ICRANet-ISFAHAN Astronomy Meeting

Origin of High-energy Galactic Cosmic Rays: Implication from Recent UHE Gamma-ray Observations

Ruo-Yu Liu
School of Astronomy and Space Science,
Nanjing University

03.11.2021, Isfahan, Iran (Online)


天鹅座
X-ray
γ-ray
High-energy
Very-High-energy
Ultra-High-energy
0.1MeV
0.1GeV
0.1TeV
0.1PeV
E
1PeV=10^3TeV=10^6GeV=10^{15}eV

Outline

Cosmic rays and UHE gamma-ray emission

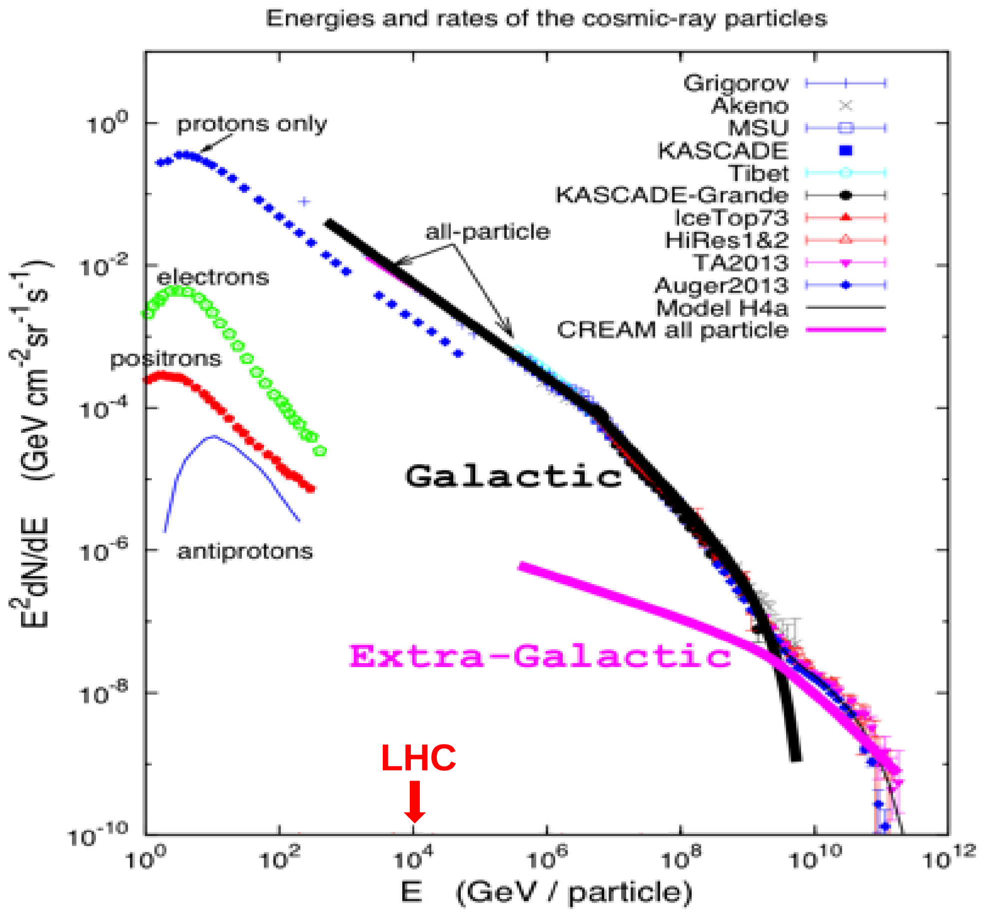
Crab Nebula and three brightest sources at 100TeV

Diffuse Galactic Gamma-ray Emission

Summary

Cosmic Rays

- Charged particles from outer space, mostly protons
- Spectrum spanning 11 order of magnitude, E<1PeV from Galaxy
- Reflect extreme processes in the universe
- Ubiquitous in the universe, important feedback on galaxy and star formation, interstellar medium and etc



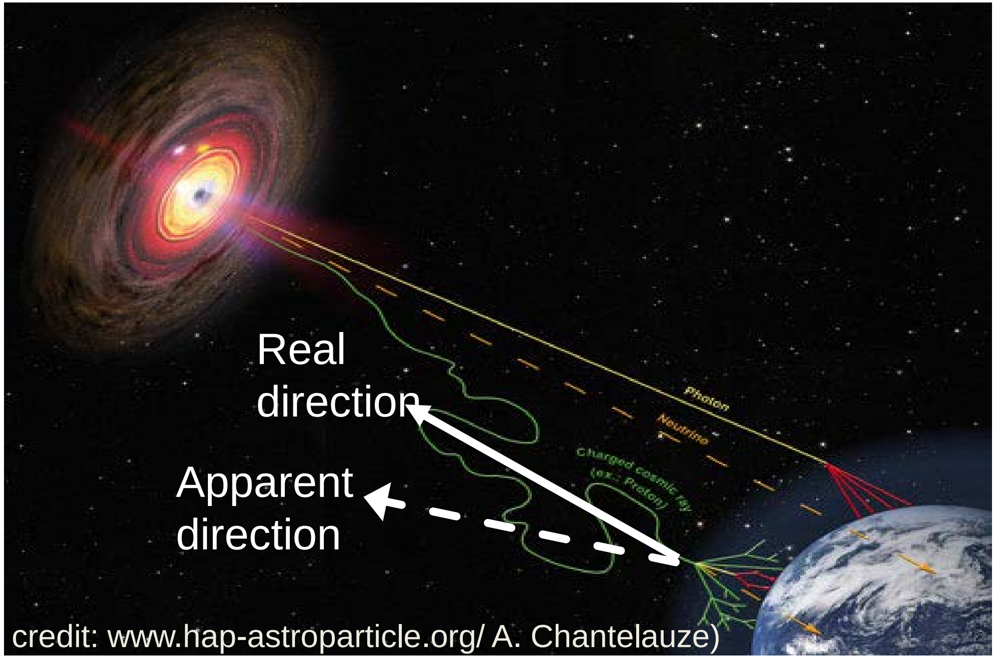
CR Deflection by magnetic field

$$\Delta\theta_{\rm irr} \simeq 1^\circ \left(\frac{E/Z}{50\,{\rm EeV}}\right)^{-1} \frac{B}{3\mu{\rm G}} \left(\frac{L}{3{\rm kpc}}\right)^{1/2} \left(\frac{L_c}{50{\rm pc}}\right)^{1/2}$$

Lower energy cosmic rays propagate more diffusively

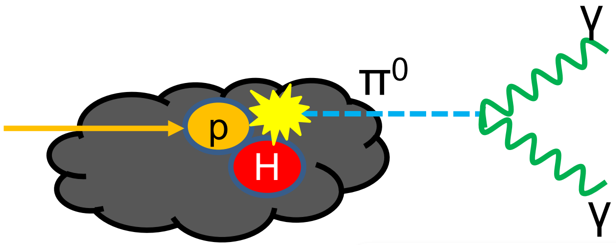
Secondary photons or neutrinos may be a solution:

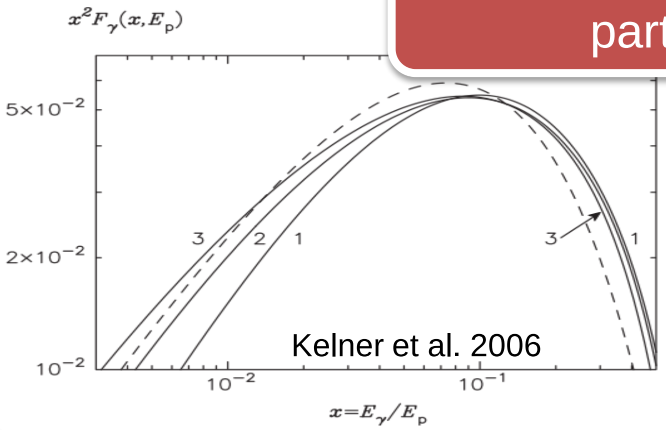
γ or ν produced by CR interaction inside or in the vicinity of the sources



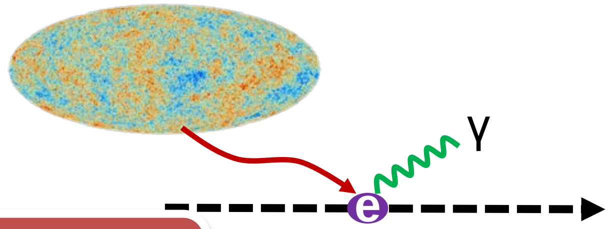
Gamma ray emission mechanism

Proton-proton collision

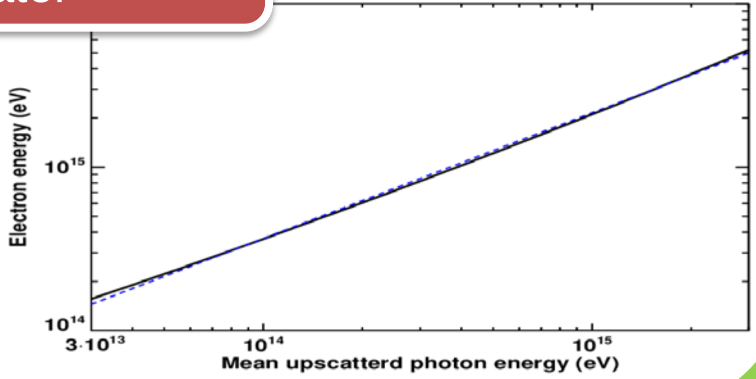




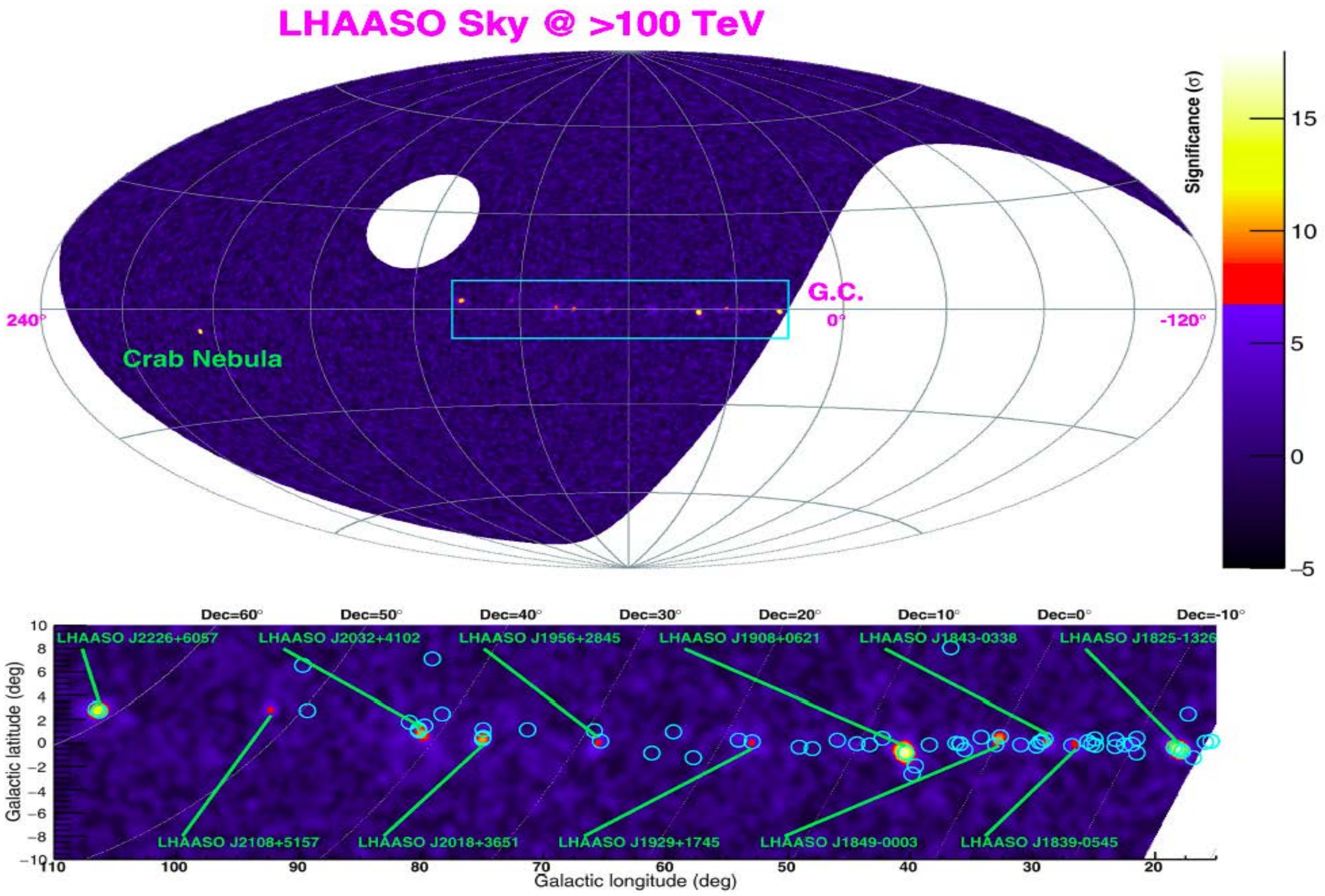
Inverse Compton scattering



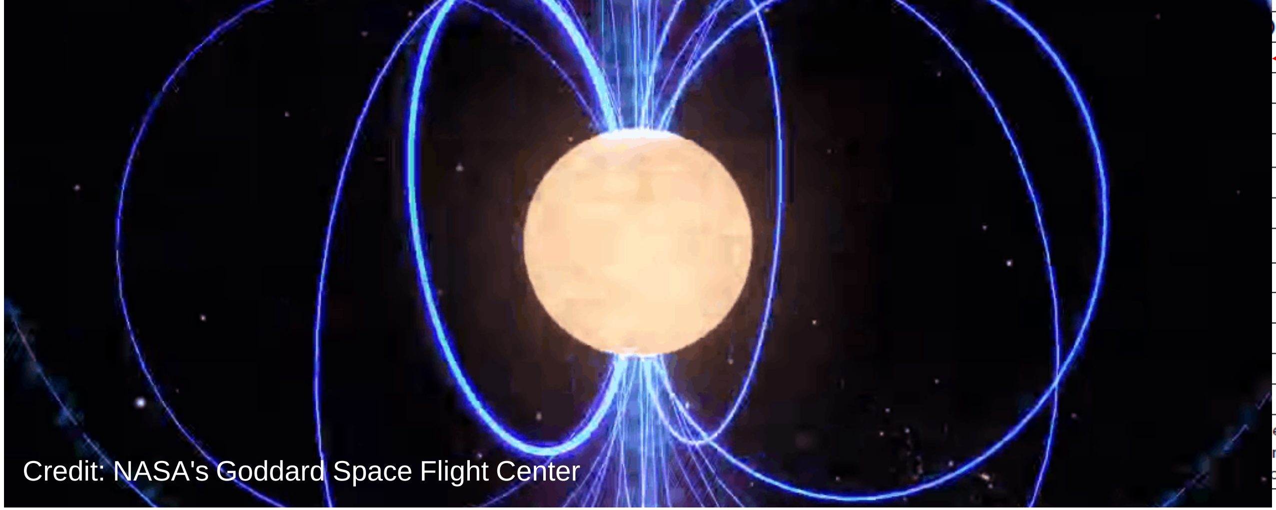
UHE emission is the probe of PeV particle accelerator



LHAASO’s first results



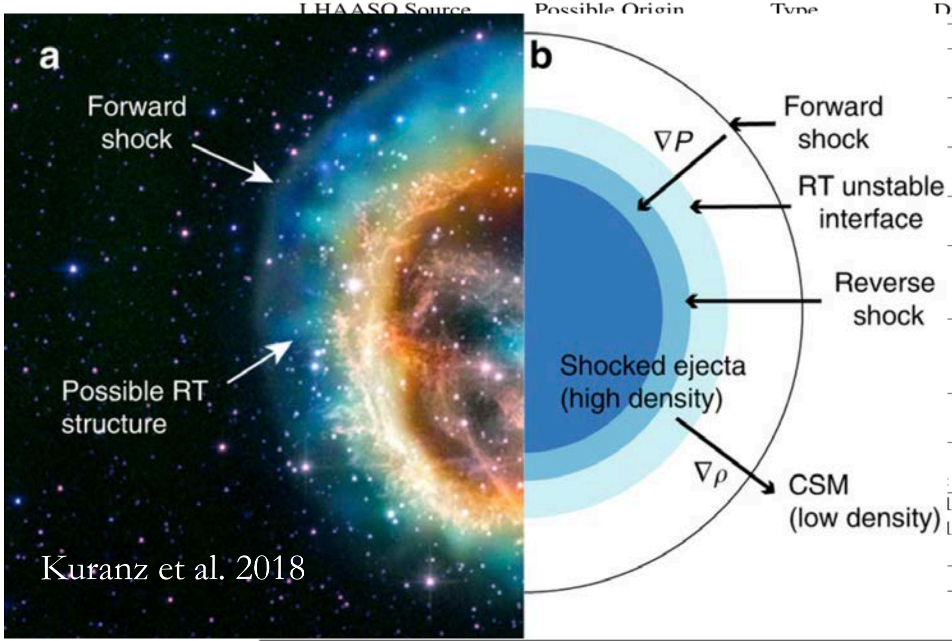
LHAASO Collaboration 2021， Nature, 594, 33

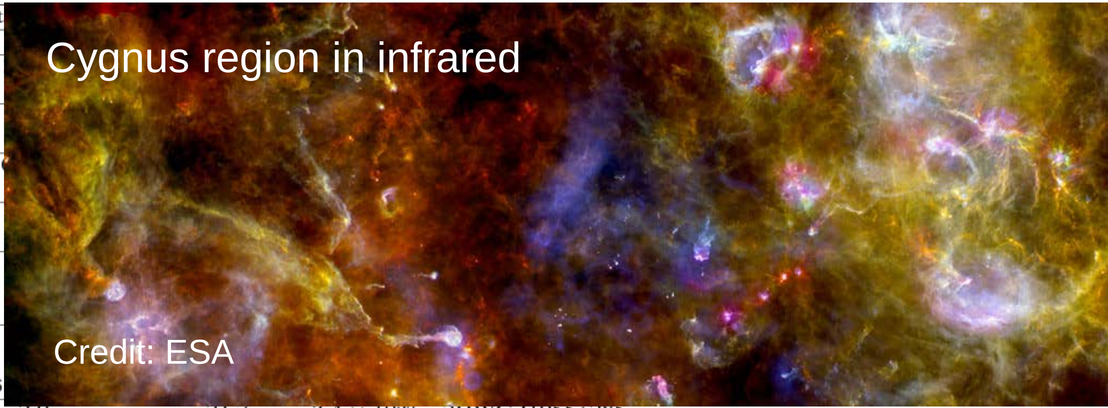


E_{max} (PeV)	Flux at 100 TeV (CU)
0.88 ± 0.11	1.00(0.14)
0.42 ± 0.16	3.57(0.52)
0.21 ± 0.05	0.70(0.18)
$0.26 -0.10^{+0.16}$	0.73(0.17)
0.35 ± 0.07	0.74(0.15)
0.44 ± 0.05	1.36(0.18)
$0.71 -0.07^{+0.16}$	0.38(0.09)
0.42 ± 0.03	0.41(0.09)
0.27 ± 0.02	0.50(0.10)
1.42 ± 0.13	0.54(0.10)
0.43 ± 0.05	0.38(0.09)
0.57 ± 0.19	1.05(0.16)

e for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension
nergies. Errors are estimated as the boundary values of the area that
on is a Gaussian and the error is 1σ.

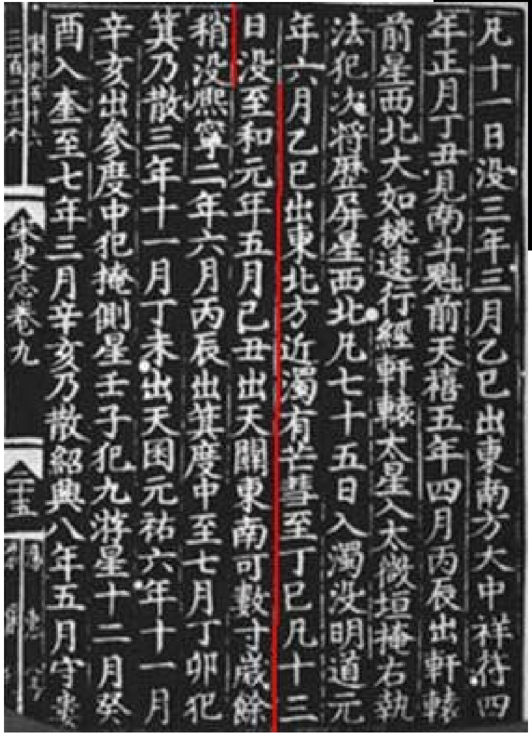
LHAASO Source Possible Origin Type Dist





2.0	21.7	$3.4 \times 10^{..}$	2HWC J1955+285
2.3 ± 0.2^d	—	—	
$1.8^{+1.7\,l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
$0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
—	—	—	VER J2032+414
—	—	—	—
0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
0.8^p	$\sim 10^p$	2.2×10^{37}	

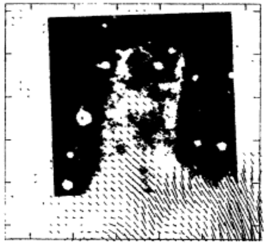
Crab Nebula



凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅大星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁
宋史志卷九

Appearing Time
Position in the sky
Duration
Brightness

The Crab Nebula and Related Supernova Remnants



edited by Minas C. Kafatos and Richard B. C. Henry
Cambridge University Press, Cambridge, 1985. ISBN 0 521 30530 6. Pp. 285 + xv, hardback, £25.00.

Twenty years ago, Geoffrey Burbidge made one of those marvellously quotable remarks: "there are two kinds of astronomy – the astronomy of the Crab Nebula, and the astronomy of everything else". The progress of both kinds of astronomy has made this comment less apposite today: on the one hand, we now understand a lot more about what is going on in the Crab Nebula, and on the other, we have turned up equally enigmatic objects of many different kinds.

But, even so, the Crab Nebula retains its fascination, for amateur and professional astronomers alike. And the discovery, since 1969, of other 'crab nebulas' has only served to

Twenty years ago, Geoffrey Burbidge made one of those marvellously quotable remarks: "there are two kinds of astronomy – the astronomy of the Crab Nebula, and the astronomy of everything else". The progress of both kinds of astronomy has made this comment less apposite today: on the one hand, we now understand a lot more about what is going on in the Crab Nebula, and on the other, we have turned up equally enigmatic objects of many different kinds.

Measuring the Universe

by Albert van Helden
University of Chicago Press, Chicago & London, 1985. ISBN 0 226 84881 7. Pp. viii + 203, hardback, £31.50.

The subtitle of this book, "Cosmic Dimensions from Aristarchus to Halley", precisely describes what it is about. Many readers may well be familiar with the method Aristarchus evolved to try to measure the distances of the Sun and Moon, and also be aware that it was "a geometric success but scientific failure" as van Helden aptly puts it. Even the improved methods of Hipparchus utilising eclipses may be known in principle, but certainly not in the detail given here. That, indeed, is the great value of this book – the wealth of interesting detail which is provided.

This pays many dividends. For instance, the discussion of Ptolemy's efforts and their follow up both in the Arab world and in the medieval West is most illuminating. And when we come to later times, especially the work of Horrocks, Riccioli and his successors, Professor van Helden's details of the battle to determine the solar parallax show something of the difficulties which even then still faced investigators.

In brief, this is a book which collects together a wealth of information about a side of early astronomy which is often ignored or at best dealt with summarily in most general texts. It has also the added advantage that Professor van Helden writes well, with a flair for clear explanation. I warmly recommend this book, and express the fervent hope that it will one day come out as a paperback so it reaches a still wider readership.

Colin A. Ronan

Protostars and Planets II

edited by David C. Black and Mildred Shapley Matthews
University of Arizona Press, Tucson, Arizona, 1985. ISBN 0 8165 0950 6. Pp xx + 1293, hardback $45.00.

One of today's astronomical bandwagons (and I don't mean this to be derogatory, as I've leapt on this bandwagon myself) is the marriage of cosmogony to the first stage of stellar evolution. The consensus is that planetary formation and star formation are intricately interwoven; they took place at the same time, in the same spot, out of the same cloud of gas and dust. Coupled with this is the feeling that planetary systems are common, and that at least 25% of the stars in our Galaxy have sets of planets not too dissimilar from our set of nine.

At Tucson, Arizona, we can see an example of what our American colleagues call 'synergistic activity', in which 200 attendees listen to 100 contributed talks on this subject. Two such jamborees were held in 1978 January and 1984 January, and a third will be held in 1990. *Protostars and Planets II* is the book of the second meeting. Normally in a debate on the origin of the Solar System (see for example the book of that title edited by S. F. Dermott, John Wiley, 1978) one stands back and lets a dozen or so cosmogonists of widely differing views argue vociferously with each other for days on end, finishing off with disharmony and lack of agreement – and a group of people looking forward eagerly to the next round. Not so in Arizona. To quote E. H. Levy: "today, to a first approximation, there exists no competing theories for the origin of our Solar System". If only science were really that easy.

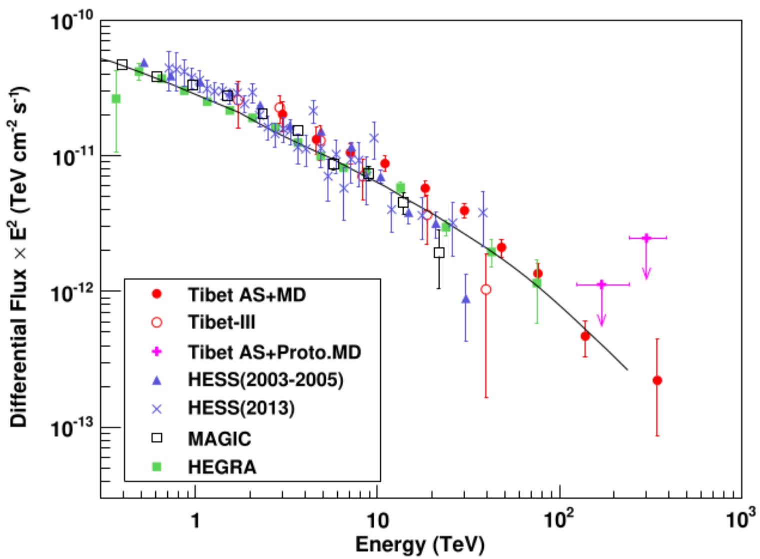
Record of the supernova explosion in ancient Chinese Chronicle （1054AD）

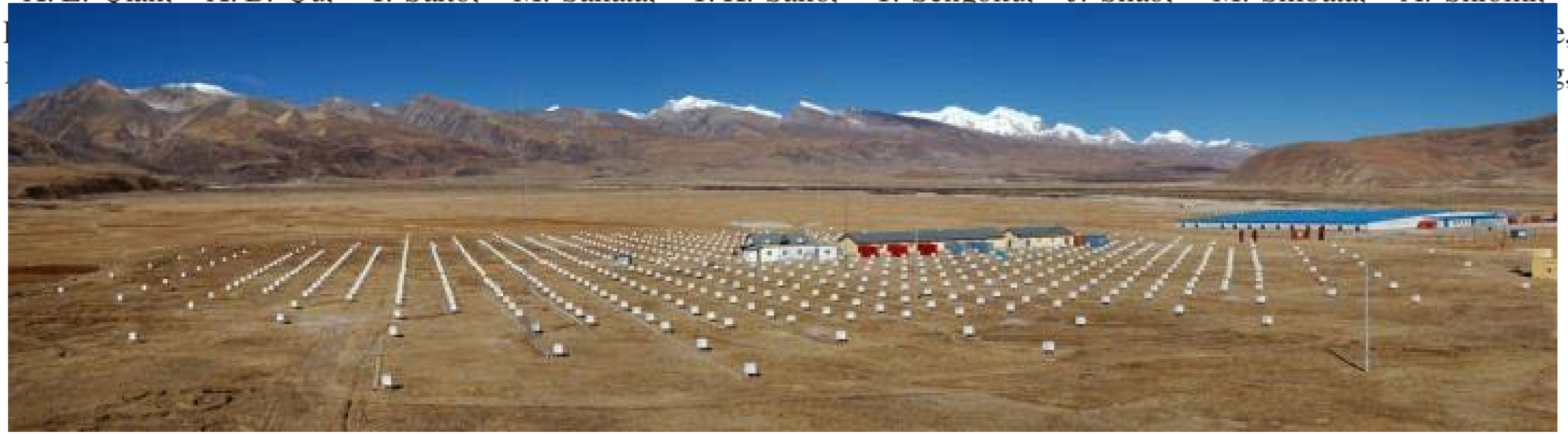
PHYSICAL REVIEW LETTERS **123**,

Editors' Suggestion   Featured in Physics

First Detection of Photons with Energy beyond 100 Te

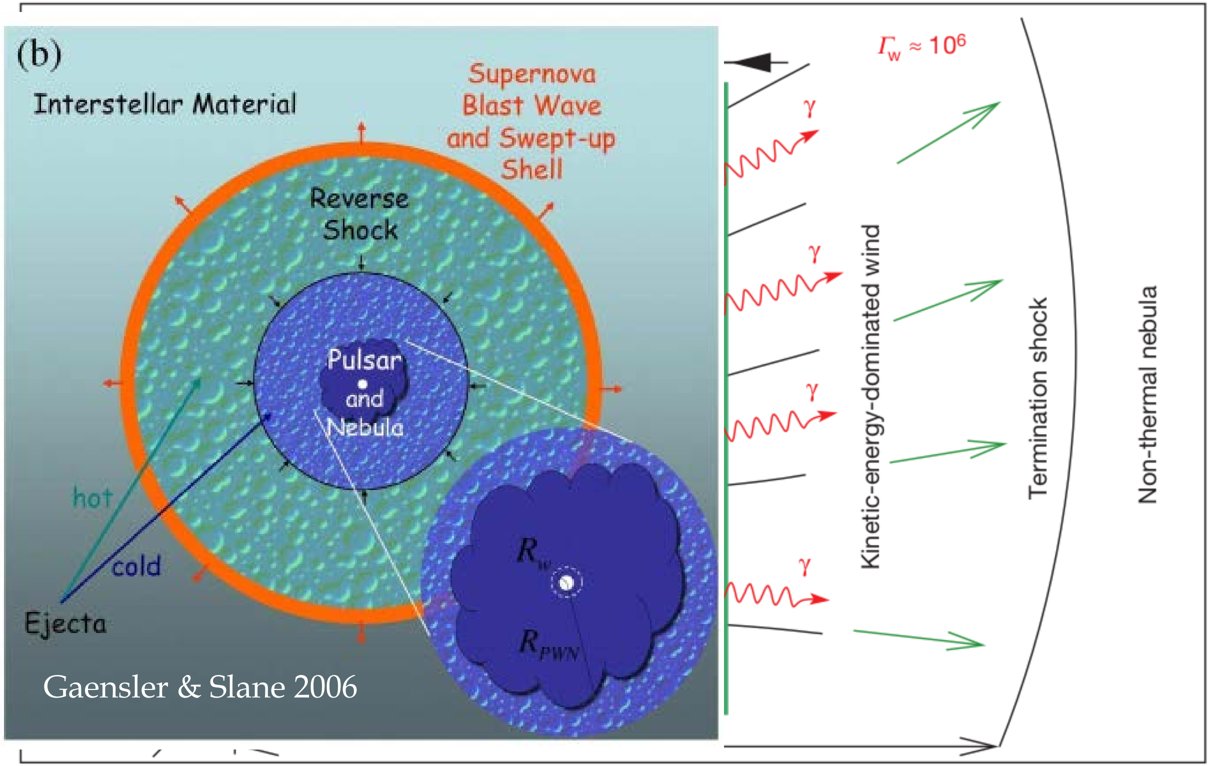
M. Amenomori,[1] Y. W. Bao,[2] X. J. Bi,[3] D. Chen,[4] T. L. Chen,[5] W. Y. Chen,[3] X
Danzengluobu,[5] L. K. Ding,[3] J. H. Fang,[3,6] K. Fang,[3] C. F. Feng,[8] Zhaoy
Y. Q. Guo,[3] H. H. He,[3] Z. T. He,[7] K. Hibino,[10] N. Hotta,[11] Haibing Hu,[5]
H. B. Jin,[4] F. Kajino,[12] K. Kasahara,[13] Y. Katayose,[14] C. Kato,[15] S. Kat
G. M. Le,[18] A. F. Li,[19,8,3] H. J. Li,[5] W. J. Li,[3,9] Y. H. Lin,[3,6] B. Liu,[2] C. Liu
X. R. Meng,[5] H. Mitsui,[14] K. Munakata,[15] Y. Nakamura,[3] H. Nanjo,[1] M. Ni
X. L. Qian,[23] X. B. Qu,[24] T. Saito,[25] M. Sakata,[12] T. K. Sako,[16] Y. Sengoku,[14] J. Shao,[3,8] M. Shibata,[14] A. Shiomi,[26]





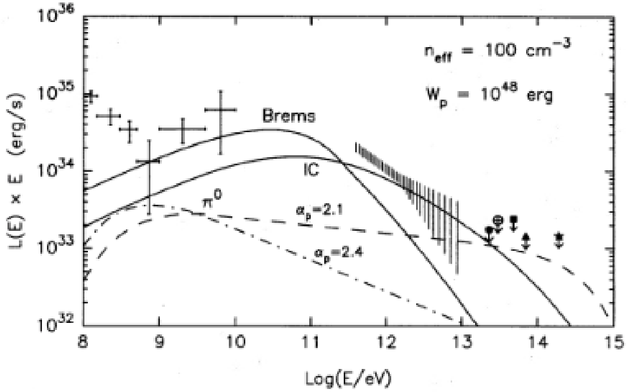
spindown energy → Magnetic energy / electron energy / proton energy?

Crab Pulsar: L_{sd}=4.5x10^{38}erg/s

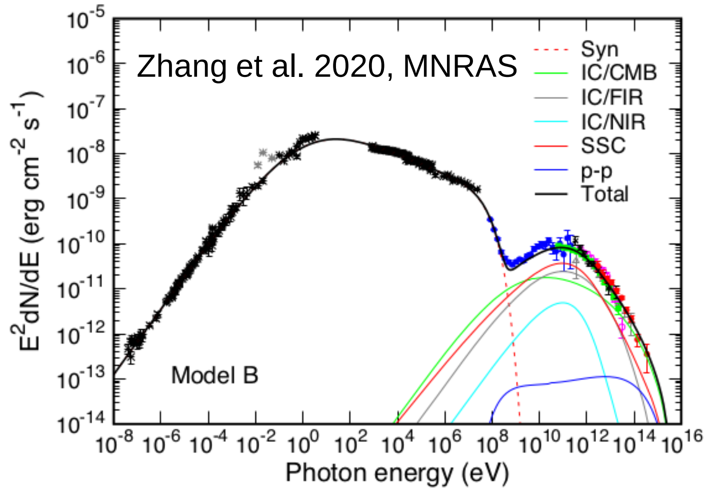


Aharonian et al. 2012, Nature

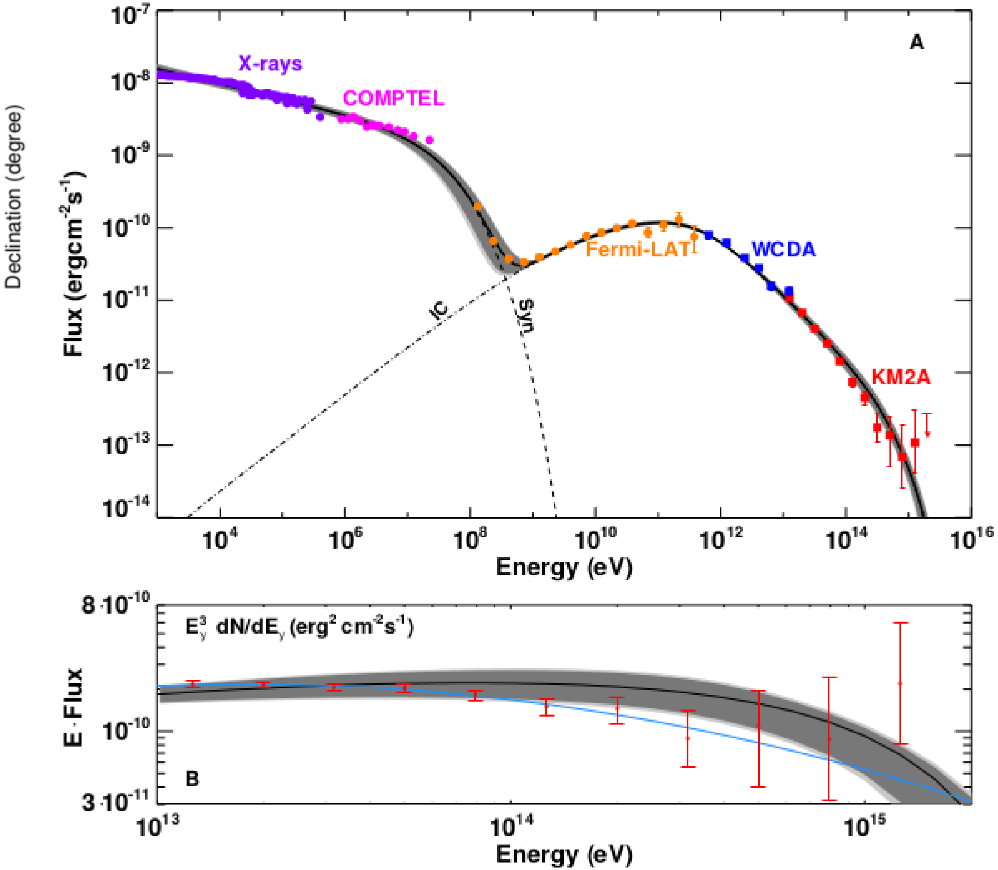
Atoyan & Aharonian 1996, A&A

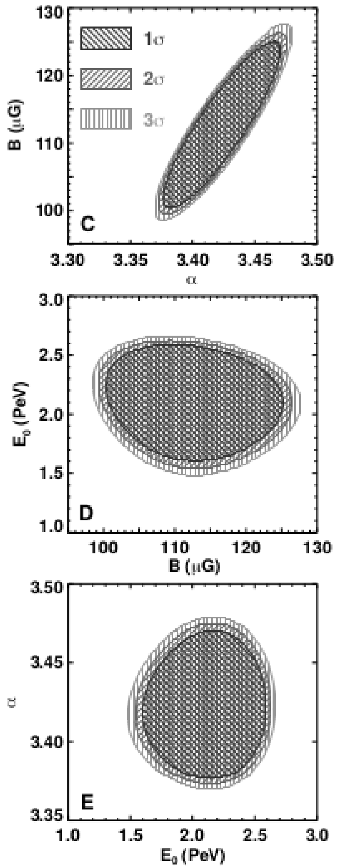


Proton fraction < 0.5% (n/10cm^{-3})$^{-1}$

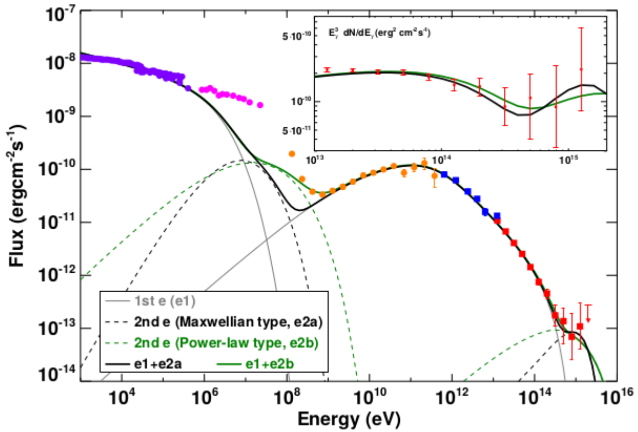


LHAASO's measurement on Crab Nebula

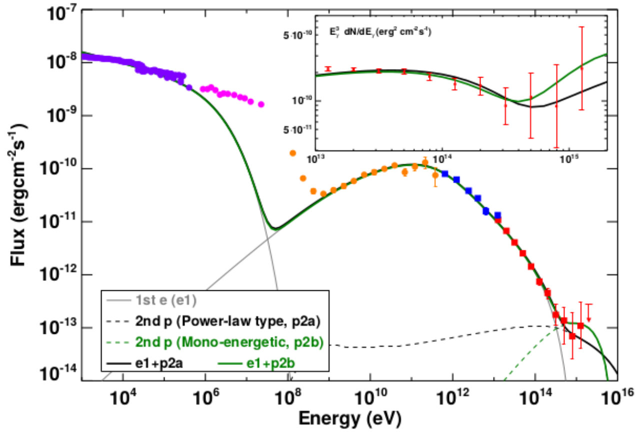




2 Leptonic components



Leptonic+Hadronic component



LHAASO Collaboration 2021, Science

How much fraction of the spindown energy can go into protons?

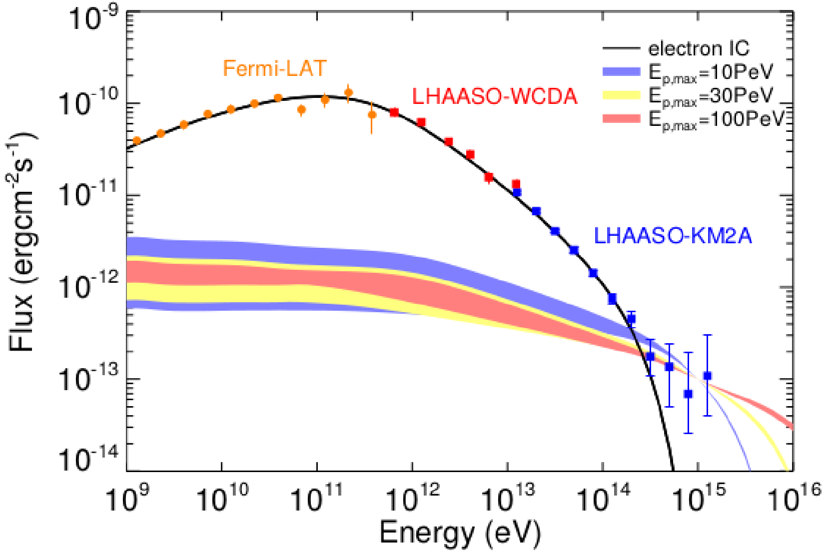
Protons injected at early time have escaped

$$r_{\rm diff} \equiv 2\left[D(E)t\right]^{1/2}$$

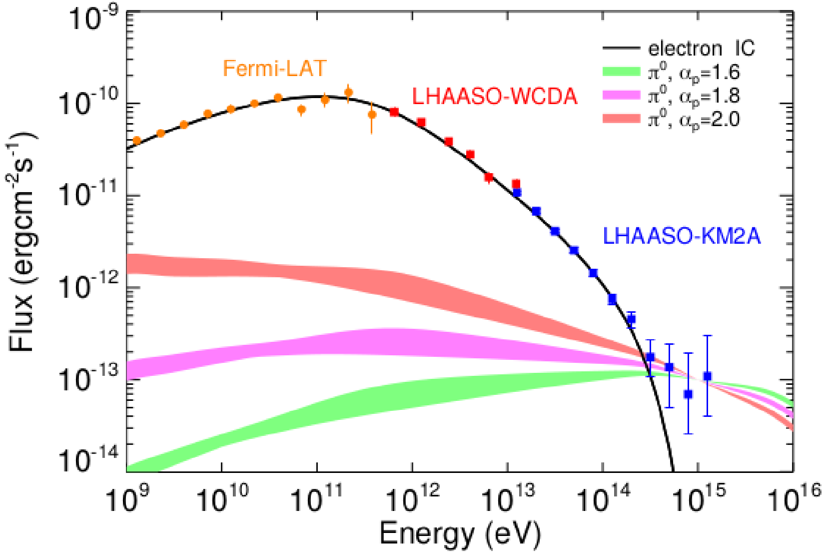
$$f_p(E_p,t) = \min[1,(r_{\rm crab}/r_{\rm diff})^3]$$

$$\frac{dN_p}{dE_p} = \int_0^{\tau_{\rm crab}} \frac{Q_0(E_p)f_p(E_p,t)}{[1+(\tau_{\rm crab}-t)/\tau_0]^\sigma}dt$$

η_p = (10 − 50)%
$E_{p,max}$ = 10 PeV, 30 PeV, 100 PeV
α_p = 1.6, 1.8, 2.0



Liu & Wang 2021, ApJ accepted



Possible contribution of pulsars to CRs beyond the knee

Crab: $2\sqrt{D_{\rm ISM}\times 7500{\rm yr}}$

$$l = 0.9(E_p/10{\rm PeV})^{1/6}\,{\rm kpc}$$

Not yet arrived

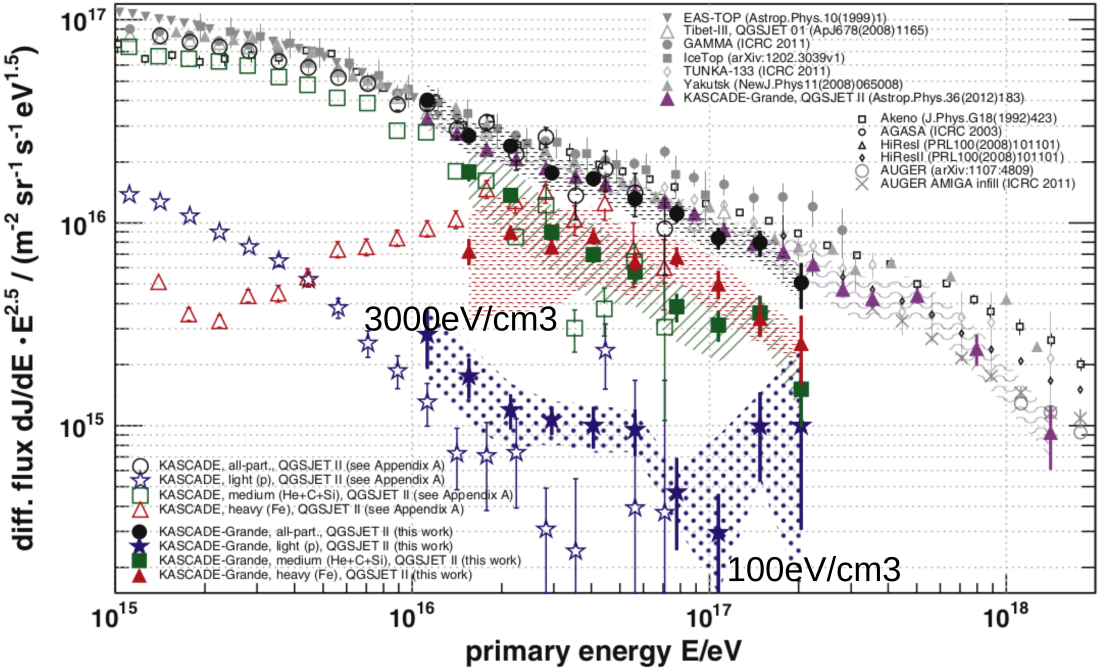
$$D_{\rm ISM} \simeq 4\times 10^{28}(E/1\,{\rm GeV})^{1/3}{\rm cm}^2{\rm s}^{-1}$$

$$F(E_p) = \frac{c}{4\pi}\frac{\eta_p L_{\rm s,tot} t_{\rm esc}}{2\pi R_{\rm Gal}^2 H_{\rm CR}\ln(E_{p,\rm max}/E_{p,\rm min})}$$

$$\approx 2\times 10^3\left(\frac{f_{\rm pul}\eta_p L_{\rm s,tot}}{10^{39}\,{\rm erg\ s^{-1}}}\right)\left(\frac{E_p}{10\,{\rm PeV}}\right)^{-1/3}$$

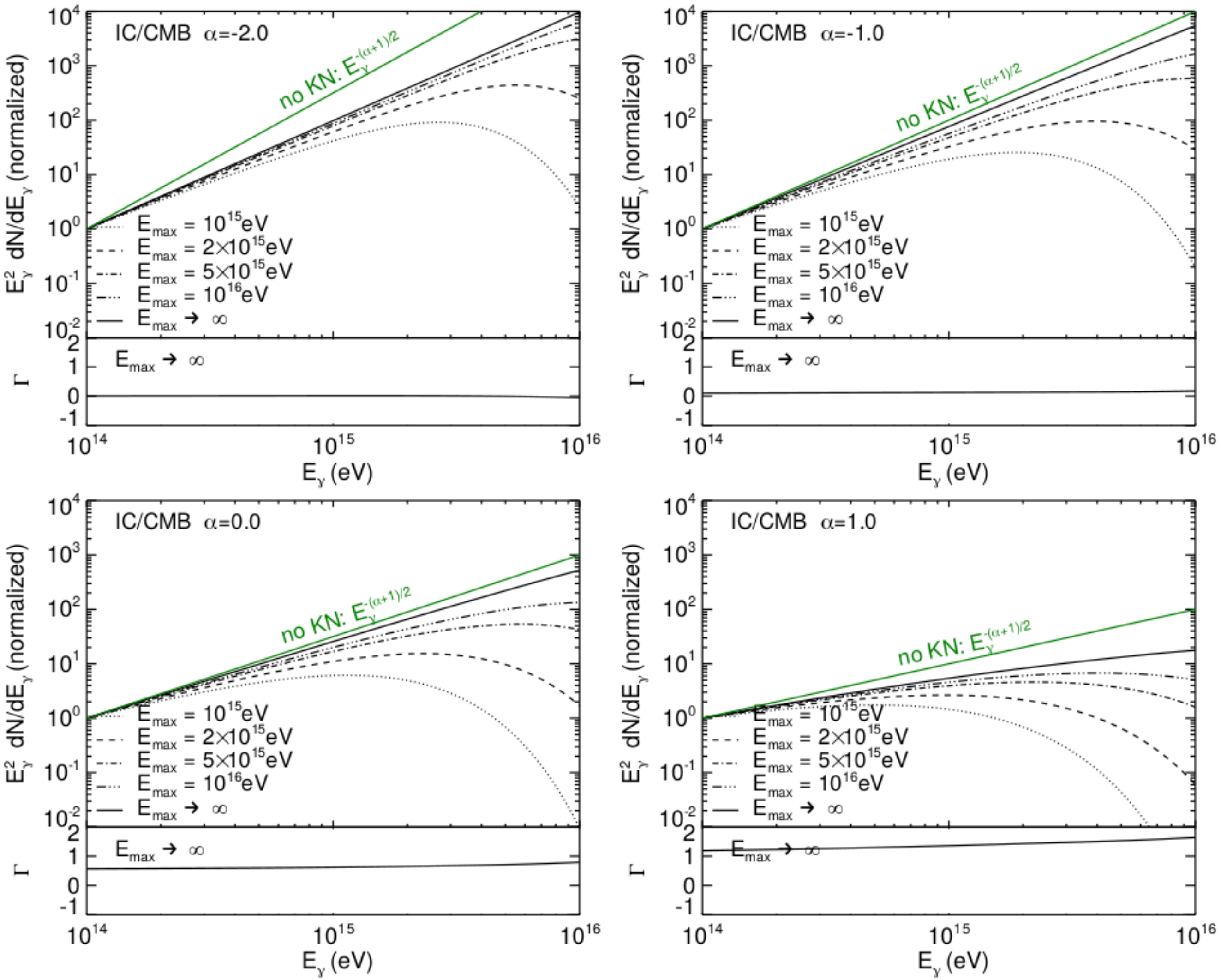
$$\times\left(\frac{H_{\rm CR}}{4\,{\rm kpc}}\right)\left(\frac{R_{\rm Gal}}{15\,{\rm kpc}}\right)^{-2}\ {\rm eV\ cm^{-2}s^{-1}sr^{-1}}$$

KASCADE-Grande



$$E_{e,\max} = 6 \left(\frac{B}{100\mu G} \right)^{-1/2} \text{PeV}$$

A leptonic scenario cannot be excluded even if several PeV photon is detected from Crab Nebula



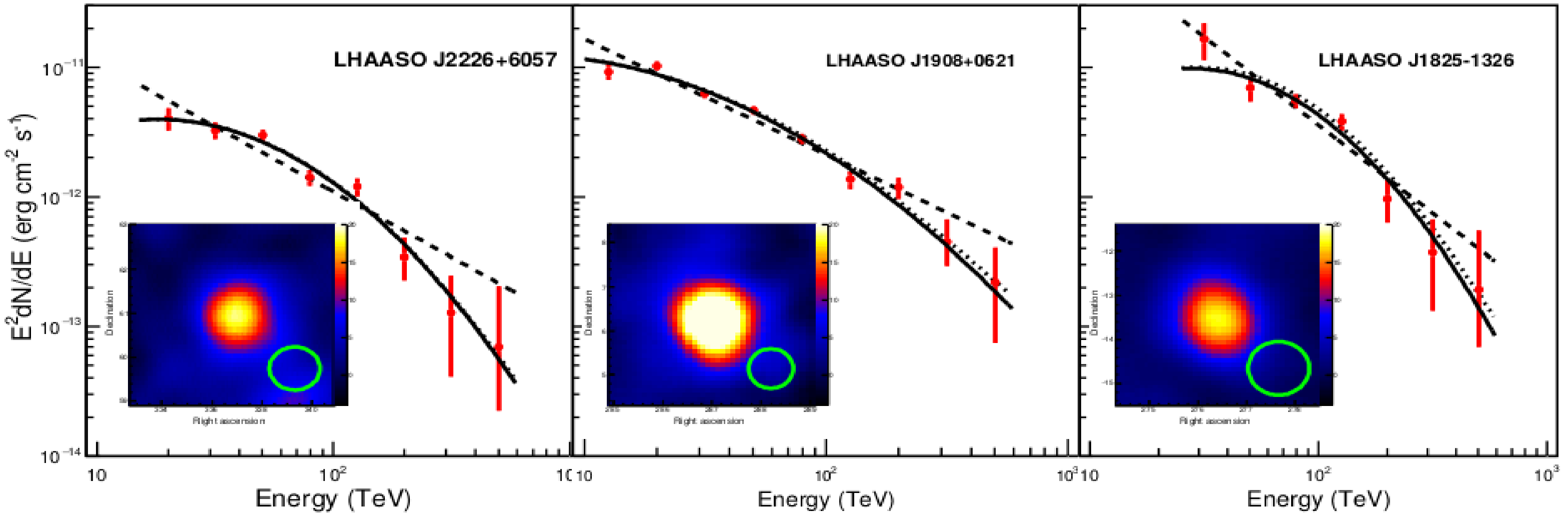
Neutrino observation might help

IceCube >100TeV ν_μ

~0.3 for 10 years

10 x IceCube

SED of three brightest sources at 100TeV



1. Gradual softening of the spectrum
2. No clear spectral cutoff
3. complex region

LHAASO J2226+6057

LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}

Blue: Atomic (HI) Cloud
Red: Molecular Cloud

Head: Interacting with HI Cloud
Tail: Expanding into a Cavity

Gamma-ray coincident with the molecular cloud

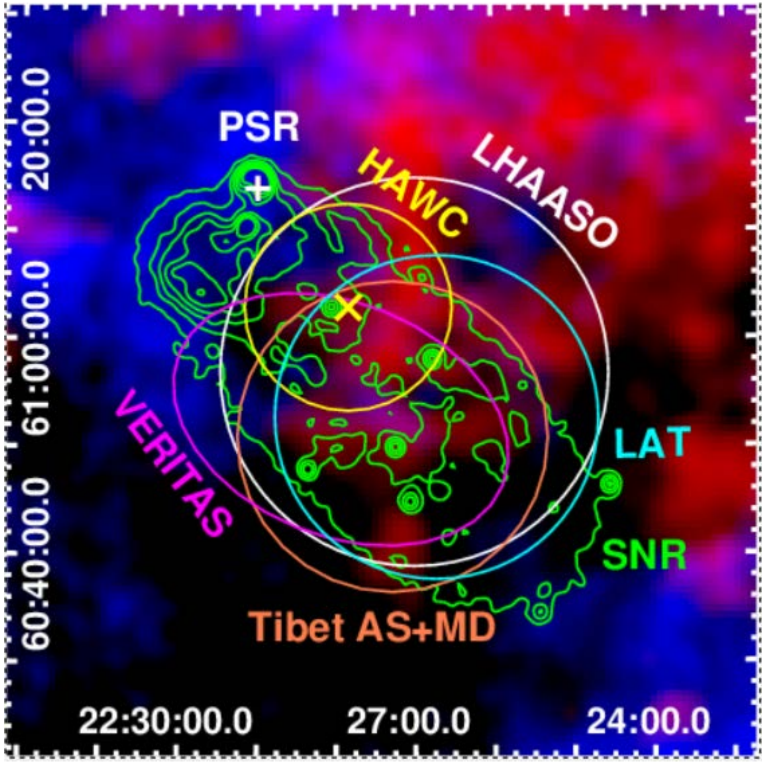
Fermi-LAT 3-500GeV (Xin et al. 2019)

HAWC 1-100TeV (HAWC Collaboration 2020)

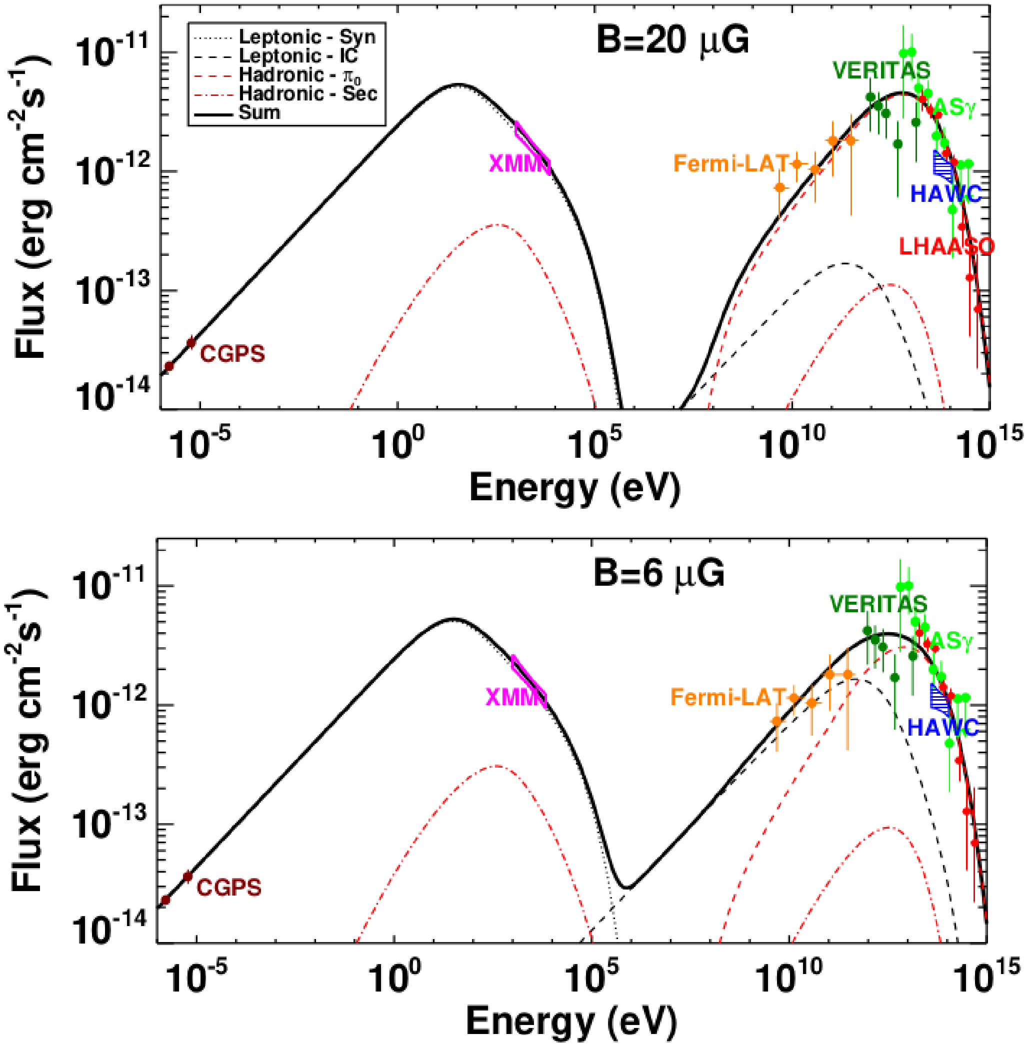
VERITAS 1-10TeV (VERITAS Collaboration 2009)

Tibet AS+MD, 10-100TeV (ASγ Collaboration 2021)

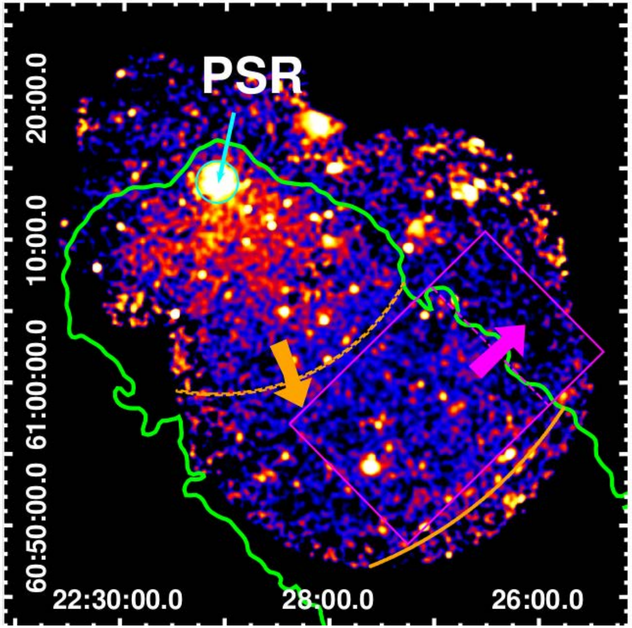
LHAASO, >100TeV (LHAASO Collaboration 2021)



Ge, **RYL,** Niu, Chen & Wang 2021, *The Innovation*, 2, 100118



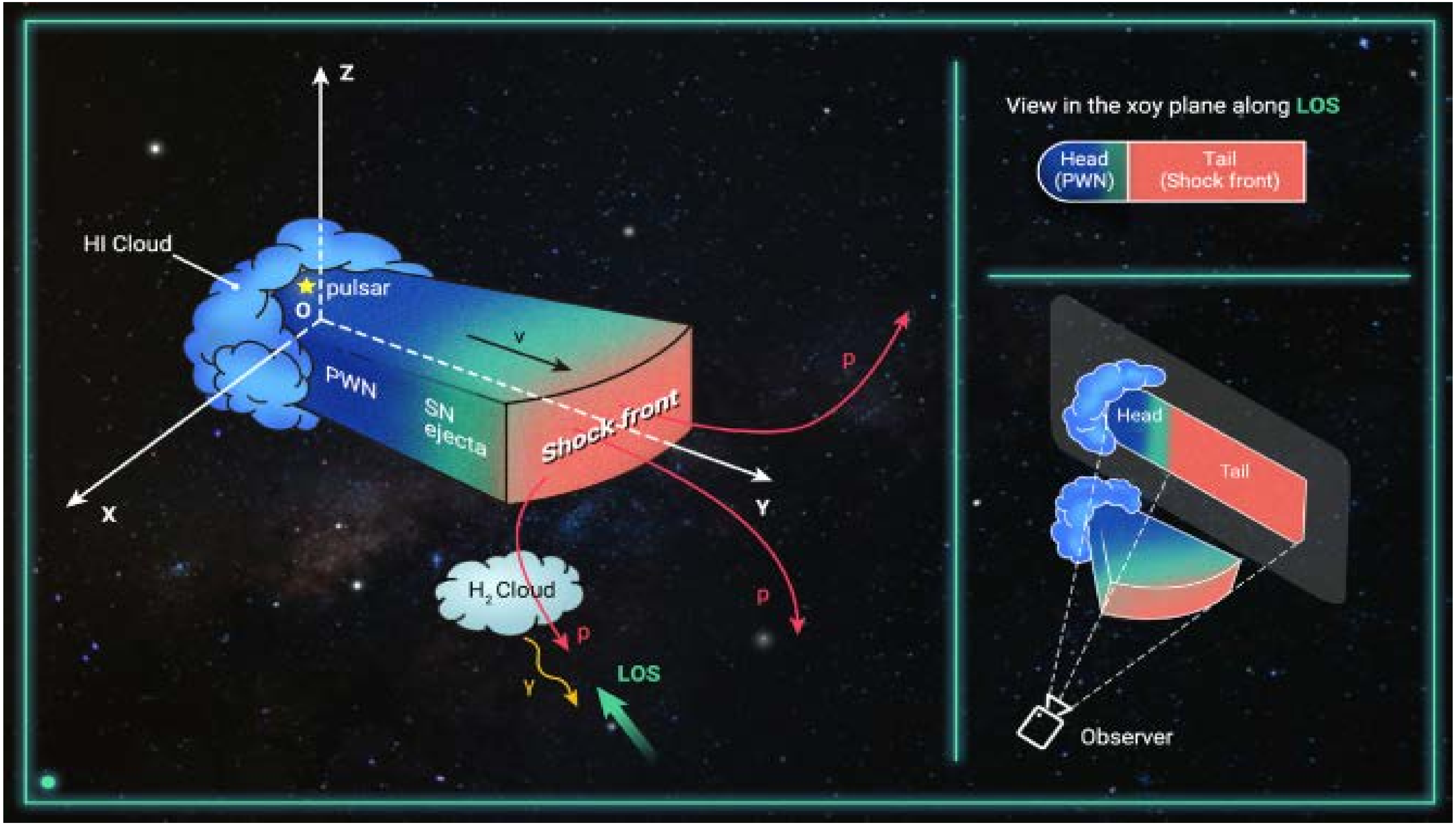
Ge, **RYL,** et al. 2021



$$\epsilon_{\rm syn,max} \approx 7\eta(v_s/3000{\rm km\ s^{-1}})^2\,{\rm keV}$$

The inferred high shock velocity empowers the shock to accelerate PeV protons!

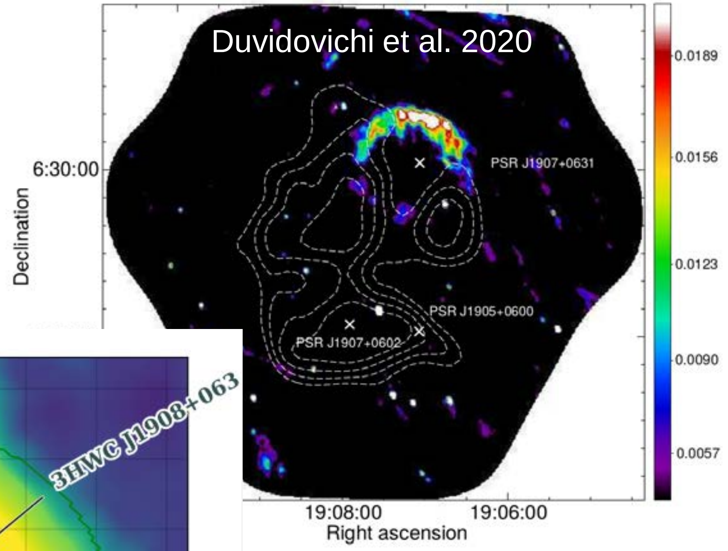
$$E_{p,\rm max} \approx 3\left(\frac{T_{\rm age}}{10\,\rm kyr}\right)\left(\frac{B}{10\mu{\rm G}}\right)\left(\frac{\epsilon_{\rm syn,max}}{7\,\rm keV}\right)\,\rm PeV$$



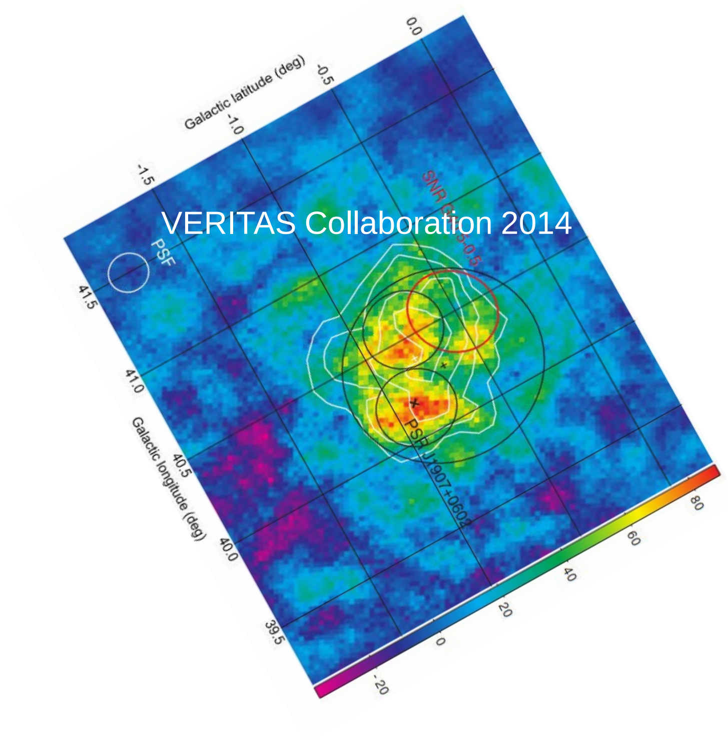
Ge, **RYL** et al. 2021

LHAASO J1908+0621

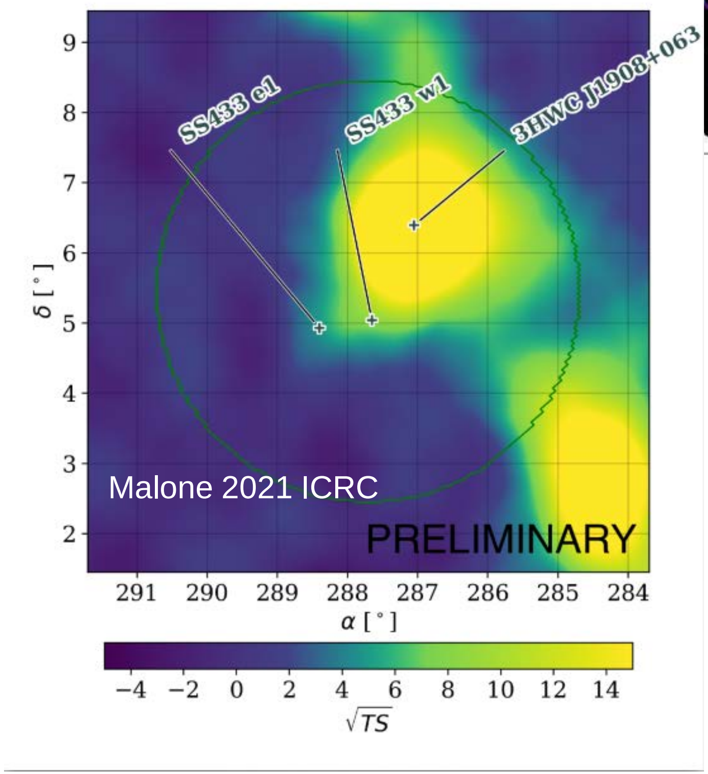
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4[i]	$\sim 10 - 20$[j]	—
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}



Duvidovichi et al. 2020

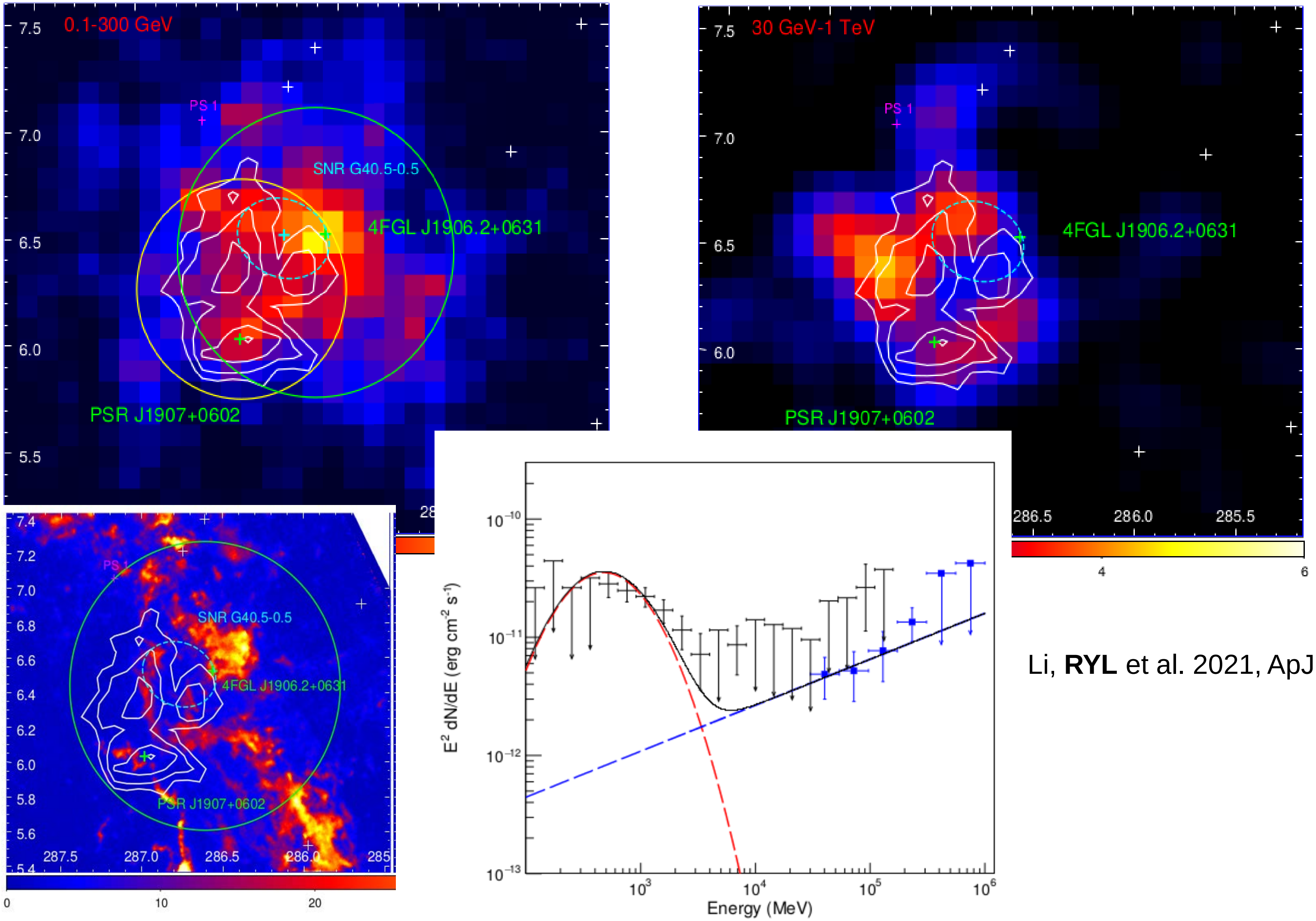


VERITAS Collaboration 2014



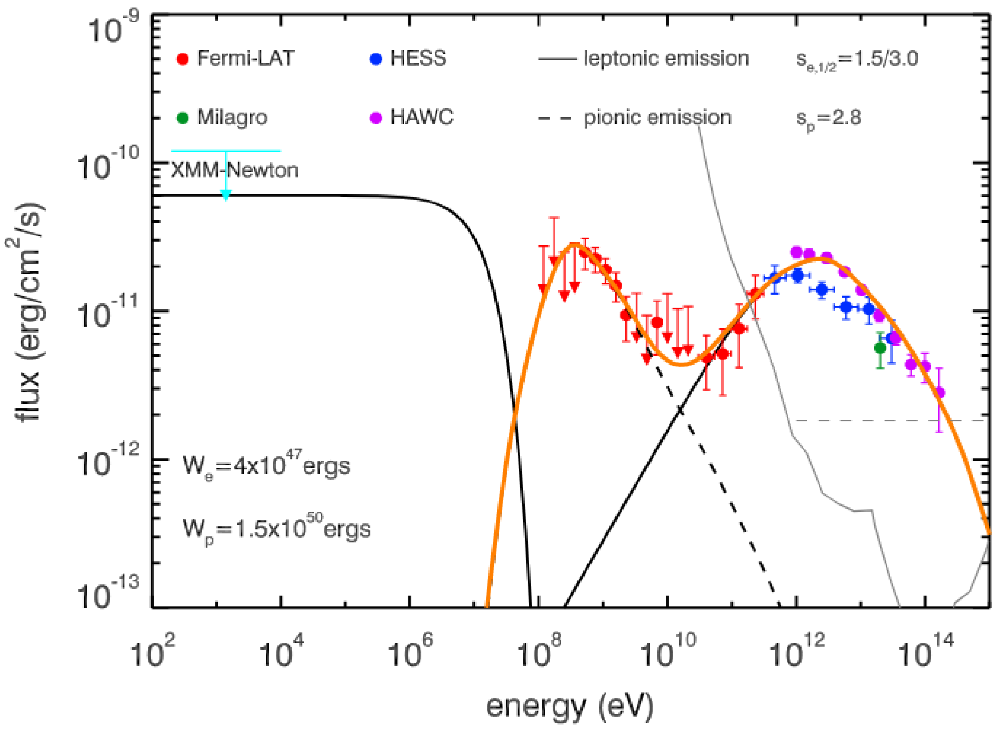
Malone 2021 ICRC

Fermi-LAT's observation



Li, **RYL** et al. 2021, ApJL

Two components



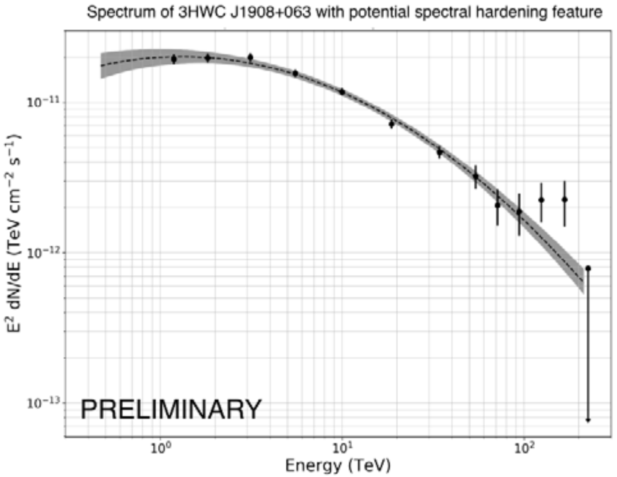
Li, RYL et al. 2021, ApJL

Muon neutrino flux upper limit by IceCube

$$dN/dE_\nu = 5.7\times10^{-13}(E_\nu/1\mathrm{TeV})^{-2}\mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}.$$

IceCube Collaboration 2020, PRL

Another hadronic gamma-ray component is allowed

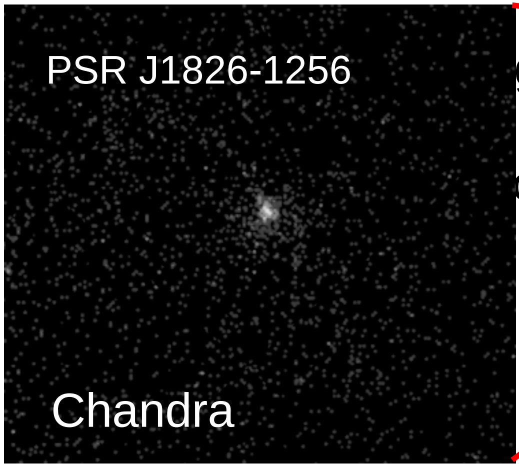


2σ deviation from best-fit function beyond 100TeV

Malone 2021, ICRC

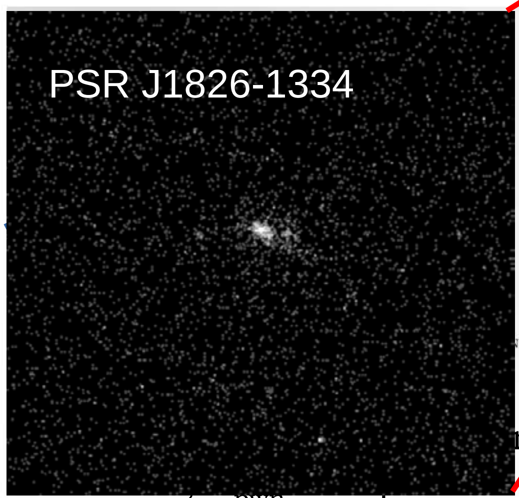
LHAASO J1825-1326

LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^{d}	21.4	2.8×10^{36}
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}



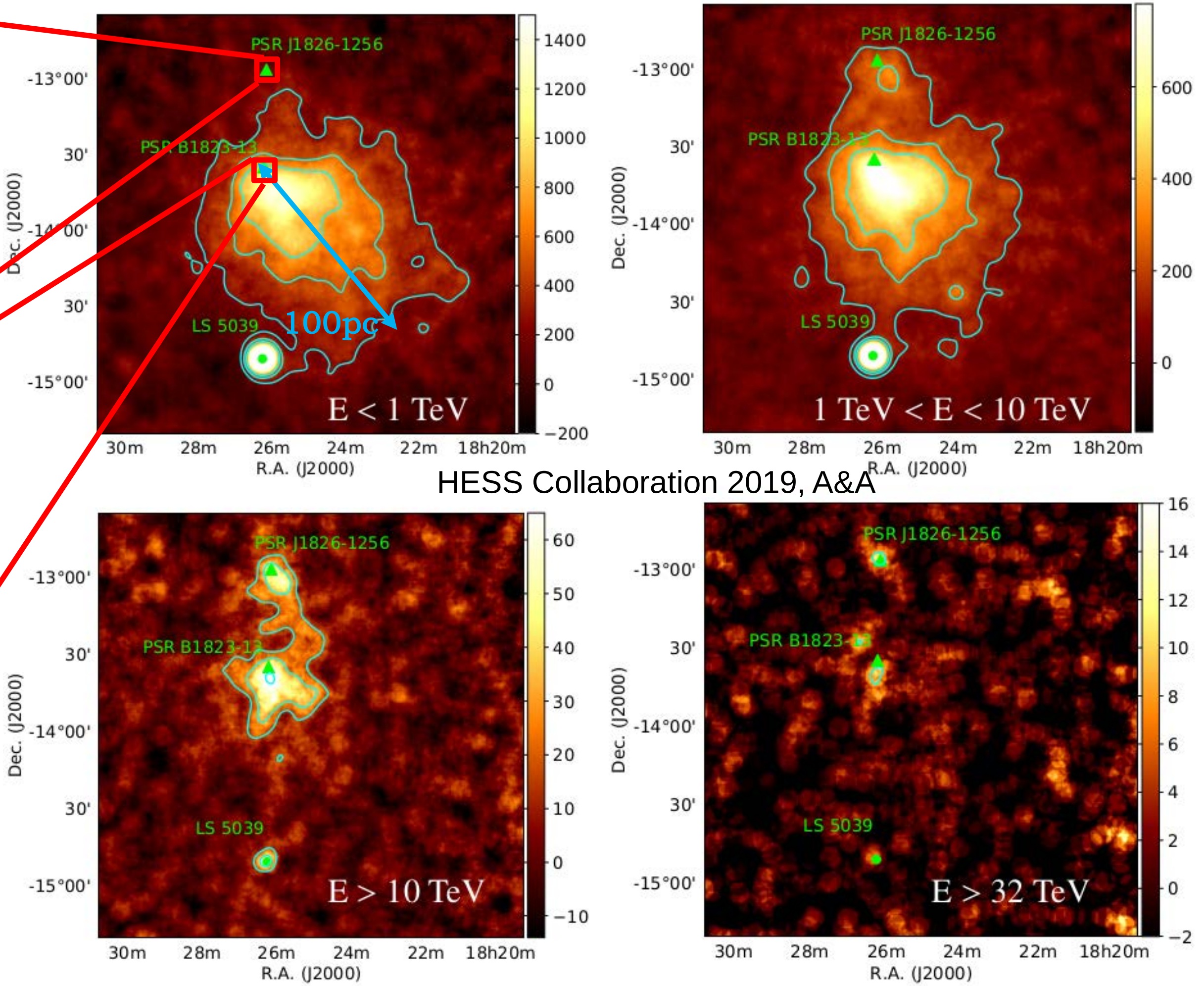
gy

orphology

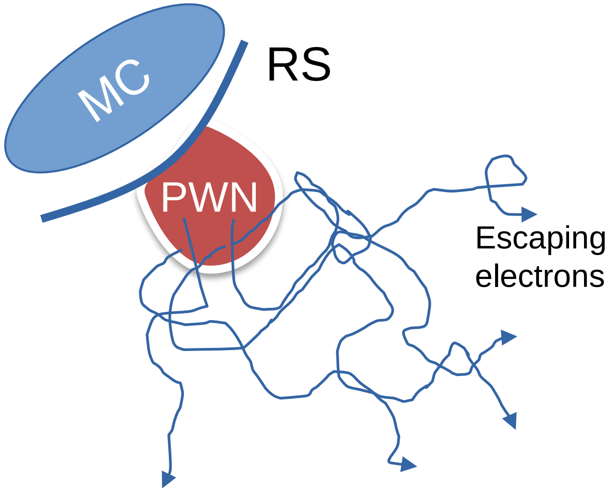


ng

pwn



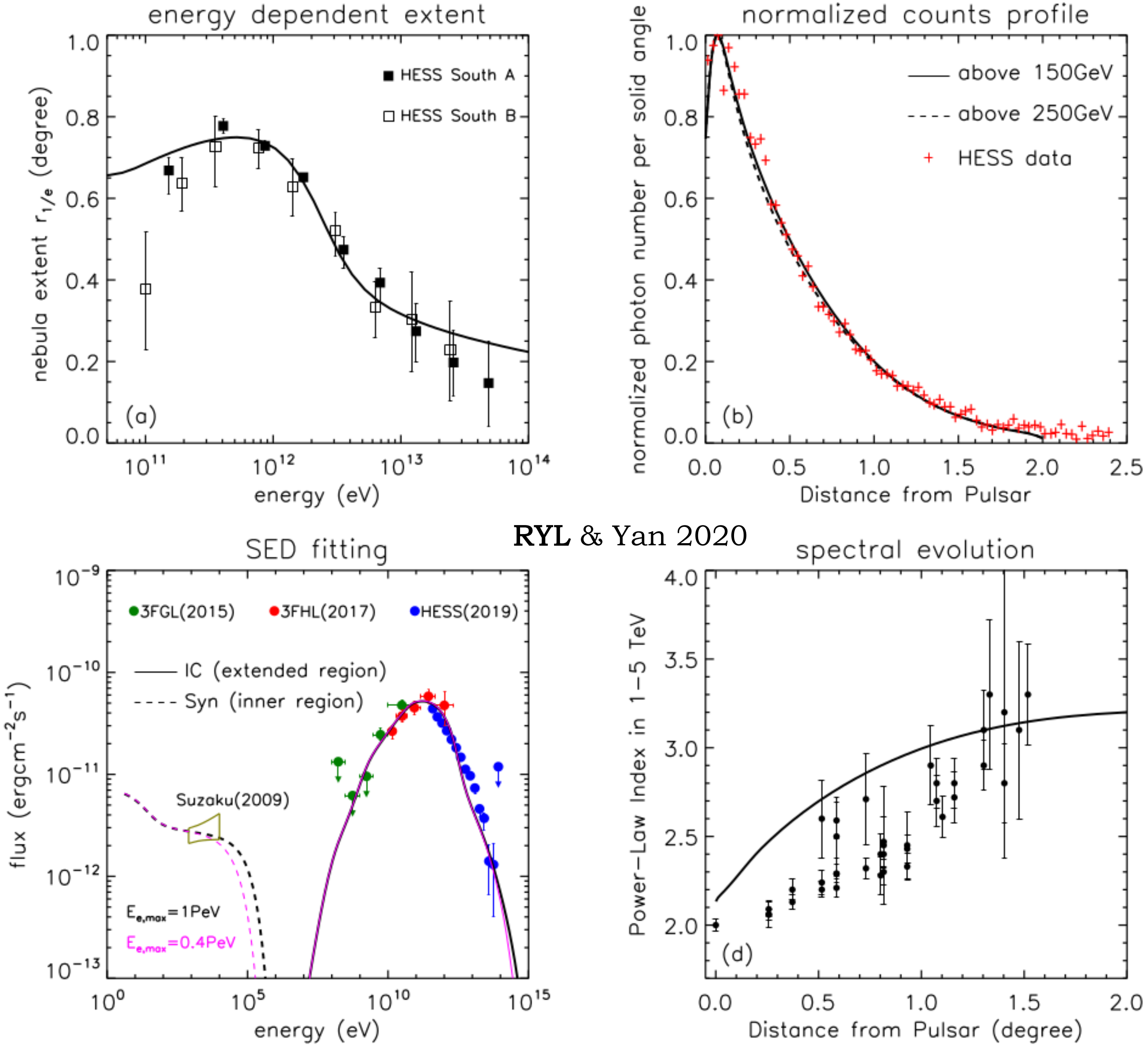
HESS Collaboration 2019, A&A



$$N(E_e,r) = \int_0^{t_{\rm age}} \frac{Q_{e,\rm inj}(E_g,t)dt}{(4\pi\lambda(E_e,t))^{3/2}} \exp\left[-\frac{r^2}{4\lambda(E_e,t)}\right] \frac{dE_g}{dE_e}$$

Energy-dependent extension can be well reproduced in a pulsar halo scenario

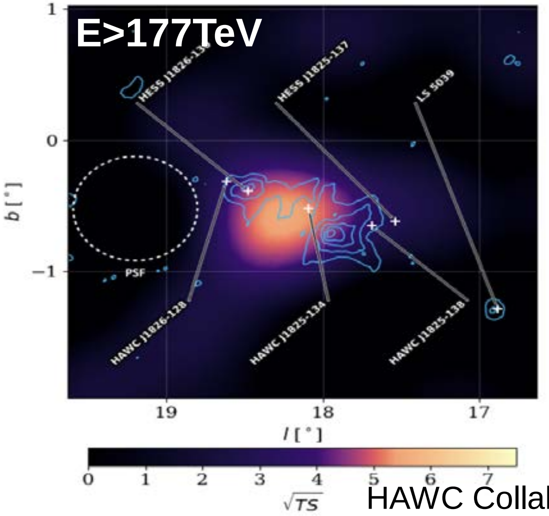
Hybrid system: pwn+halo



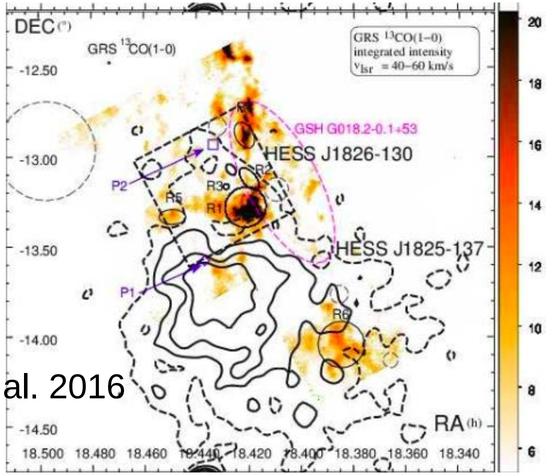
RYL & Yan 2020

Possible Contribution from an additional hadronic component

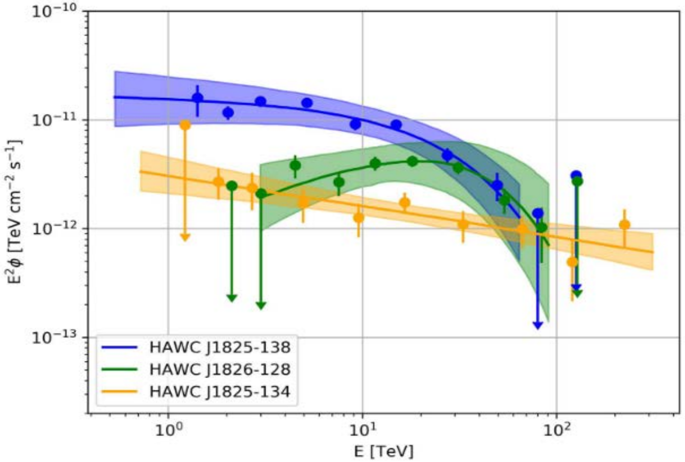
Interaction between CR and MC



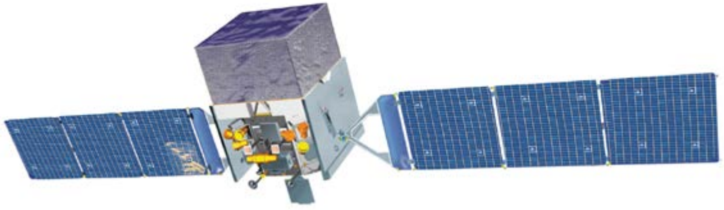
HAWC Collaboration 2021

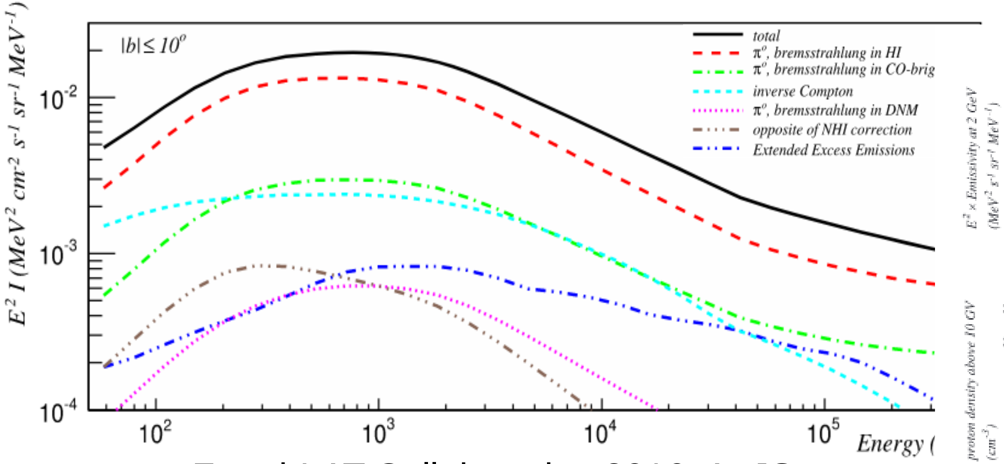


Voisin et al. 2016

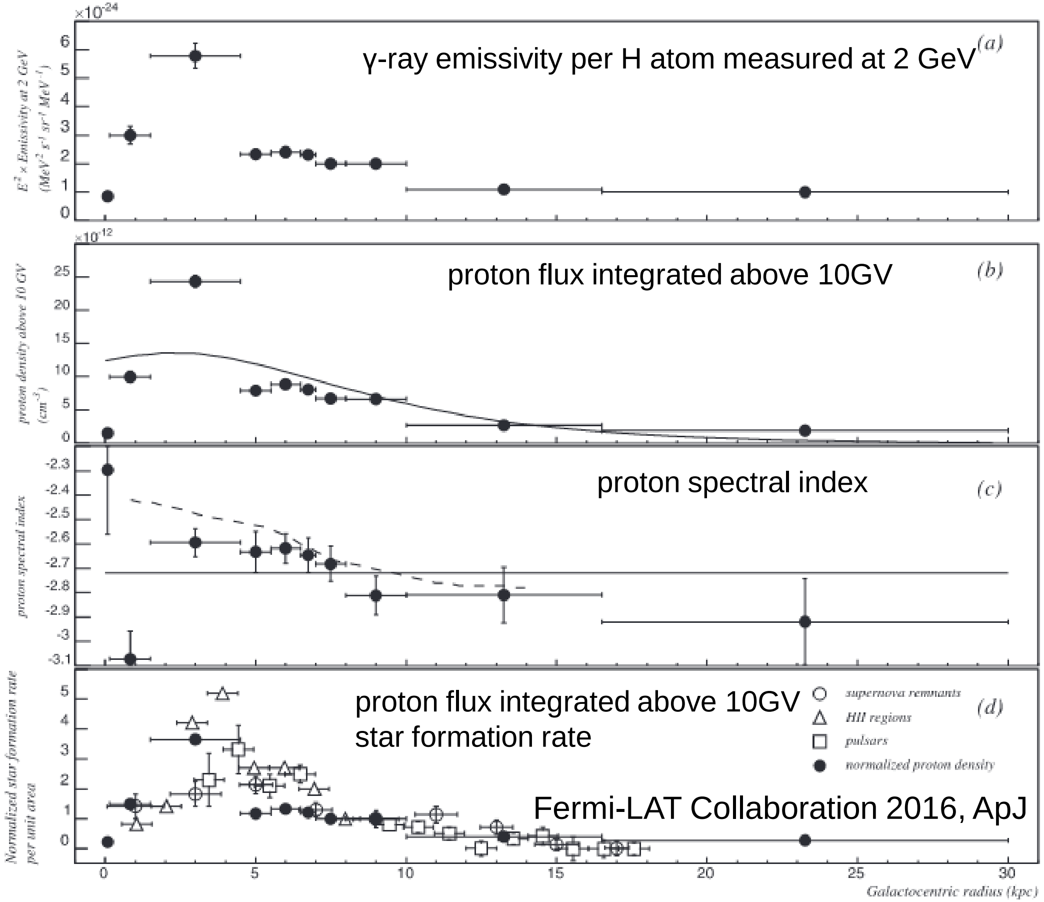


Galactic Diffuse Gamma-ray Background





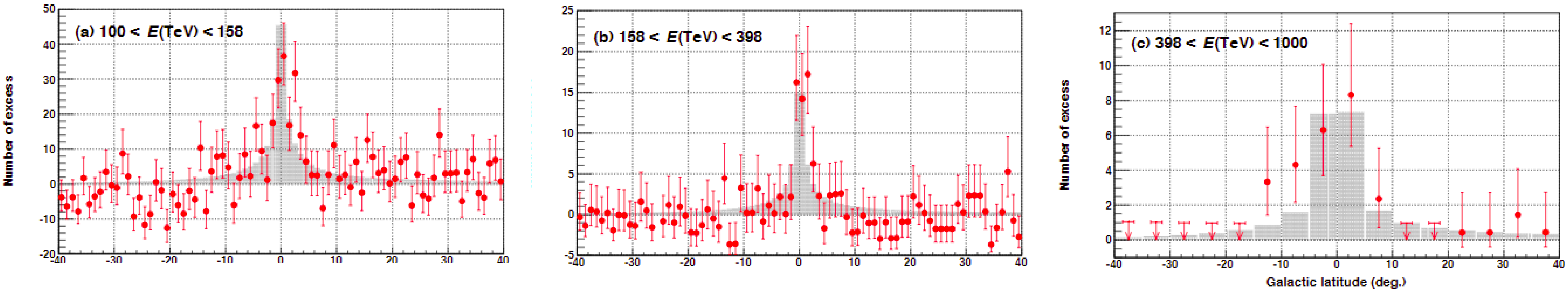
Fermi-LAT Collaboration 2016, ApJS

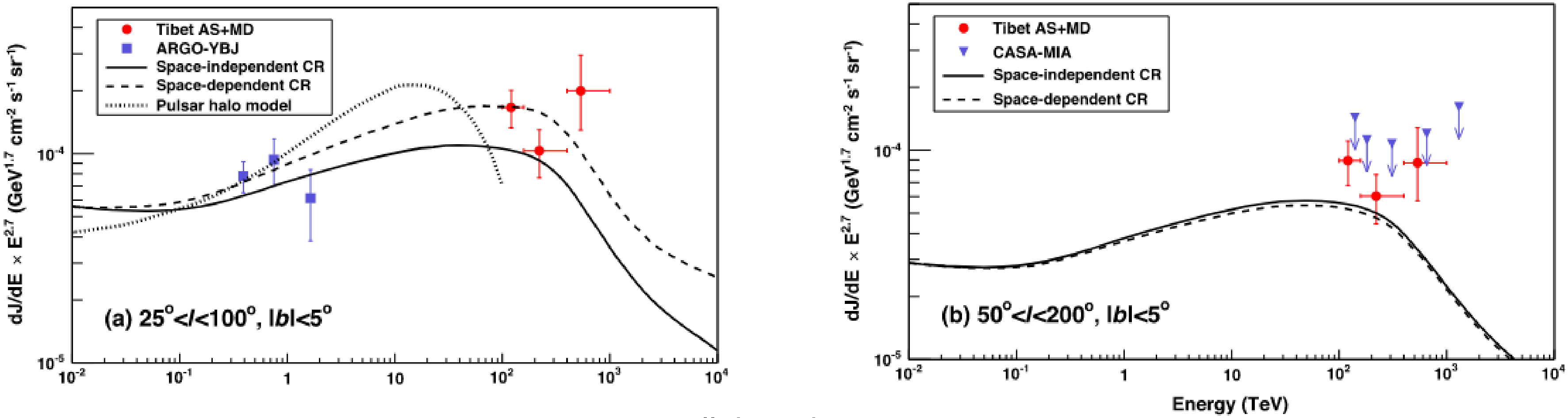


Fermi-LAT Collaboration 2016, ApJ

Interaction between CR protons and ISM

DGE at sub-PeV

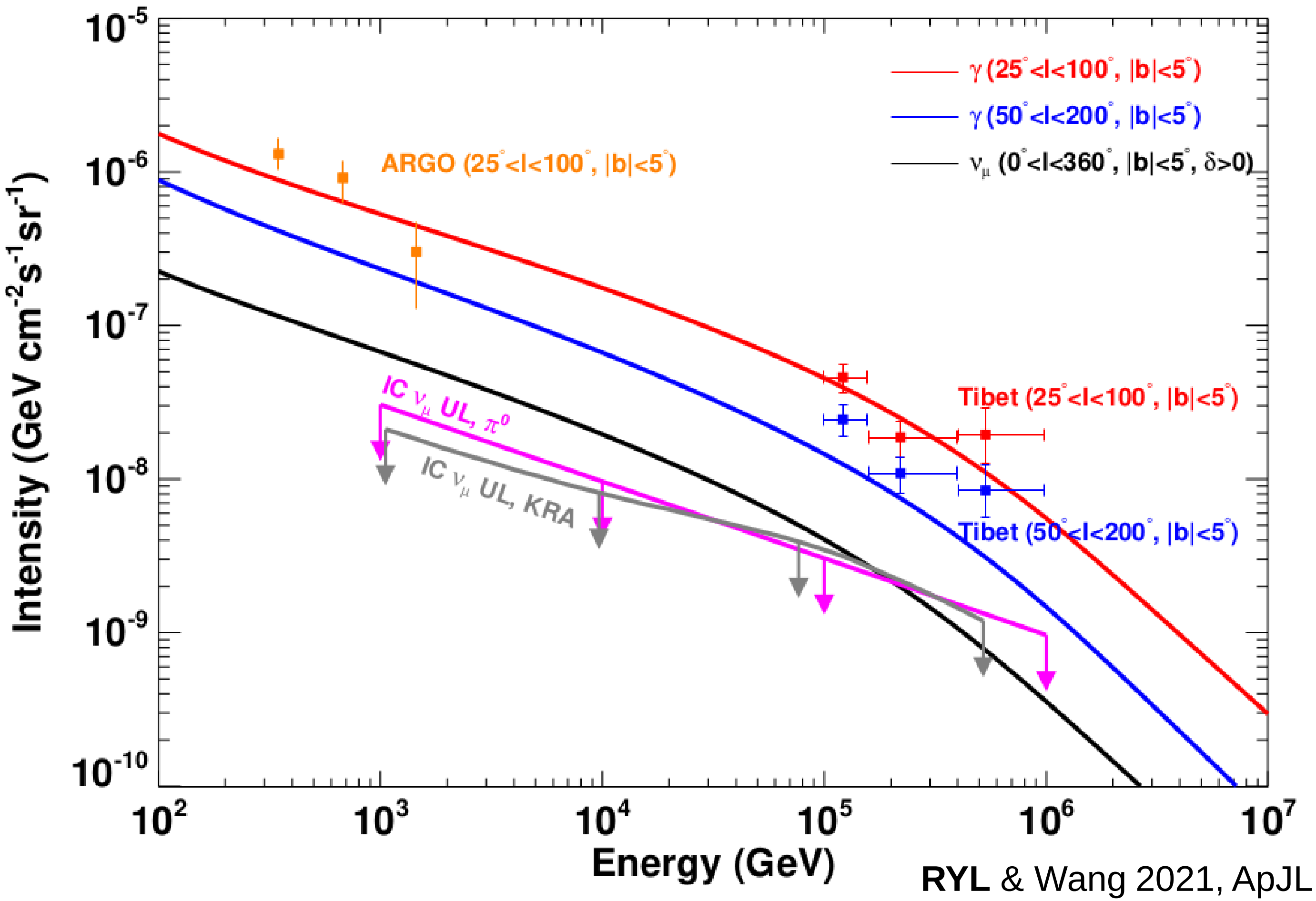




ASγ Collaboration 2021, PRL

Co-produced Neutrino would exceed the IceCube's upper limit

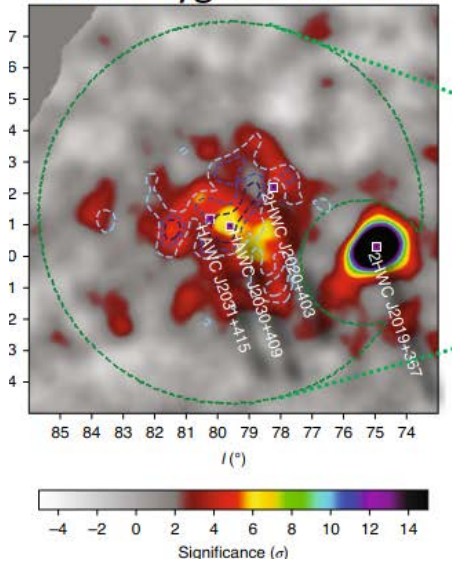
$\pi^0 \rightarrow \gamma \quad \pi^{\pm} \rightarrow \nu$



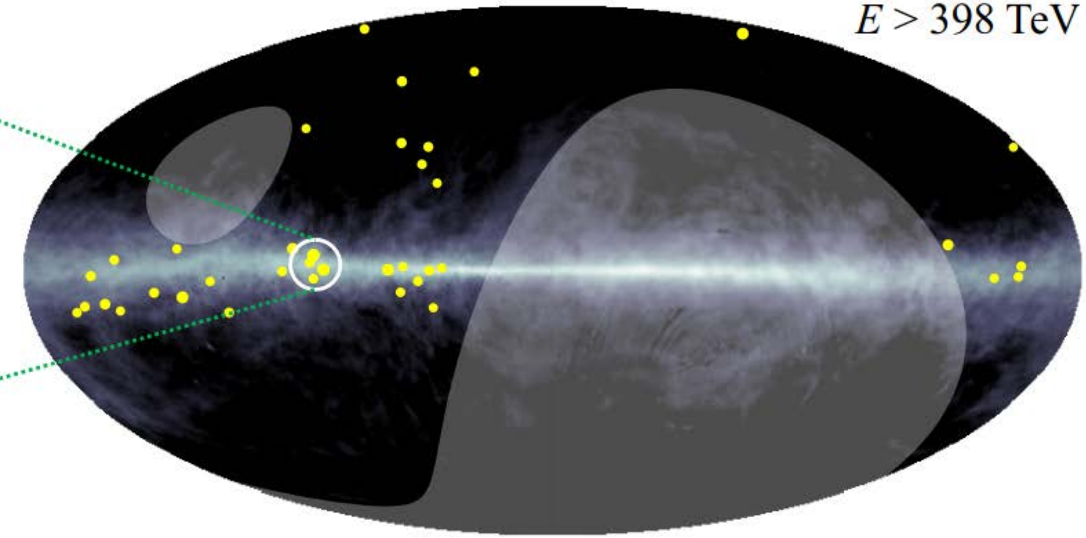
RYL & Wang 2021, ApJL

Abeysekara et al., Nature Astronomy (2021)

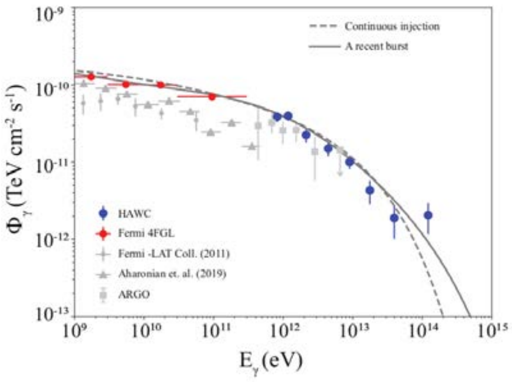
HAWC Cygnus Cocoon



Galactic Coordinates

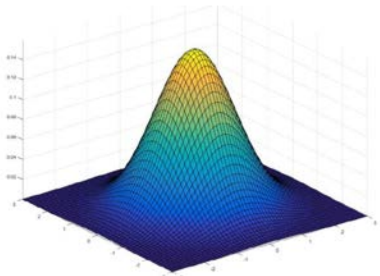


ASγ Collaboration ICRC2021



Gaussian Profile
σ=2.1 deg
0.5 deg ~ ¼ σ

¼ σ : only ~3% of total flux



The UHE diffuse gamma-ray emission detected by ASγ contains source contribution!

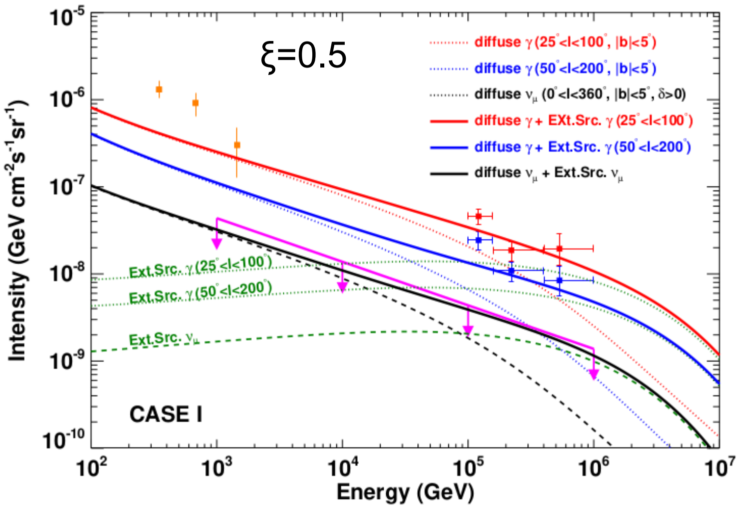
Insufficient mask

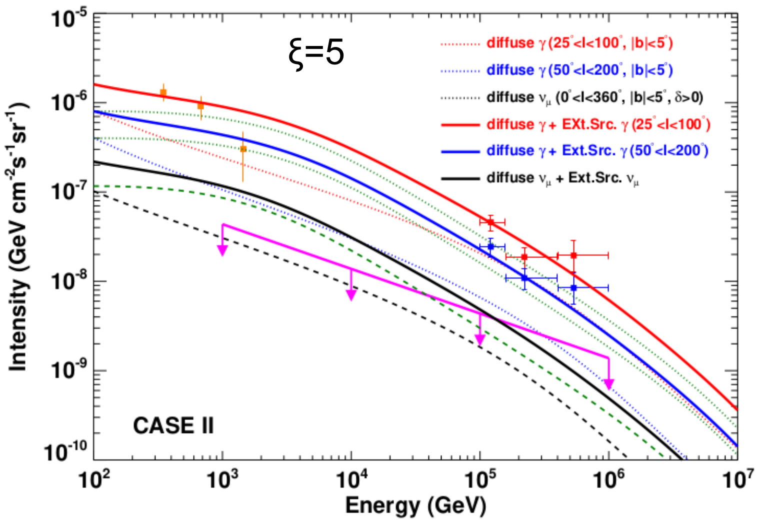
Diffusive + Source Contribution

RYL & Wang 2021, ApJL

$$I_{\rm Ext.Src,\gamma}(E_\gamma) = \Omega_\gamma^{-1}(1+\xi)F_{{\rm cyg},\gamma}(E_\gamma)$$

ξ: ratio of contribution between other sources to Cygnus Cocoon





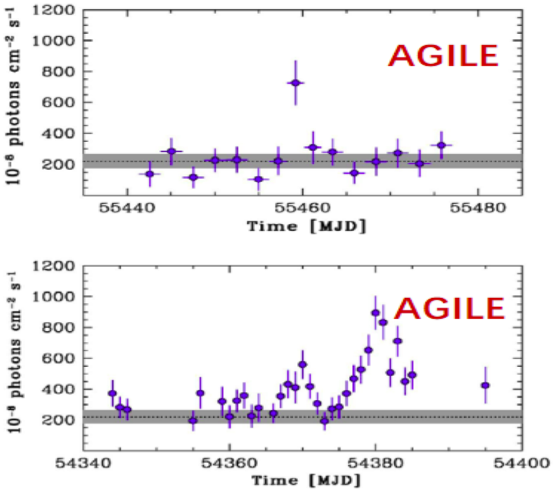
Source Catalog	Number of Sources	p-value	n_s	γ	Upper Limit $\phi_{90\%}$
Milagro Six	6	30%	31.8	3.95	3.98×10^{-20}
HAWC Hotspots	10	31%	17.3	2.38	9.48×10^{-21}
SNR with mol. clouds	10	25%	16.5	3.95	2.23×10^{-19}
SNR with PWN	9	34%	9.36	3.95	1.17×10^{-18}
SNR alone	4	42%	3.82	2.25	2.06×10^{-19}

Summary

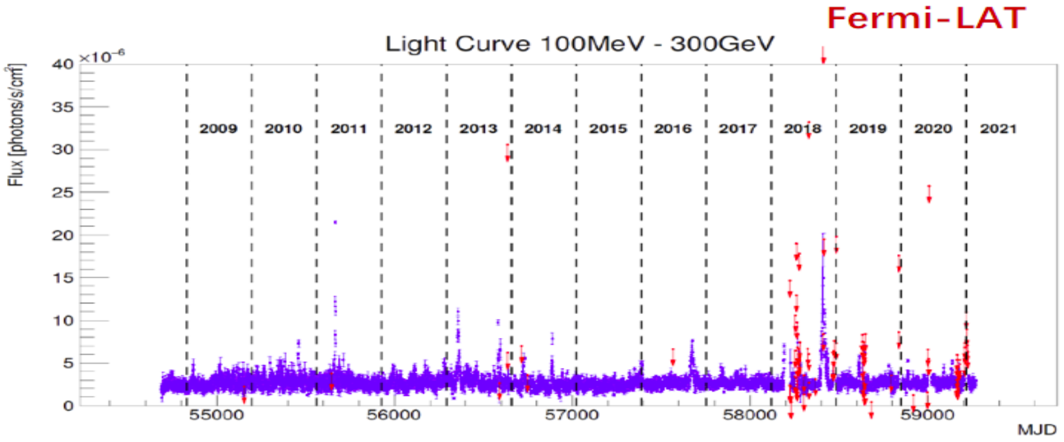
Thanks for your attention!

- Ultrahigh-energy gamma-ray sources are probes of extreme particle accelerators. Currently more than 10 have been detected.
- The spectrum of Crab Nebula extends up to 1.1PeV, consistent with a leptonic model, but also shows a possible indication of an additional spectral component above several hundred TeV.
  - The second spectral component could either be hadronic or leptonic origin. In the case of hadronic origin, the fraction of pulsar’s spindown energy converted to protons can reach as high as (10-50)%
- LHAASO J2226+6057, LHAASO J1908+0621, LHAASO J1825-1326 are brighter than Crab Nebula at 100TeV. They are extended sources in spatial coincidence with more than one candidates (PWNe and SNRs mostly). There are hints of (a fraction of) the emission being hadronic for all three sources.
- Diffuse Galactic sub-PeV Gamma-ray emission detected by Asgamma are probably partly contributed by extended sources and unresolved sources.

Crab flares



Tavani M. et al. **Science**, 2011, 331: 736-739

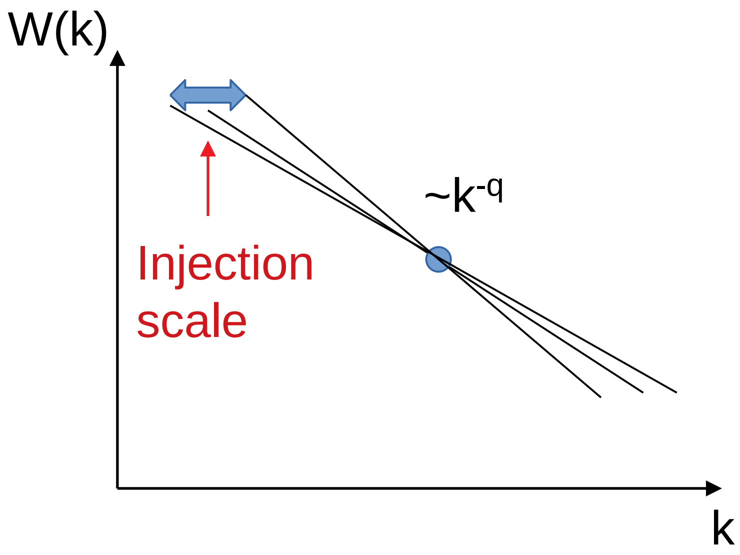


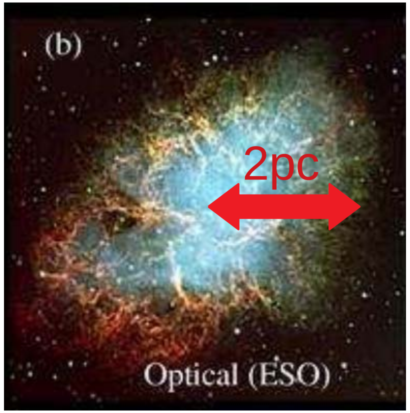
https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/source/Crab_Pulsar

fast acceleration and synchrotron cooling of PeV electrons in compact ($R \leq 0.01$ pc) highly magnetized ($B \geq 1$ mG) regions

Tang & Chevalier 2012, ApJ

Object	D (cm^2 s^{-1})	B (μG)	$\lambda = D/c$ (10^{16} cm)	Particle Energy (TeV)
Crab	2.4×10^{26}	300	0.8	0.6
3C 58	2.9×10^{27}	80	10	40
G21.5-0.9	2.0×10^{27}	180	7	30

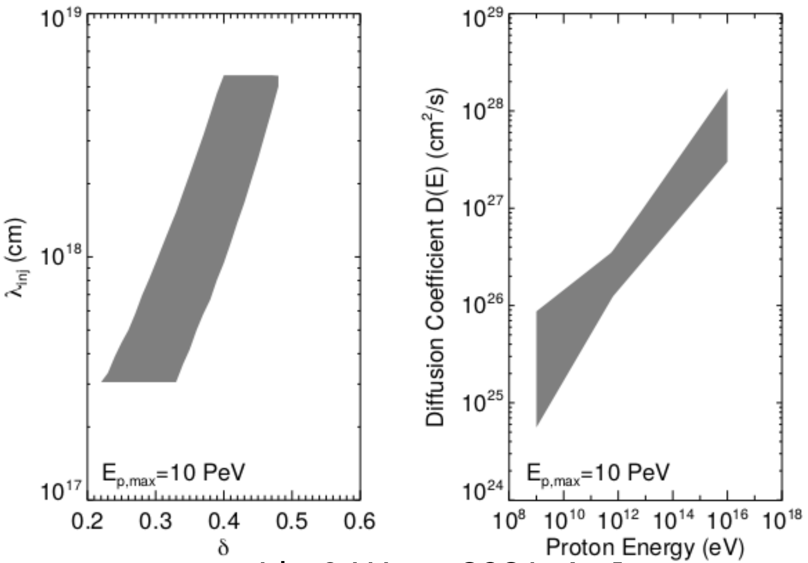




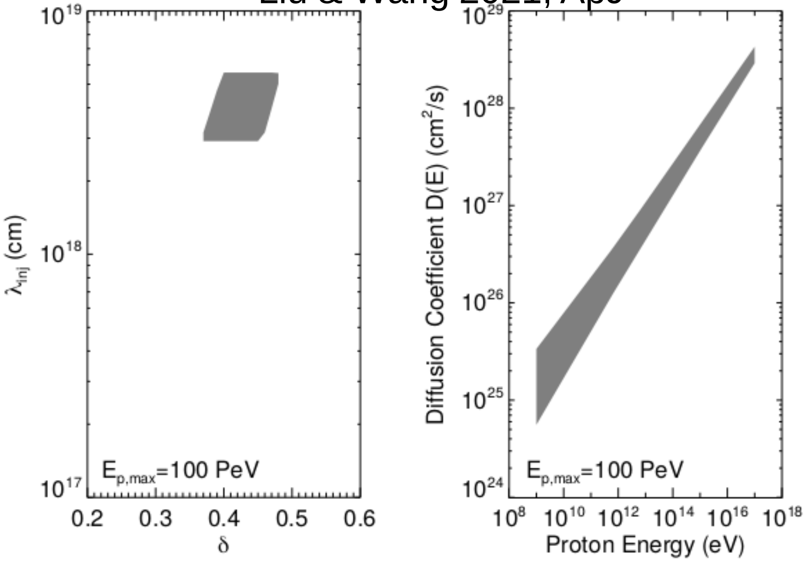
$L > \lambda_{inj} > r_{g,max}$

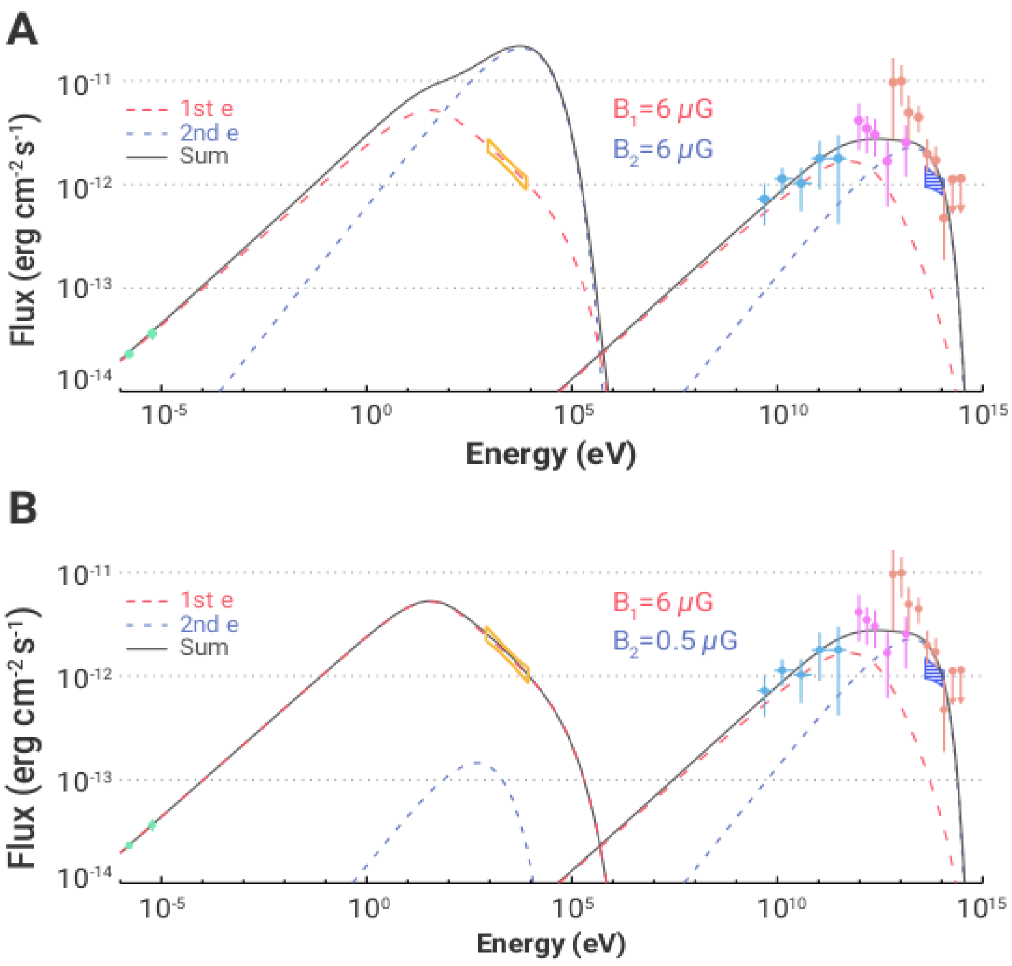
Wave-particle interaction $k \sim 1/\lambda \sim 1/r_g$

$D(E) \sim E^{2-q}$

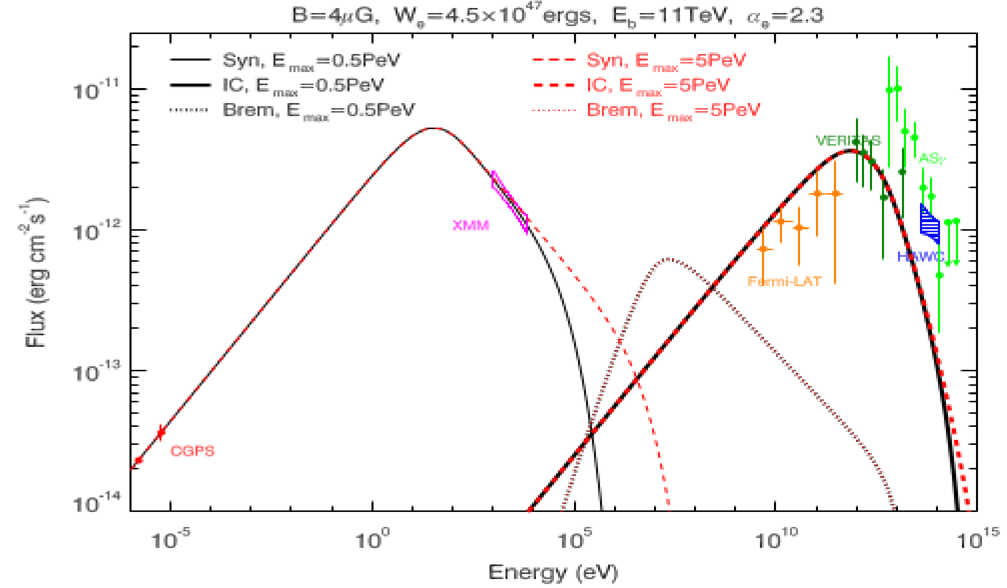


Liu & Wang 2021, ApJ

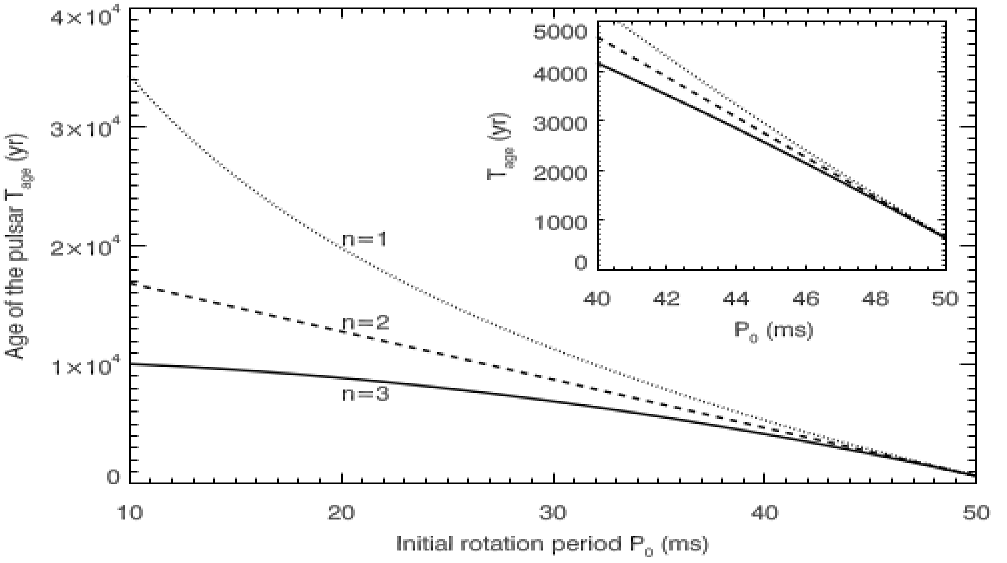




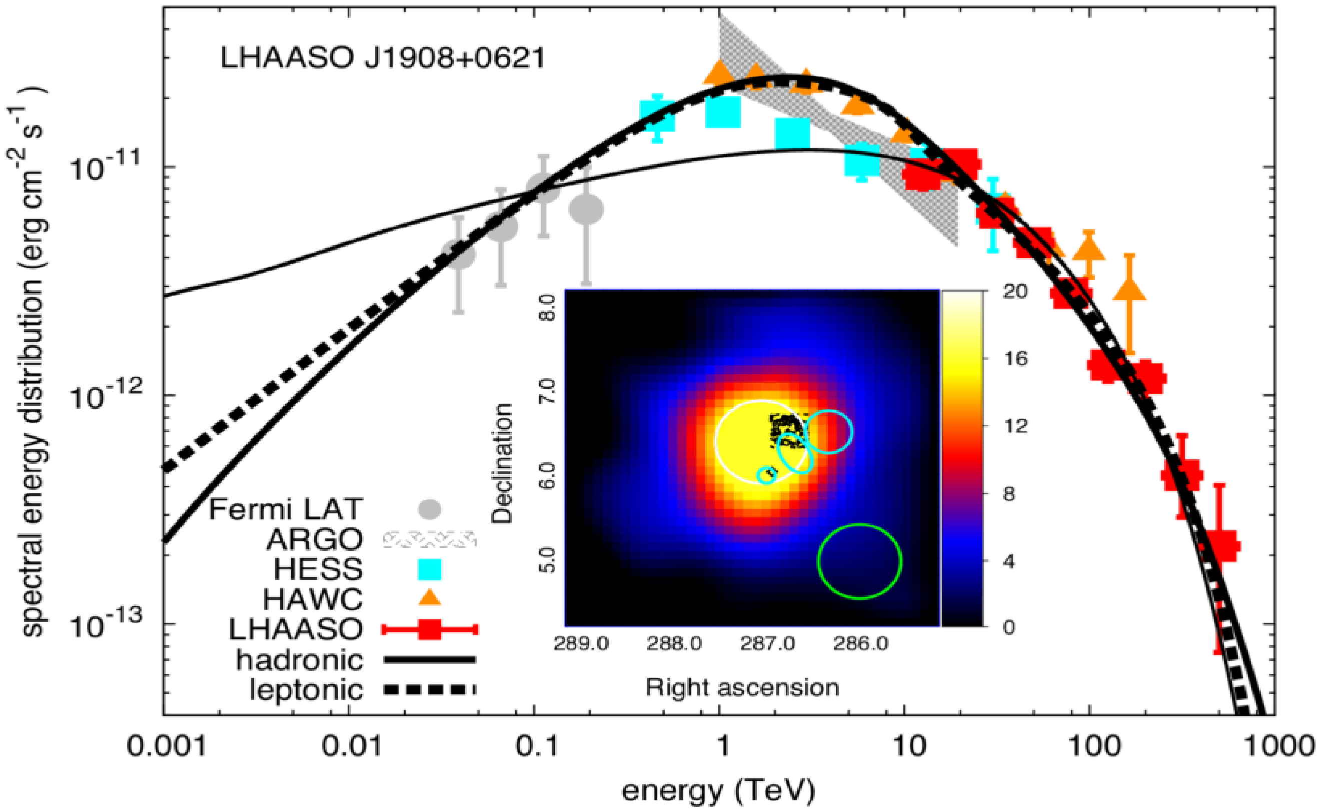
A
B
1st e
2nd e
Sum
B_1=6 μG
B_2=6 μG
B_2=0.5 μG
Flux (erg cm^{-2}s^{-1})
Energy (eV)



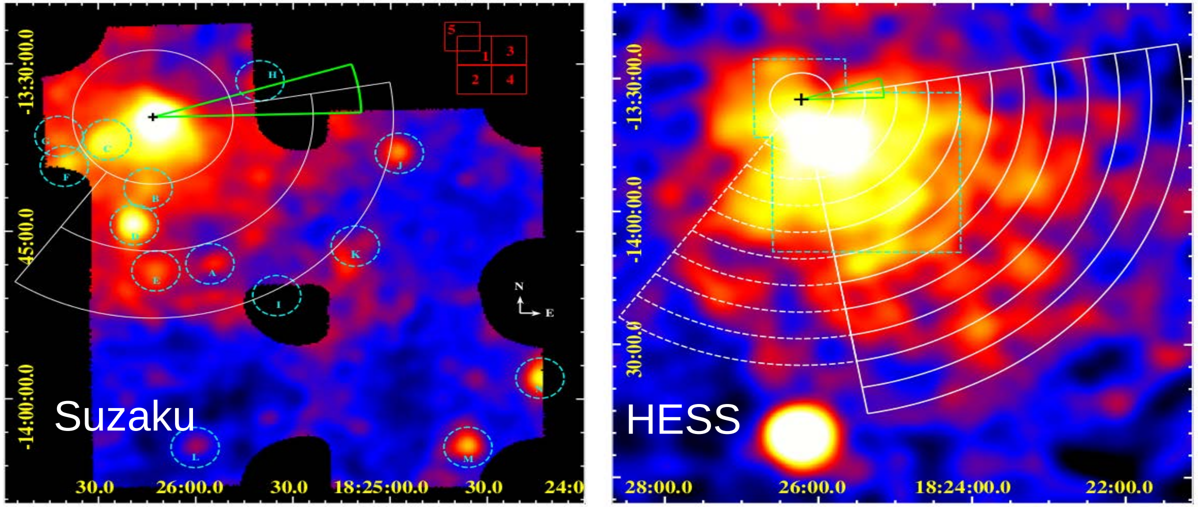
B=4μG, W_e=4.5×10^{47}ergs, E_b=11TeV, α_e=2.3
Syn, E_{max}=0.5PeV
IC, E_{max}=0.5PeV
Brem, E_{max}=0.5PeV
Syn, E_{max}=5PeV
IC, E_{max}=5PeV
Brem, E_{max}=5PeV
CGPS
XMM
Fermi-LAT
VERITAS
ASγ
HAWC
Flux (erg cm^{-2}s^{-1})
Energy (eV)



n=1
n=2
n=3
Age of the pulsar T_{age} (yr)
Initial rotation period P_0 (ms)
T_{age} (yr)
P_0 (ms)



LHAASO Collaboration 2021

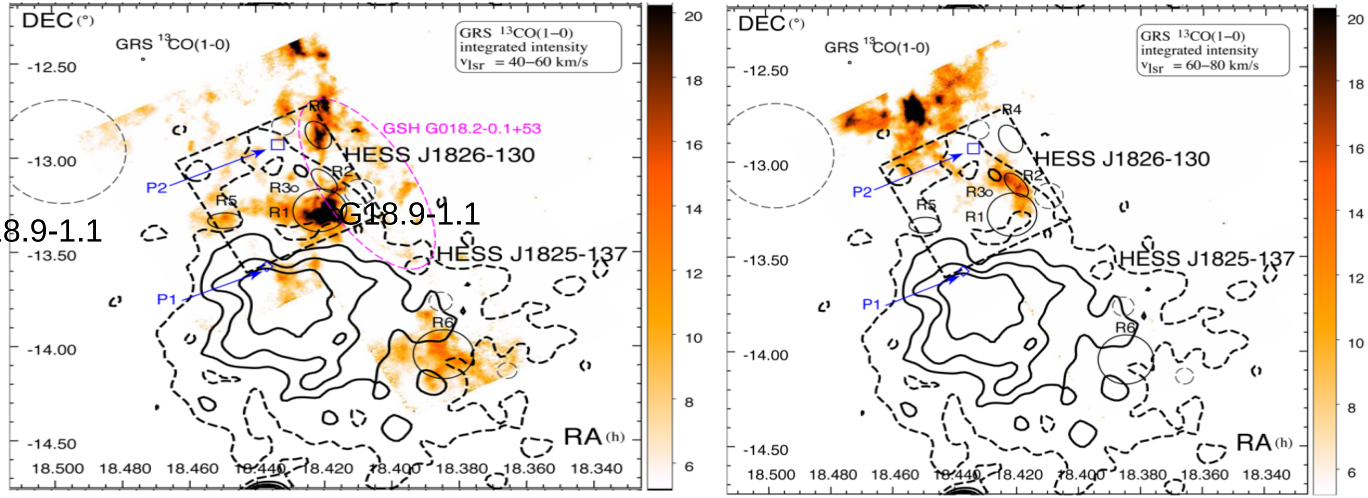


Van Etten & Romani 2011

HESS Collaboration 2006,2019

X-ray:
Compact nebula
+diffuse nebula

G18.9-1.1



Voisin et al. 2016