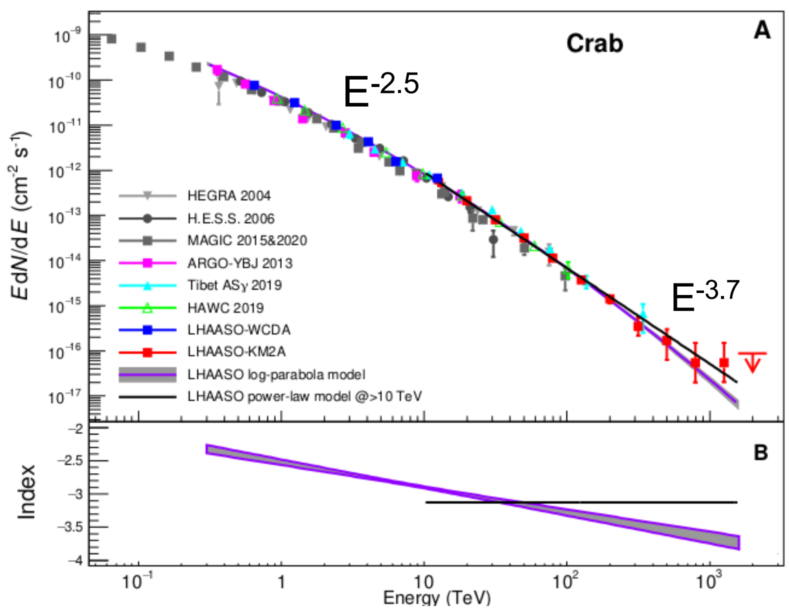
837 day dataset

The error bars on the flux points are statistical only The shaded grey and green shaded bands denote systematic uncertainties.

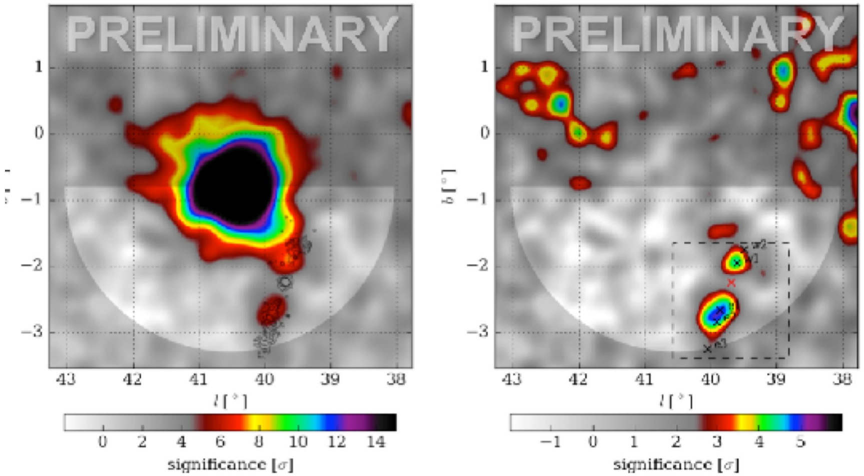
First Crab spectra that goes past 100 TeV in reconstructed energy

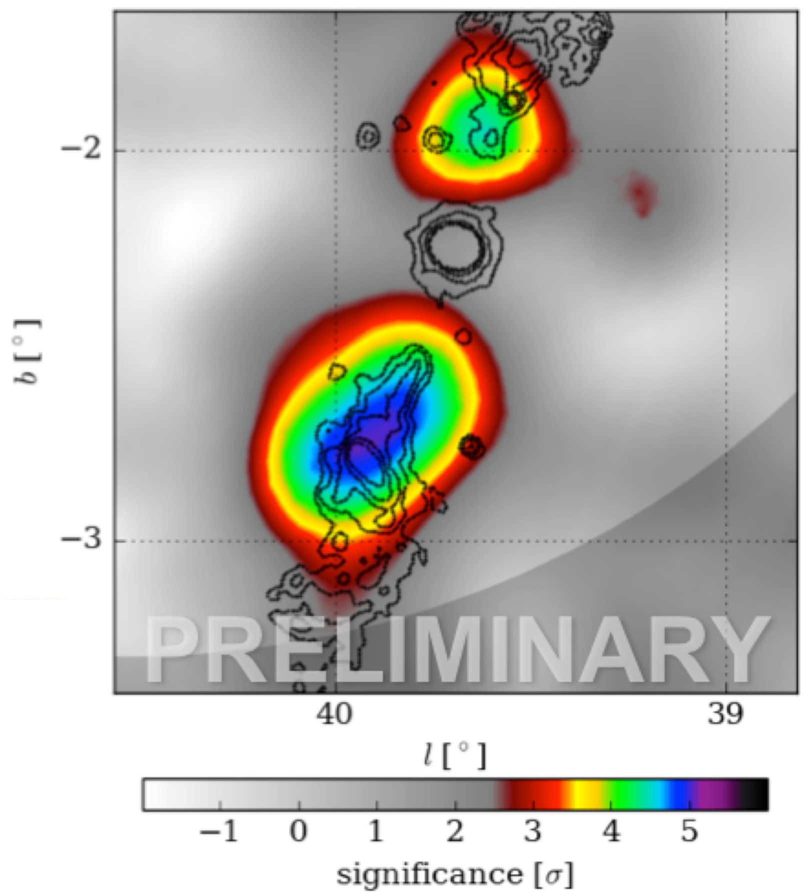
PeV photons from the Crab !





LHAASO Coll Science+21



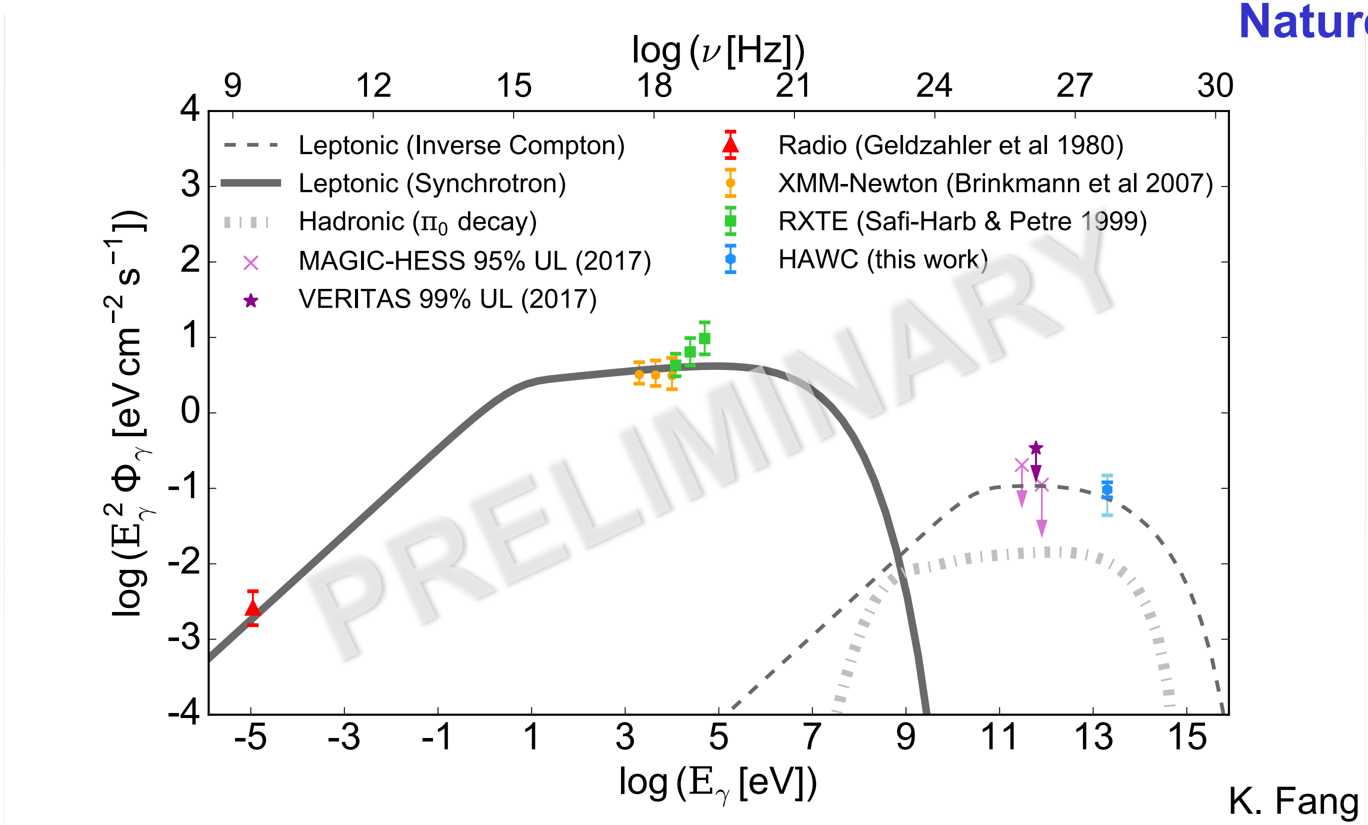


Microquasars as gamma-ray sources: SS433 Lobes

- SS 433 is a Galactic micro-quasar observed in radio-X-rays.
- SS433 is a binary system formed by a Supergiant 30 solar masses star and a compact object, either a neutron star or a black hole
- Two jets, the most powerful known in the Galaxy, extend perpendicular to the line of sight and terminate in W50 nebula and produce western and eastern X-ray lobes
- SS433 jet : 10^{39-40} erg/s
- SS433 jet speed roughly c/4
- Baryon loaded
- Particle acceleration is believed to occur at the lobes where strong radiation is expected to be emitted at GeV and TeV energies

Origin of the emission (e1)

Nature, HAWC Coll 2018



K. Fang

- IC scattering off CMB photons, scattering off optical and infrared suppressed electron acceleration
- Electrons of at least 130 TeV required in a magnetic field of 16microGauss
- Hadronic emission assumes 10% conversion of jet energy into protons and 0.05 cm-3 density

Conclusions and Outlook

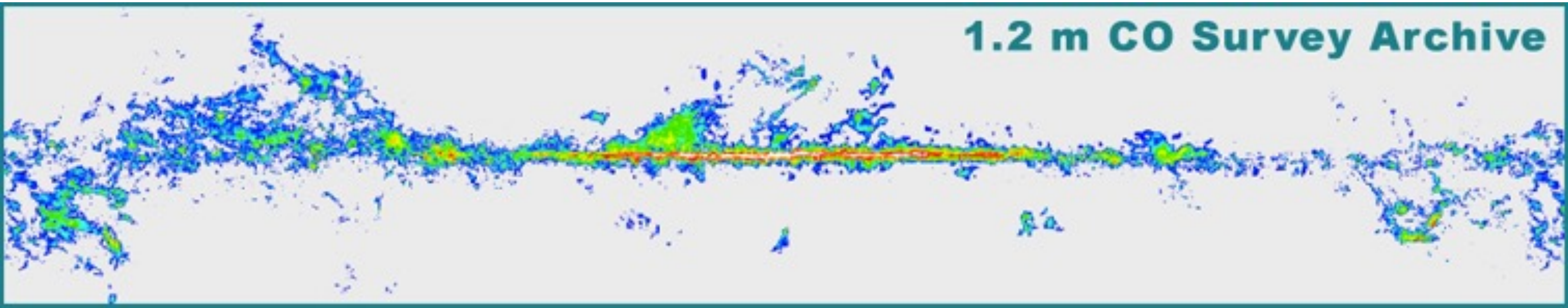
- Both target analysis and discoveries in blind survey searches brought recently new insights in the search for the Galactic PeVatrons

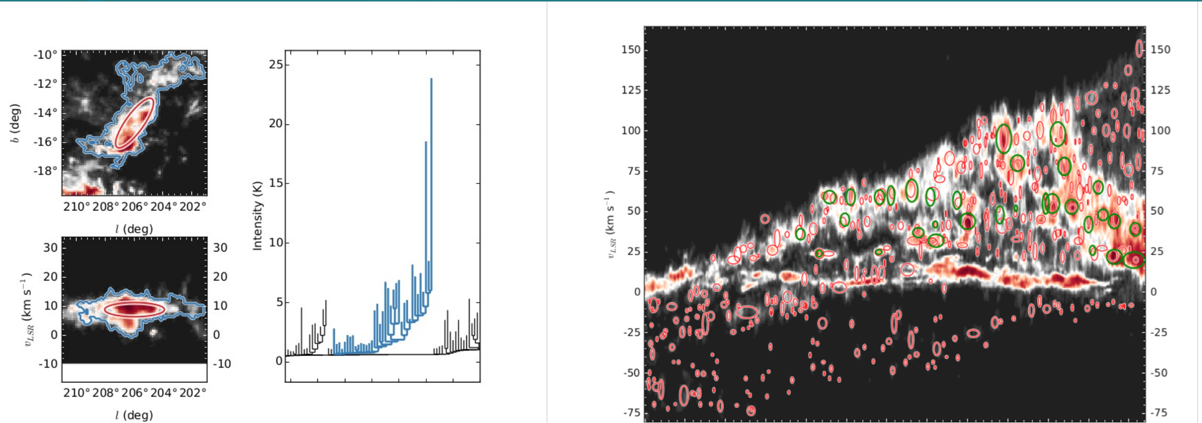
- We have **not yet** pinned down the origin of PeV particles but we now know that the Galaxy is rich in multi-TeV up to PeV gamma-ray sources

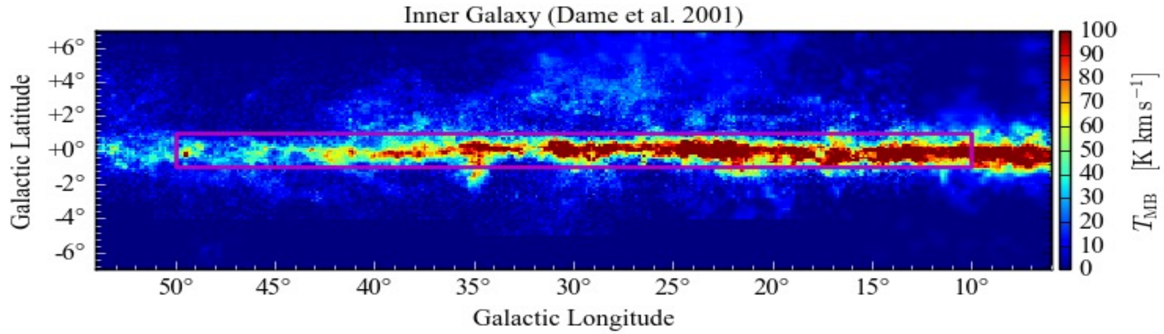
- Synergy: imaging and wide FoV instruments
  - High discovery potentials with HAWC/LHAASO and SWGO
  - Detailed morphology with HESS/VERITAS/MAGIC and CTA
  - Combined spectra over many ranges in energies from GeV to PeV
  - Gas (great improvements in resolution of surveys in infrared, submm and radio)

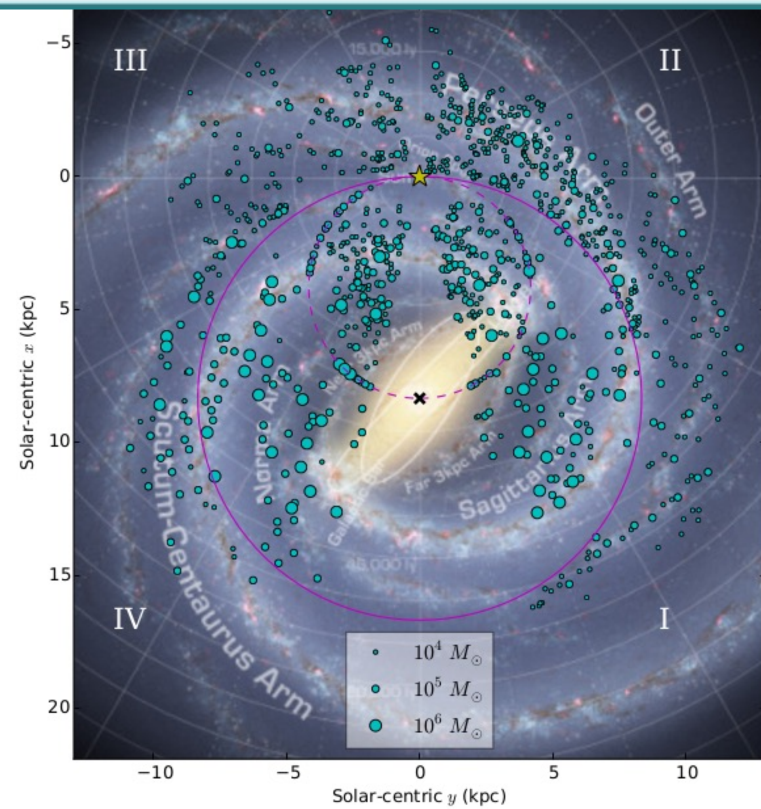
The CfA Survey of Molecular Gas

Dame+1987, Dame+2001,Rice+2016,Miville-Dechenes+2018

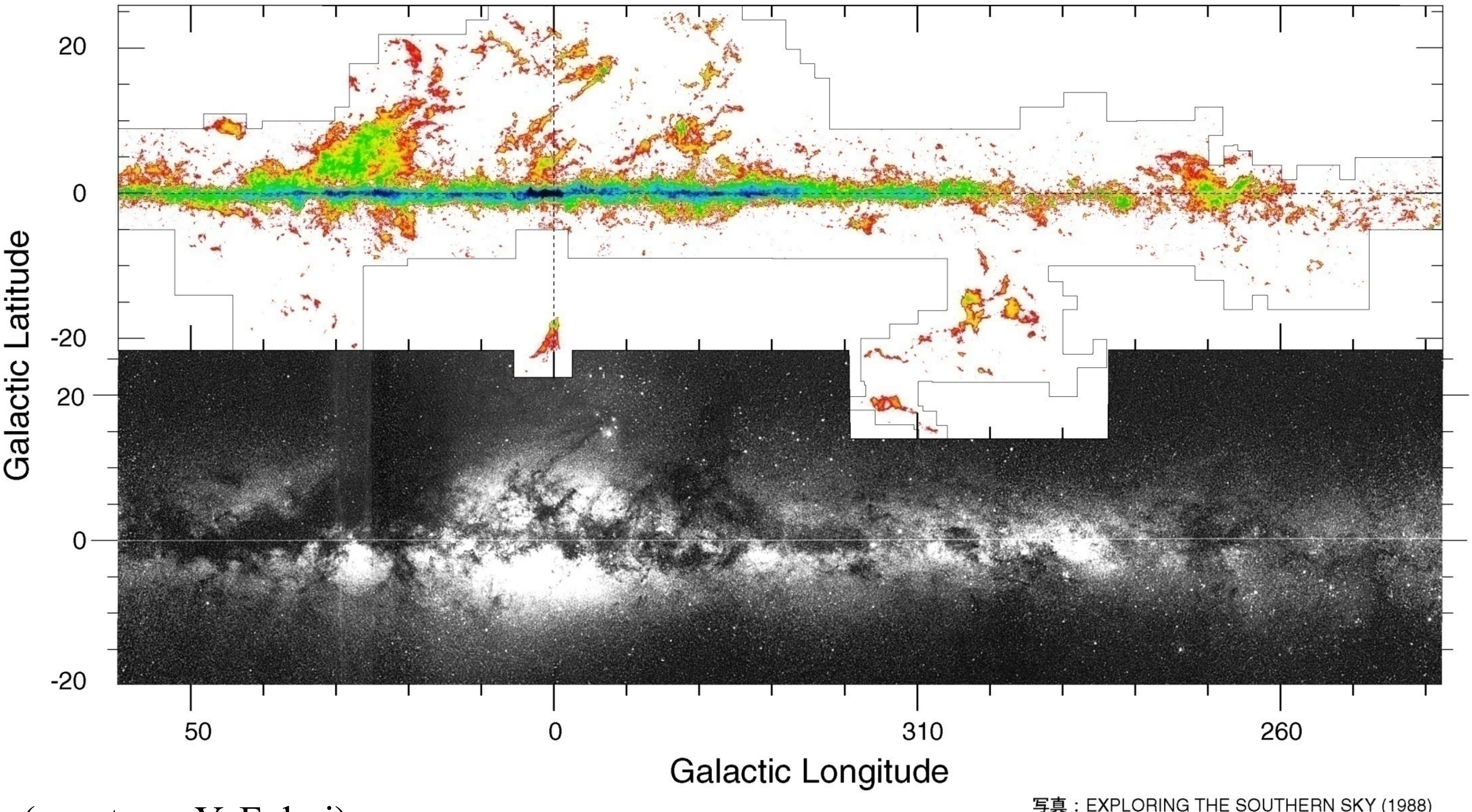






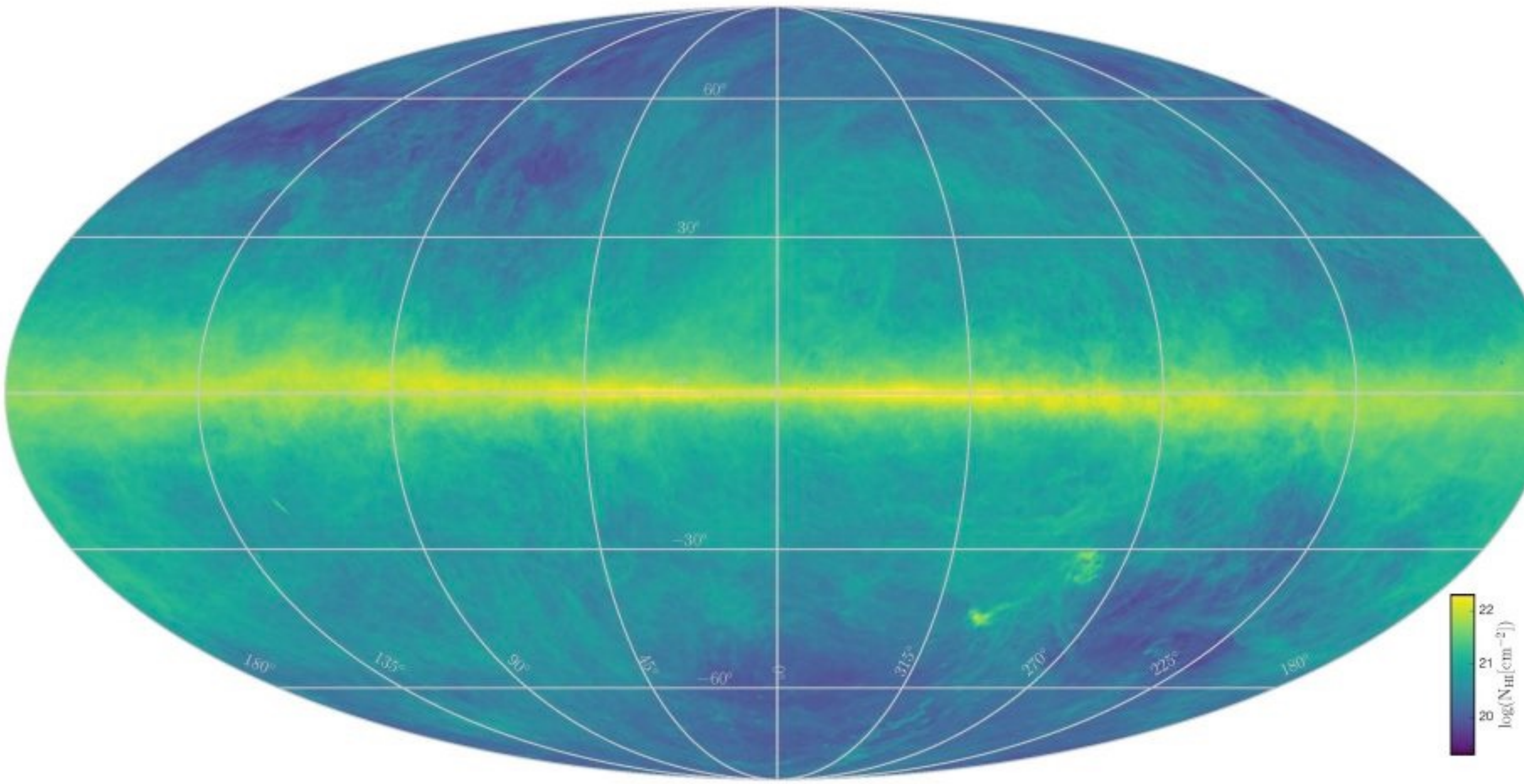


The Milky Way in Molecular Clouds (Nanten survey)



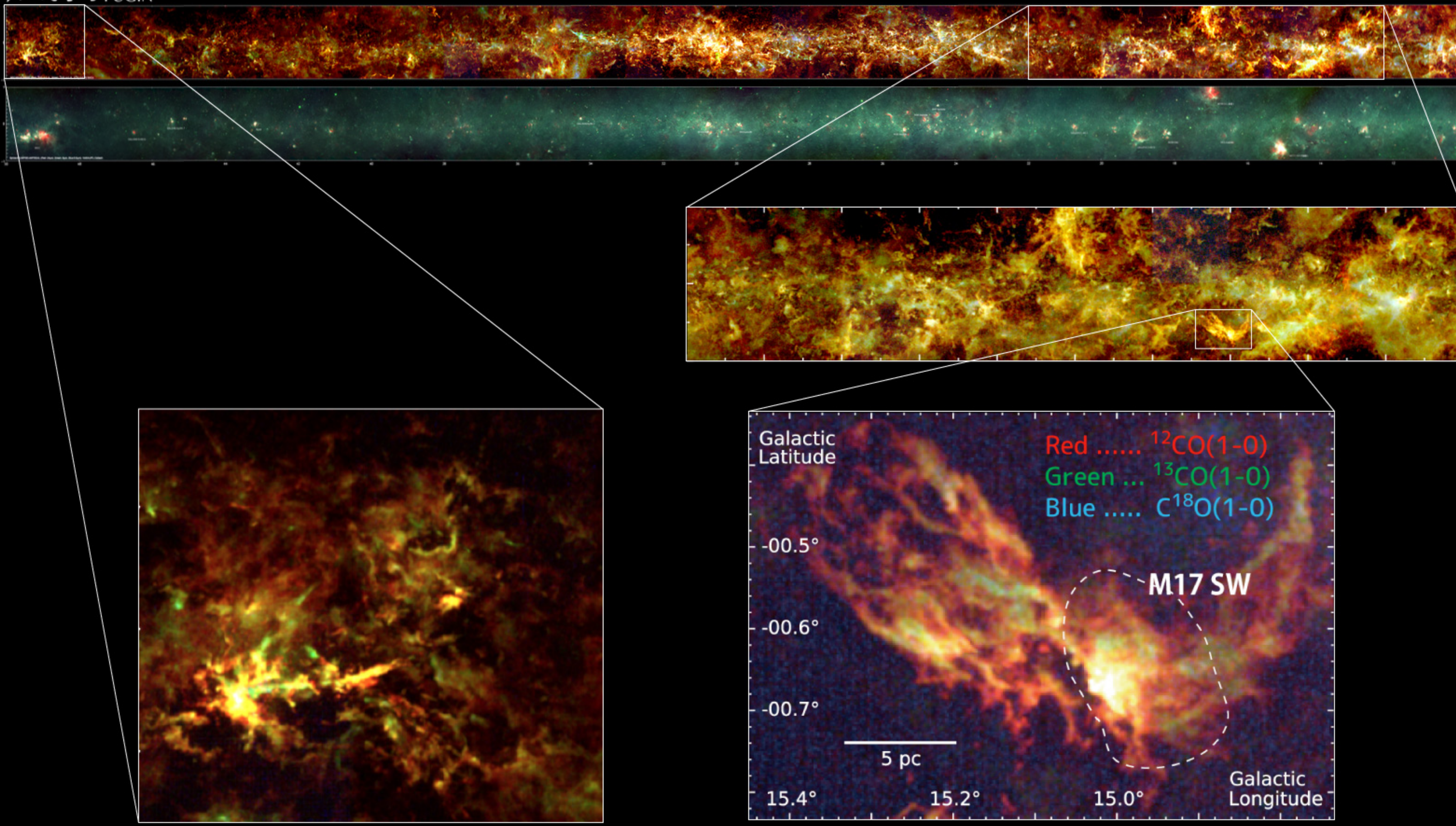
(courtesy: Y. Fukui)

The 4PiHI Survey of Atomic Gas



FUGIN

風神FUGIN FOREST Unbiased Galactic plane Imaging survey with Nobeyama 45-m telescope



NOBEYAMA FOREST

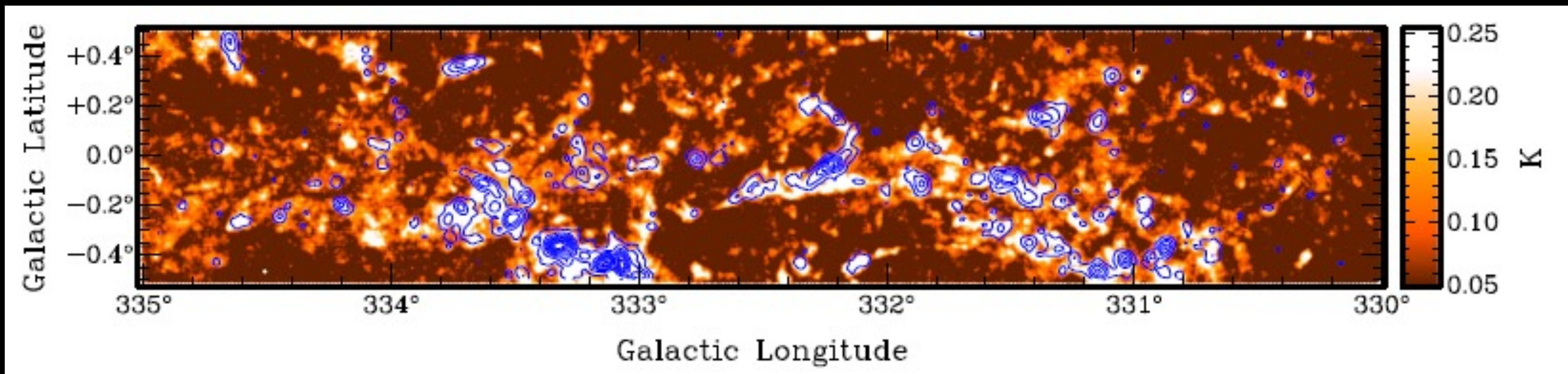
Credit: NAOJ/NASA/JPL-Caltech

MALT45   7mm Survey with ATCA

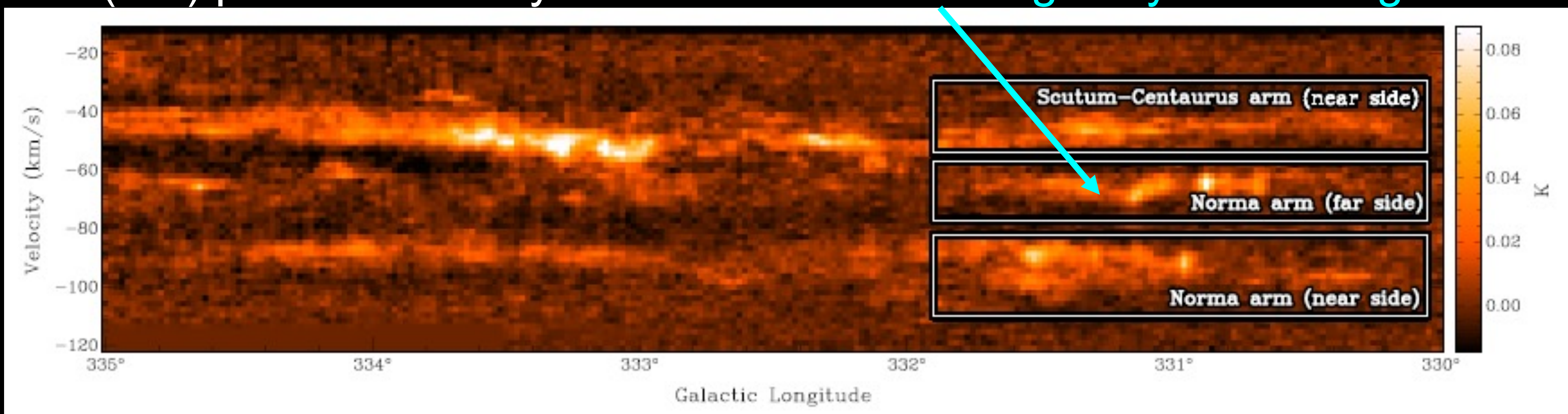
> 5x more sensitive than Mopra   (1 arc-min resolution)

Credit: G Rowell

CS(1-0) peak pixel image with HOPS NH3(1,1) contours (Jordan etal 2013, 2015)



CS(1-0) position/velocity → can see far side of galaxy in dense gas!



From 2017 "Full Strength MALT 45"   l = 300 to 360   (Breen et al..)

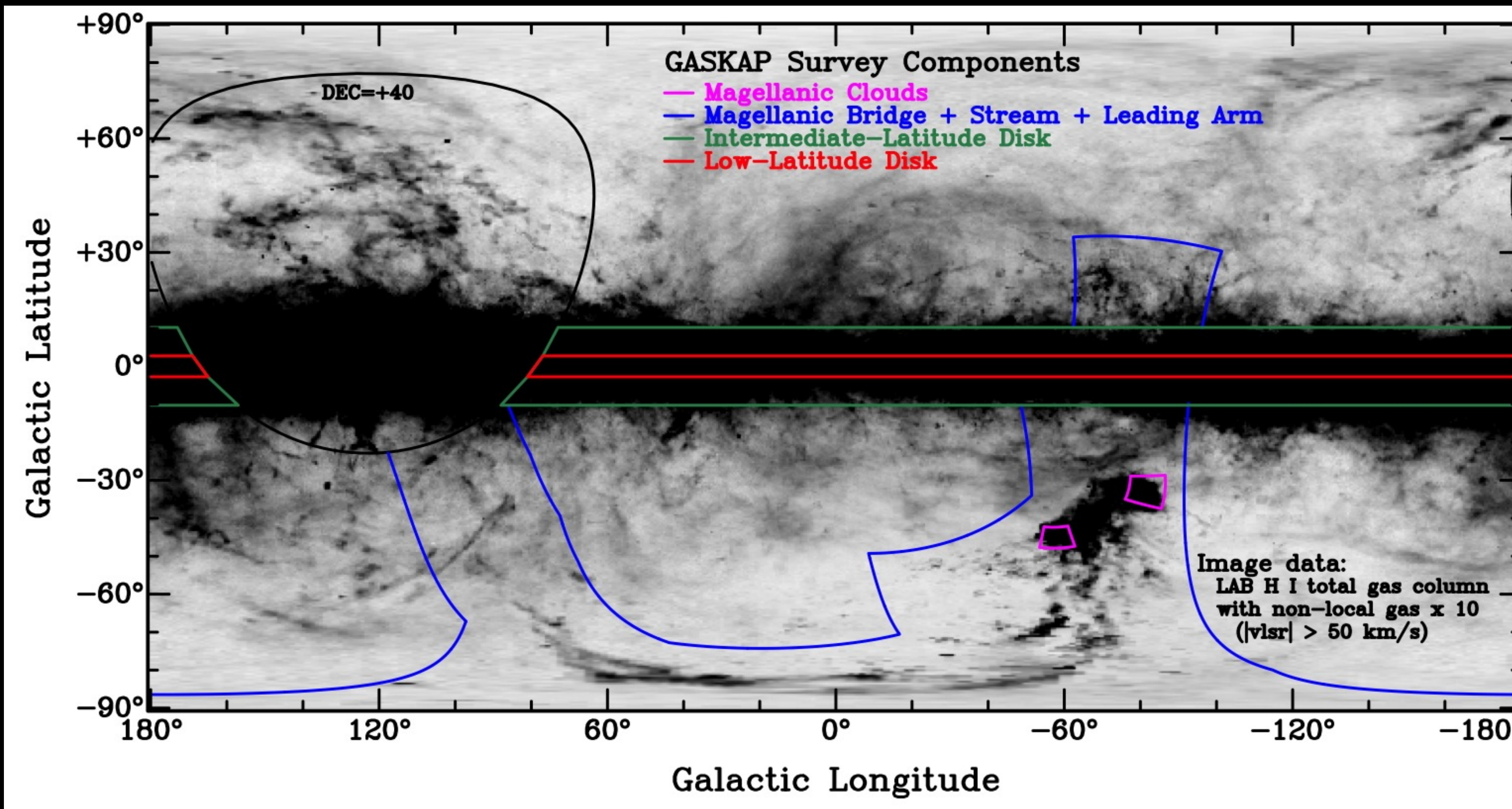
→ dense gas ISM survey over southern gal. plane

GASKAP

New HI + OH survey with the ASKAP
- 30 arc-sec resolution
- Commencing 2018

Credit: G Rowell

www.atnf.csiro.au/research/GASKAP/



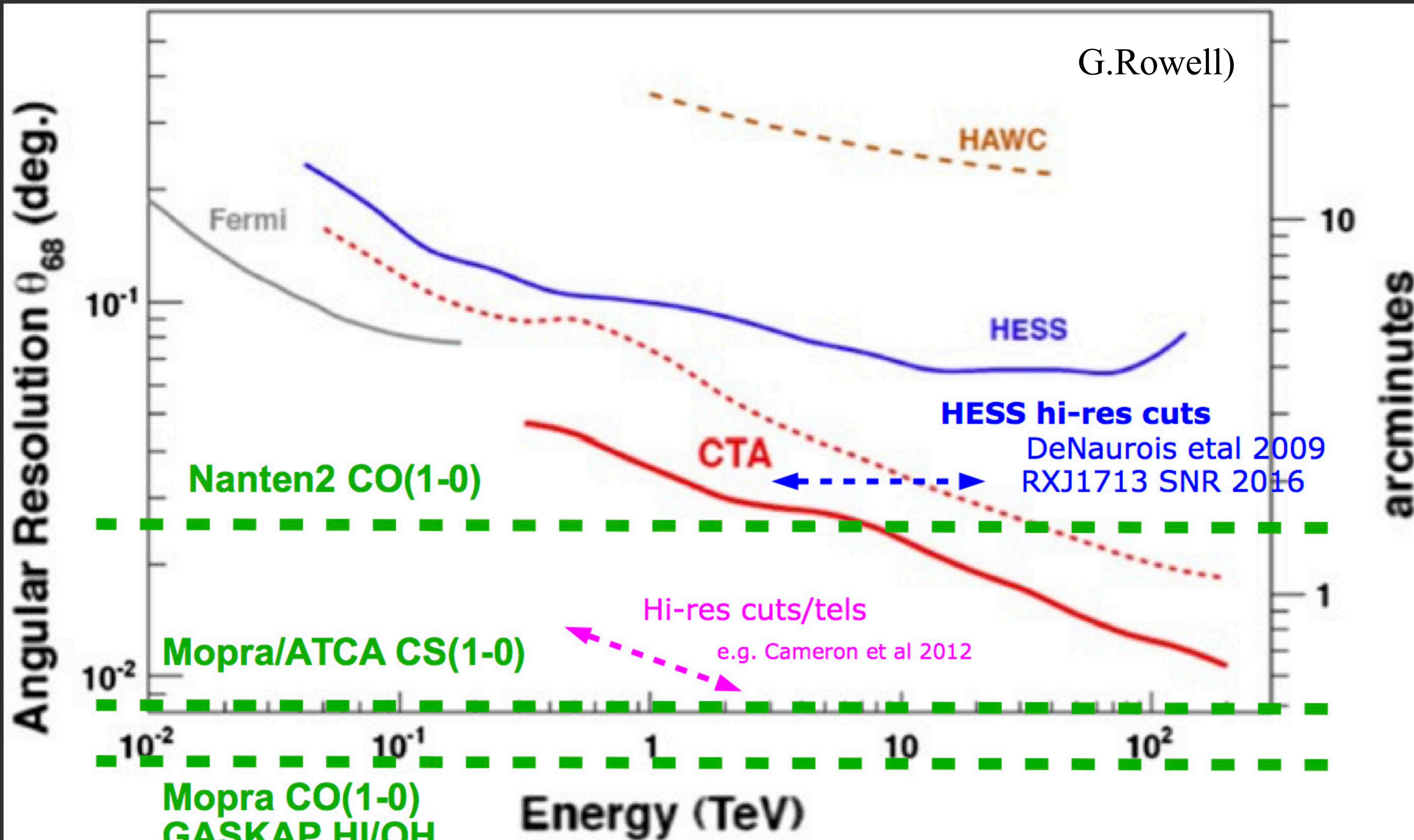
ASKAP - Australian Square Kilometre Array Pathfinder

Phased array feeds (PAFs) *30-beams*

- Continuum survey, HI & OH lines, B-field strength & turbulence, transients

Angular Resolution 68% PSF (HESS, CTA..)

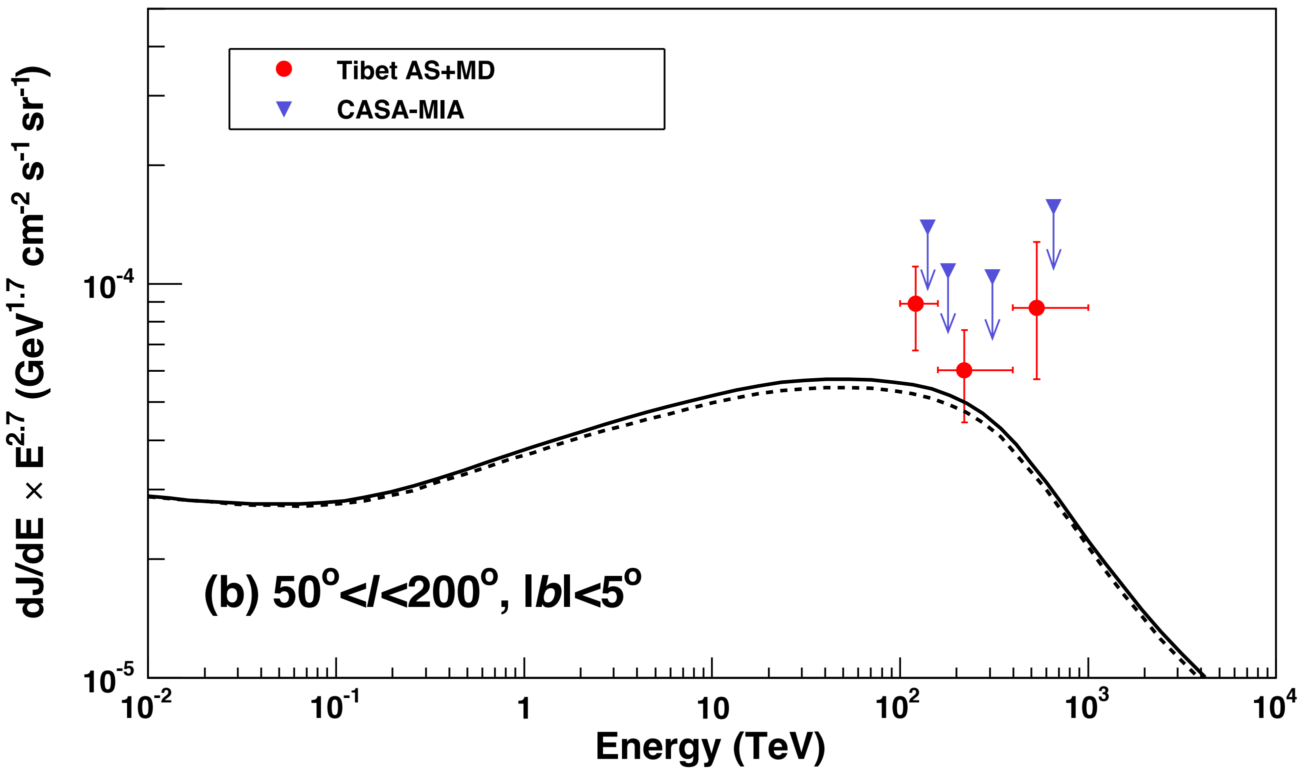
Acharyara etal 2013



Beam Sizes 68% containment radius

Diffuse γ-rays at hundred TeVs

Amenomori+21, Tibet AS



- The fractional source contribution to the diffuse component is estimated to be 13%.
- All events above 398 TeV observed more than 0.5 deg apart from known sources. PeV electrons cannot easily explain such emission
- Above 398 TeV 4 out of 10 events are detected within 4◦ from the centre of the Cygnus cocoon If these 4 events are simply excluded, the observed flux at the highest energy agrees with the model prediction.