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Clouds illuminated by supernova remnants as an explanation for LHAASO unidentified sources

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Searches for PeVatrons

Accelerators of Galactic Cosmic Rays to ~10^{15} eV

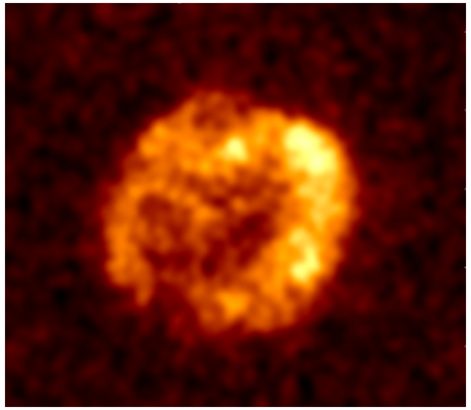
Suitable candidates satisfy: $E_{\max} = Ze\beta cBL > 10^{15}\,\mathrm{eV}$

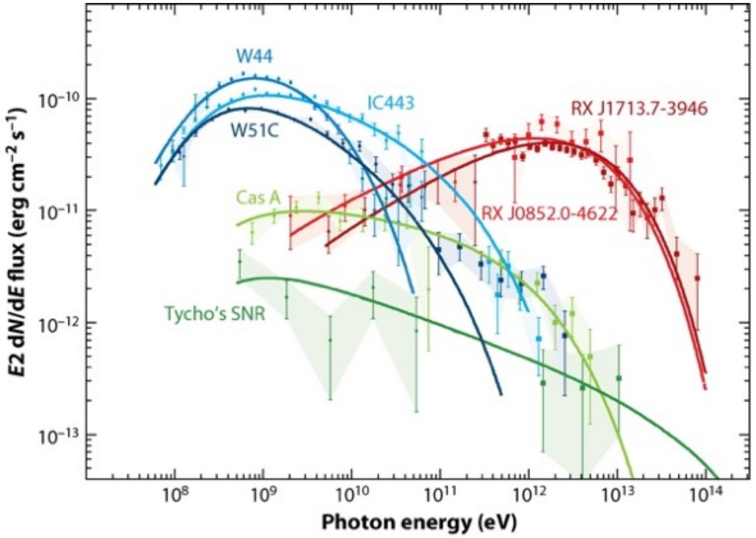
Supernova remnants are prime candidates as a Galactic source:
~10^{51} erg per explosion,
~10% into CR acceleration,
~3 per century in the Milky Way

—> sufficient to power Cosmic Rays
—> Evidence for pion-bump and molecular cloud interactions

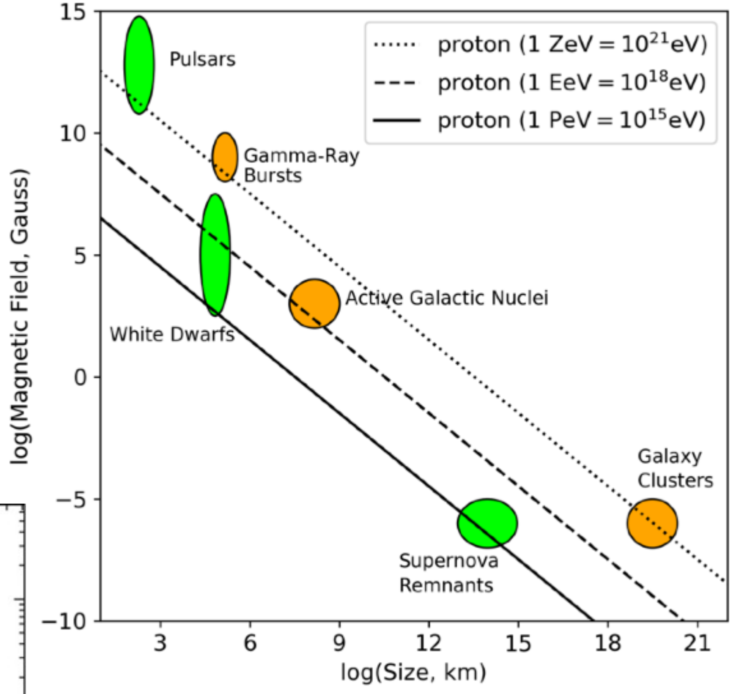
BUT —> no active **PeVatron** SNRs seen to date

Only act as accelerators for a short period of time?



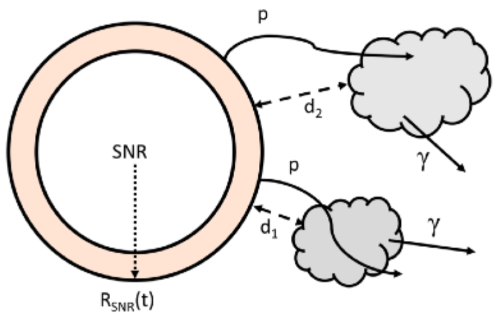


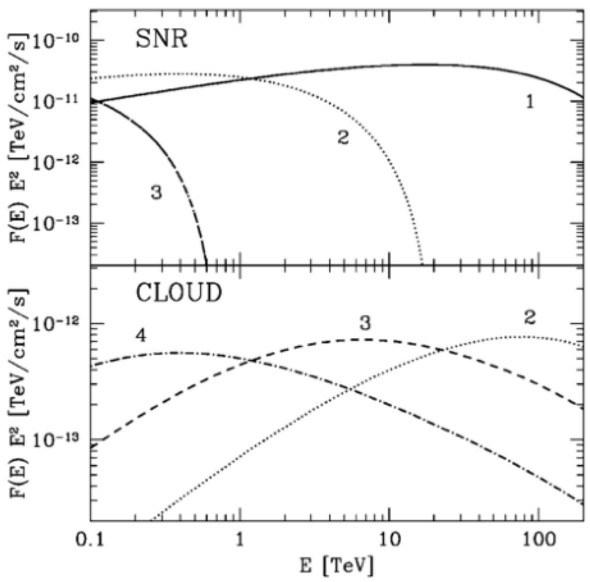
Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77



Supernova Remnants — illuminating nearby clouds?

Highest energy particles will be produced at early times
—> escape and travel from ISM
—> potential to interact with nearby clouds





Gabici & Aharonian ApJ **665** (2007) L131-L134

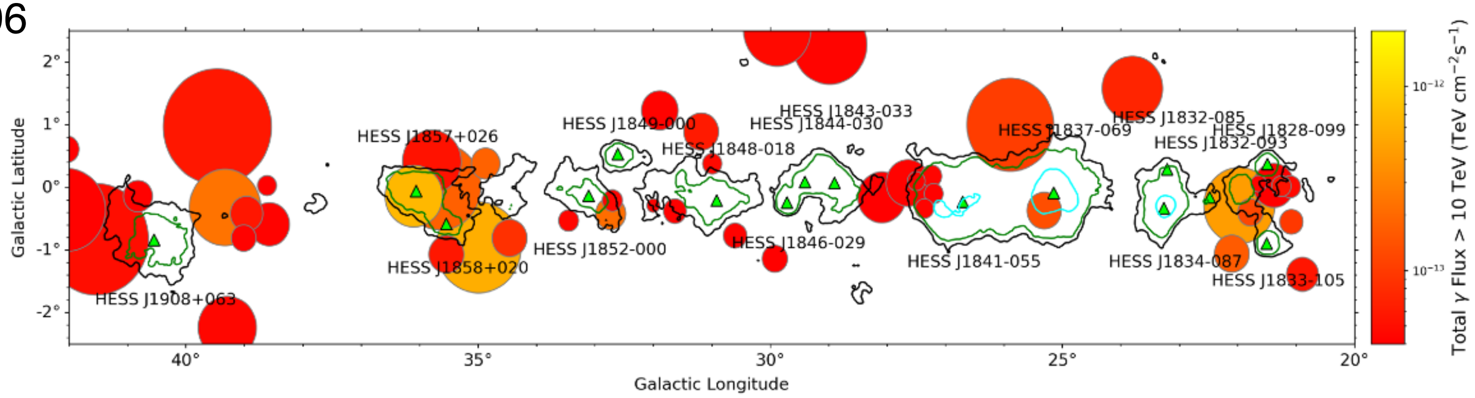
Catalogue of known SNRs & known clouds —> model evolution & expected emission

Q: if SNR X was a PeVatron *at some point*, which clouds are the most promising targets?

Proton spectrum from SNR, propagate through intervening space with $D(E) = \chi D_0 \left(\frac{E/GeV}{B(n)/3\mu G}\right)^{\delta}$

and gamma-ray formulation from Kelner et al. 2006

$$\Phi_\gamma(E_\gamma, r', t') = cn \int_{E_\gamma}^{\infty} \sigma_{\text{inel}}(E) f(E, r', t') F_\gamma\left(\frac{E_\gamma}{E}, E\right) \frac{dE}{E}$$



AM et al. MNRAS **503** (2021) 3522-3539
AM et al. MNRAS **520** (2023) 300-304

LHAASO — Large High Altitude Air Shower Observatory: Ultrahigh-energy photons from 12 sources (2021)

Highest energy ~1.42 PeV from Cygnus region (now ~2.5 PeV)

Many sources associated with pulsars or with multiple potential associations

One source stands out as being first detected at Ultra high energies without any known counterparts —> LHAASO J2108+5157

Extended Data Table 2 | List of energetic astrophysical objects possibly associated with each LHAASO source

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2[d]	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3[e]	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3[f]	< 2[f]	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7[g]	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5[h]	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4[i]	$\sim 10 - 20$[j]	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8}_{-0.7}$[d]	$1.8 - 3.3$[k]	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2[d]	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7}_{-1.4}$[l]	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	3.3 ± 0.3[m]/4.0 ± 0.5[n]	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08[o]	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08[o]	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8[p]	~ 10[p]	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8[p]	~ 10[p]	2.2×10^{37}	

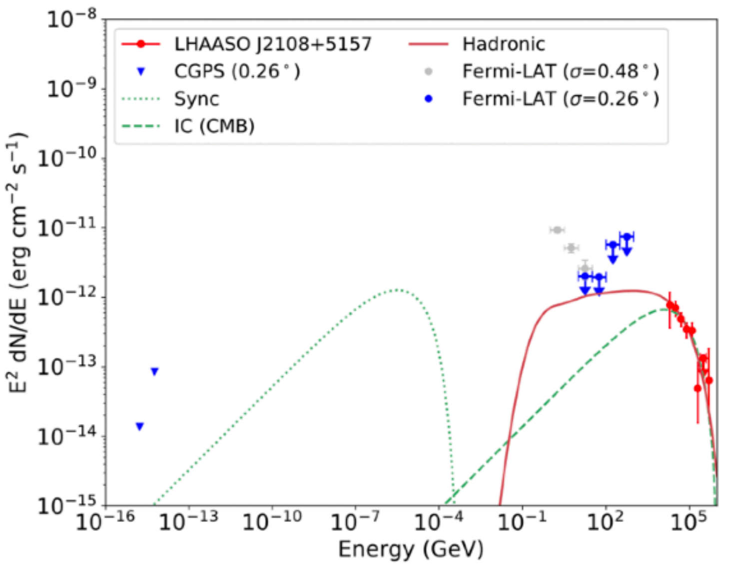
Cao et al. Nature **594** (2021) 33-36

LHAASO J2108+5157

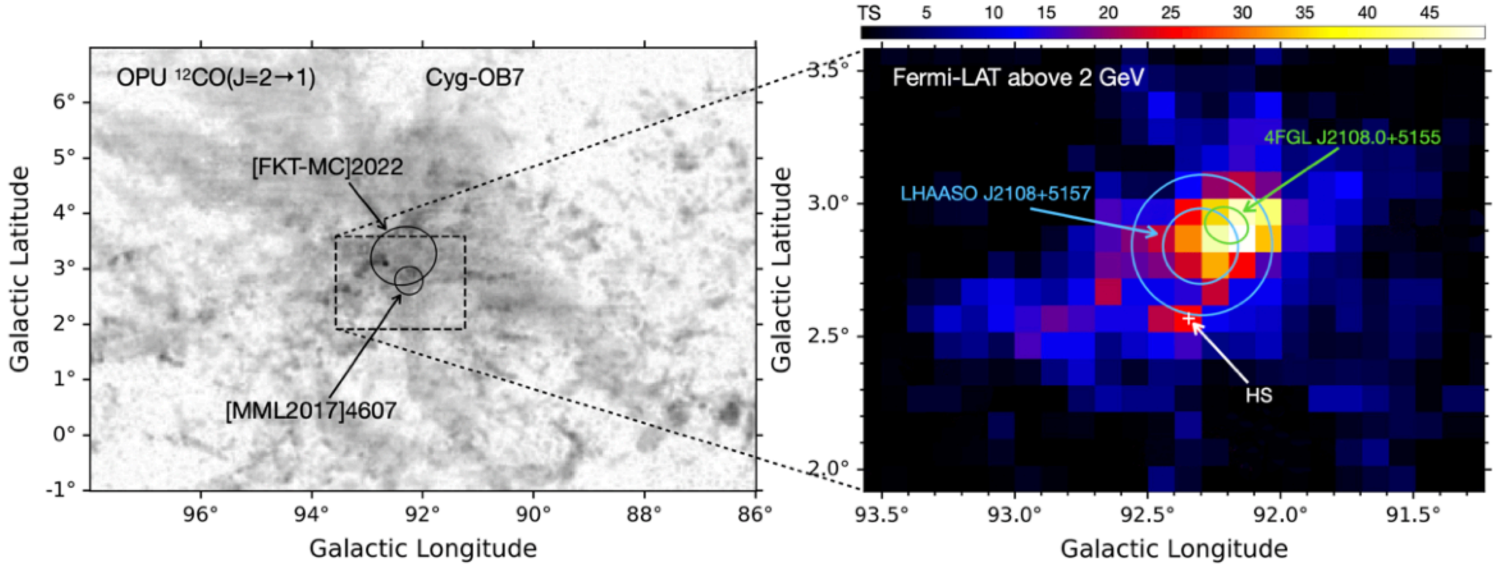
Mysterious dark source - the only one to be discovered by LHAASO without a previously known VHE association

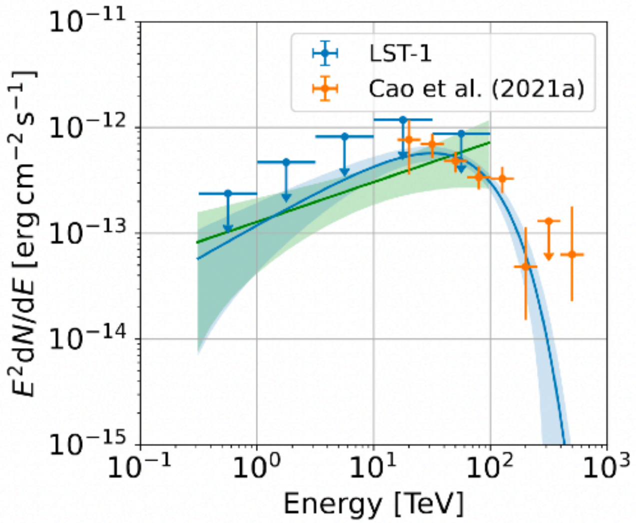
Evidence for a molecular cloud at the location of the source

Follow-up studies by LST (3.7 sigma), Fermi-LAT (~4 sigma), searches for clouds etc.



Cao et al. ApJL **919** L22 (2021)





de la Fuente et al. PASJ **75** (2023) 546-566, arXiv:2303.5712
de la Fuente et al. A&A (AA/2023/6681) arXiv:2306.1921

Abe et al. A&A **673**, A75 (2023)

Is LHAASO J2108+5157 a cloud illuminated by an SNR?

If so, what properties must the SNR have?

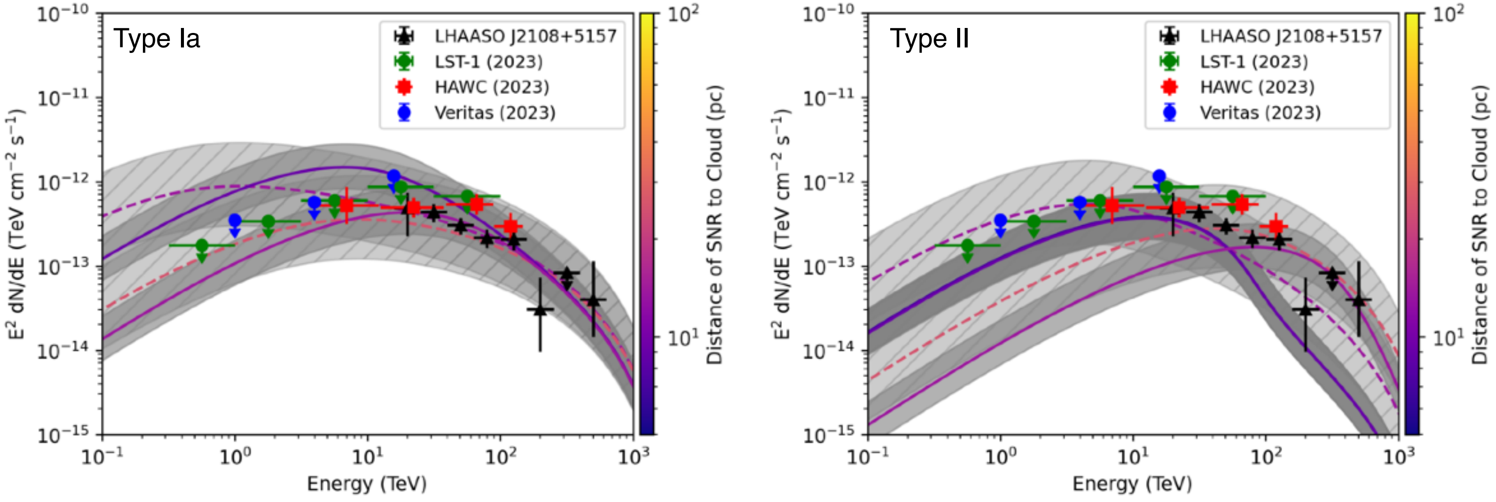
Properties of the molecular clouds are known —> fix cloud properties and scan possible SNR parameters

Adopt for the two clouds “MML” (solid) and “FKT” (dashed) the model that best matches the data uncertainty bands from quoted parameter uncertainties.

Find that a hypothetical young SNR (<10 kyr) near to the cloud (≤ 40-60 pc) would provide a reasonable match

No such SNR currently known, but radio surveys are continually finding more (ASKAP, MeerKAT)

Cloud	MML[2017]4607	FKT[2022]
(l (deg), b (deg))	(92.272, 2.775)	(92.4, 3.2)
d (kpc)	3.28	1.7 ± 0.6
n (cm^{-3})	30	37 ± 14
Size (deg)	0.5	1.1 ± 0.2



AM, A&A **684** A66 (2024)

Table 3. Combinations of SNR age, t and separation distance, Δd for the model curves that best match the LHAASO data, listed in ranked order. These curves are shown in figure 3.

Cloud	t (kyr)	Δd (pc)	SN type	χ^2
MML[2017]4607	1	37	Ia	5.1
FKT[2022]	4	37 *	Ia	6.7
FKT[2022]	4	57	Ia	9.3
FKT[2022]	4	57	II	15.5
FKT[2022]	8	24 **	II	17.0
MML[2017]4607	4	24 **	II	24.4
MML[2017]4607	2	37	II	25.0
MML[2017]4607	1	24	Ia	28.2

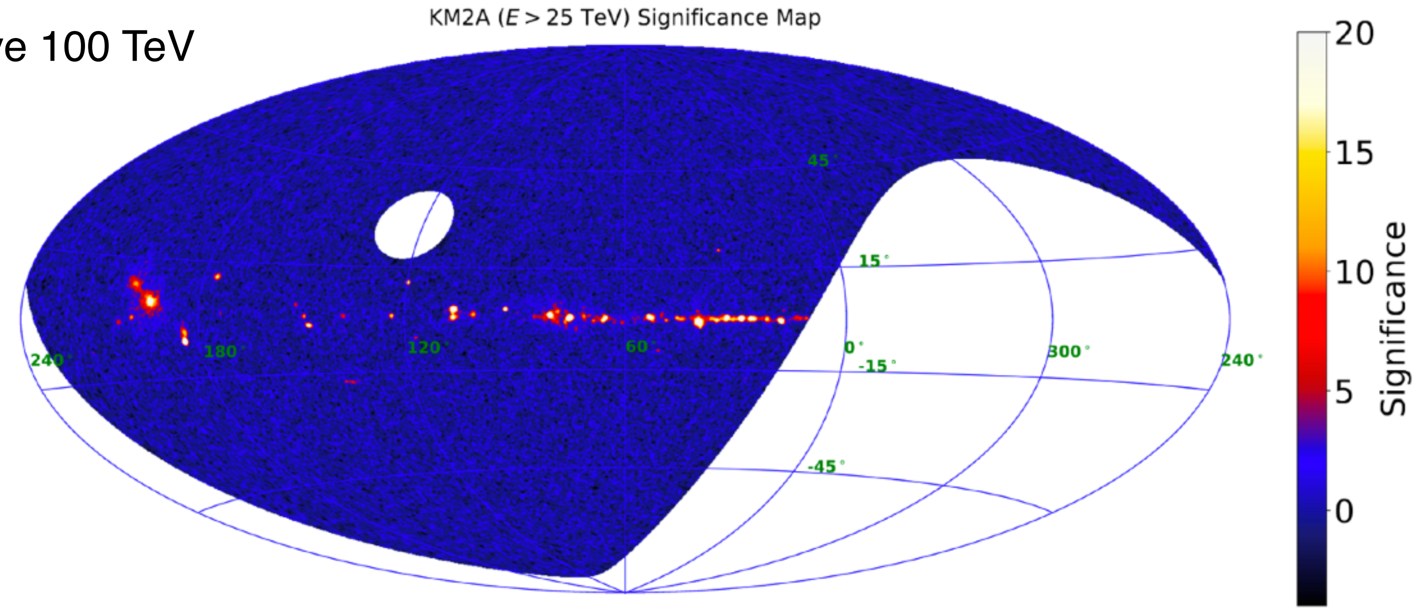
* Model curves for the same SNR age yet with smaller distances provided a comparable fit to the LHAASO data, but severely overestimated the LST-1 upper limits and are hence not shown.
** Model curves for the same SNR age yet with a distance of 10 pc and 15 pc were comparable to the 24 pc distance quoted.

The first LHAASO catalogue

No fewer than ~75 sources above 25 TeV and 43 above 100 TeV

— All located in our Galaxy, many unidentified

Compare clouds illuminated by nearby SNRs in our model to spatially coincident 1LHAASO sources

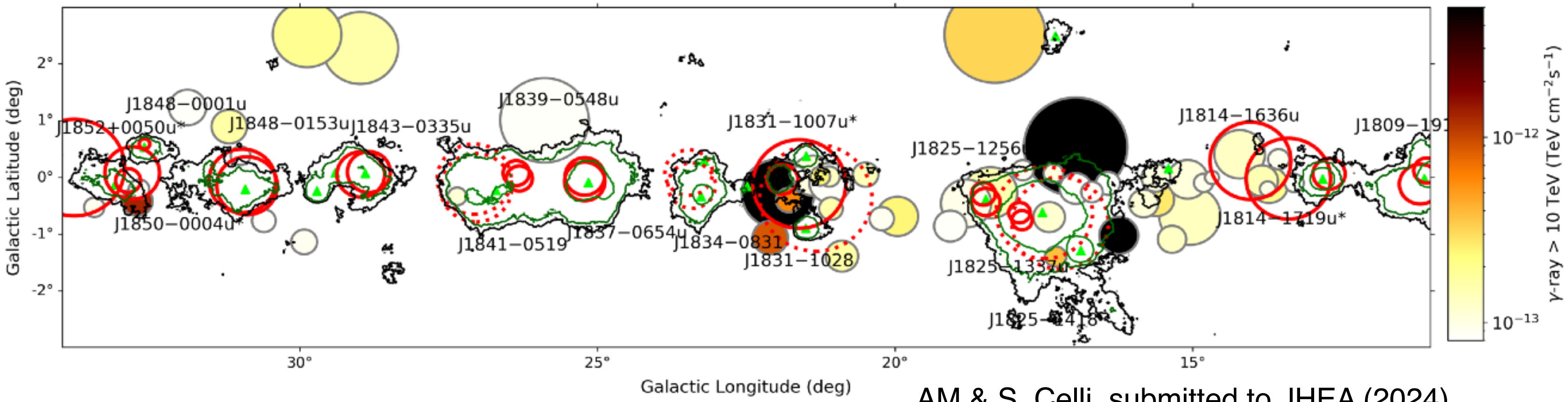


Cao et al. ApJSS **271** 25 (2024)

Example section of the galactic plane:

H.E.S.S. contours from HGPS A&A **612**, A1 (2018)

Molecular clouds from Rice et al. ApJ **822**, 52 (2016)



AM & S. Celli, submitted to JHEA (2024)

Modelling illumination of clouds by SNRs

Pair SNRs to molecular clouds:

— Angular separation and distance must imply a physical separation < 100 pc

— If no SNR distance available (SNRcat), assume the SNR is at the same distance as the cloud

Model assumptions:

— Protons escape after the Sedov time in an energy-dependent manner: $t_{\rm esc} = t_{\rm sed} \left(\frac{p}{p_M}\right)^{-1/\beta}$

where $\beta = 2.5$, $p_M = 3\,\mathrm{PeV/c}$ and the Sedov time is ~1.6 kyr for type II SNe, and ~234 yr for type Ia SNe.

— Diffusion mildly suppressed with respect to the galactic average $D_0 \sim 3 \times 10^{26}\ \mathrm{cm^2 s^{-1}}$ at 1 GeV

— CR conversion efficiency ~10%, ISM density ~1cm^{-3}, and a contribution from the sea of Galactic CRs using
AMS Collab. (2015), PRL 114 171103

—> For spatial coincidences with unidentified 1LHAASO sources, we compare the spectral energy distributions

Example: 1LHAASO J1857+0203u

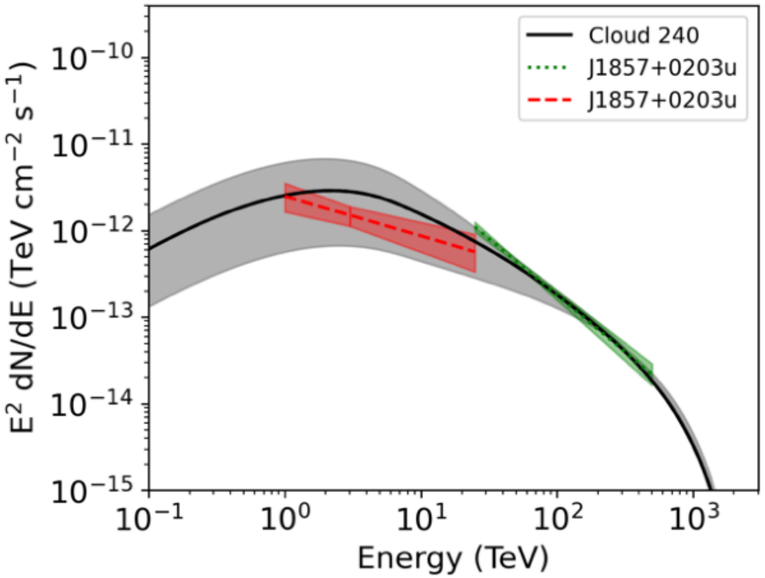
Unidentified source, coincident with HESS J1858+020

Clouds 240 and 190 are both spatially coincident and illuminated by SNR G036.6-0.7

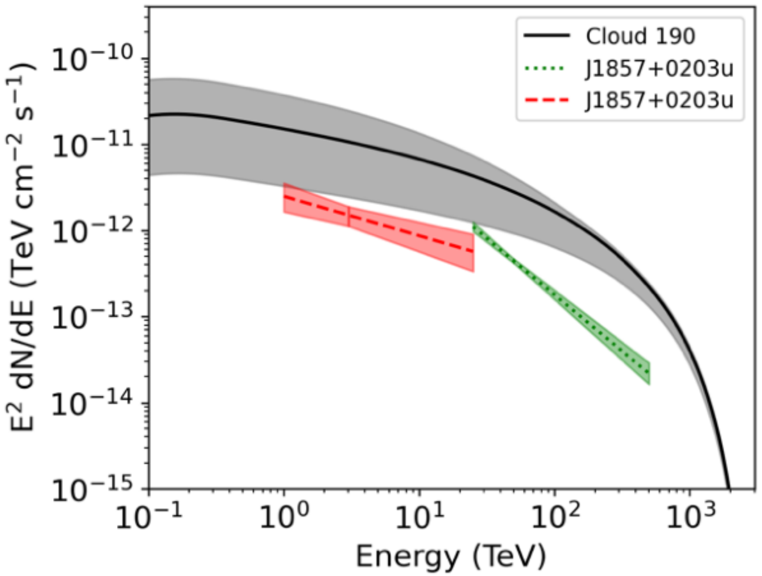
Shaded band indicates uncertainties from varying input parameters:

D_0 and χ by a factor 10; age of SNR; ~20% uncertainty on the distance; contribution from galactic CRs…

Note: assumed 10% CR efficiency, true value likely lower



Type II SN
3.4 kpc distance
$n = 90\,\mathrm{cm}^{-3}$



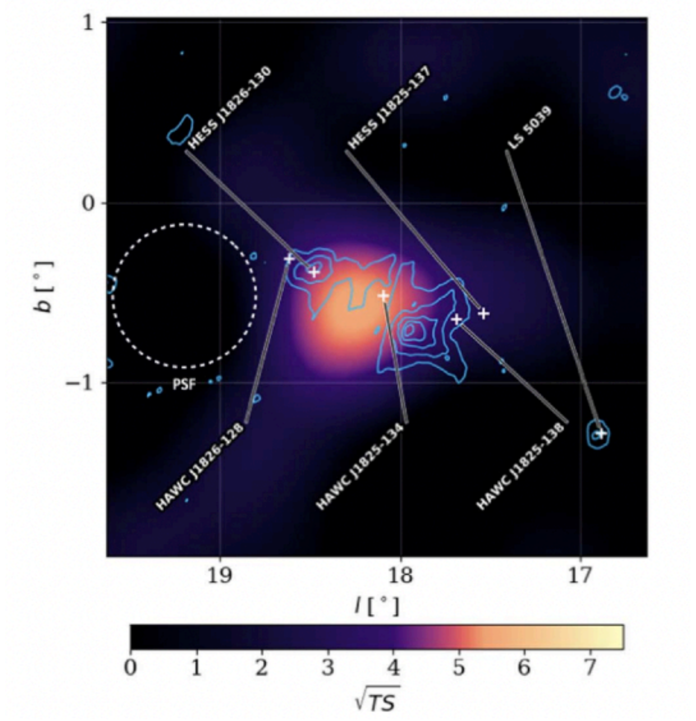
Type Ia SN
1.86 kpc distance
$n = 36\,\mathrm{cm}^{-3}$

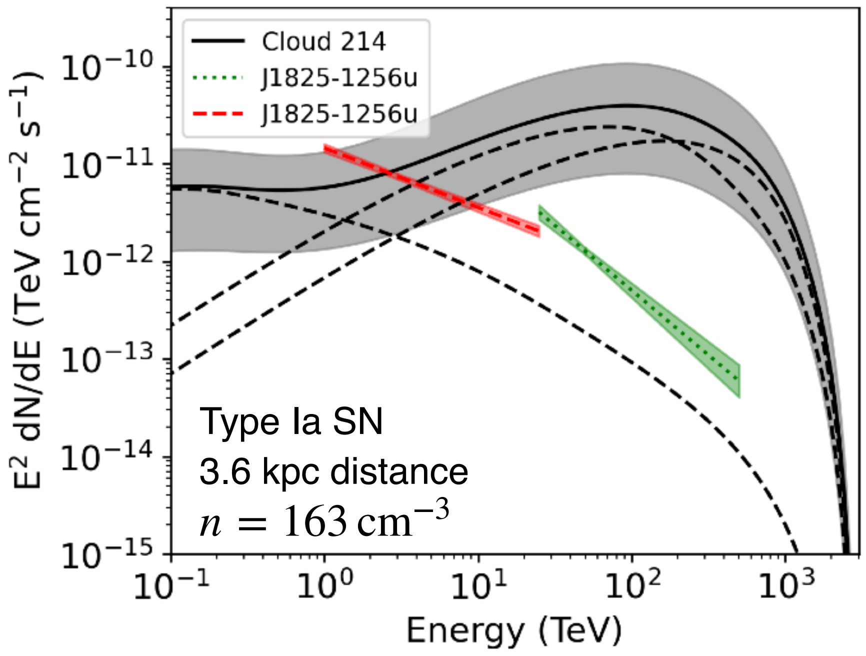
Example: 1LHAASO J1825-1256u

A formally unidentified source in a complex sky region

Observations indicate molecular clouds in the region and a potential coincident emission component.

HAWC collaboration ApJL **907** L30 (2020)





Here, multiple SNRs contribute to the total flux
G017.0-0.0, G017.4-0.1, G019.1+0.2
—> their contributions can also be considered individually

—> shaded range also applies to the contributions separately

Summary and Outlook

Recent experimental results reveal a rich sky full of sources at the highest energies

The most energetic particles — approaching ~PeV — will escape their source at early times

Potentially illuminating nearby molecular clouds?

—> The spectrum of particles arriving at a molecular cloud **is different from** that at the accelerator

A new population of gamma-ray sources may emerge at the highest energies, coincident with target material rather than accelerators themselves

The scenario of molecular clouds illuminated by nearby SNRs appears viable to explain several unidentified UHE sources

Further efforts are needed in detailed modelling and multi-wavelength observations to better constrain each case.

Thank you for your attention