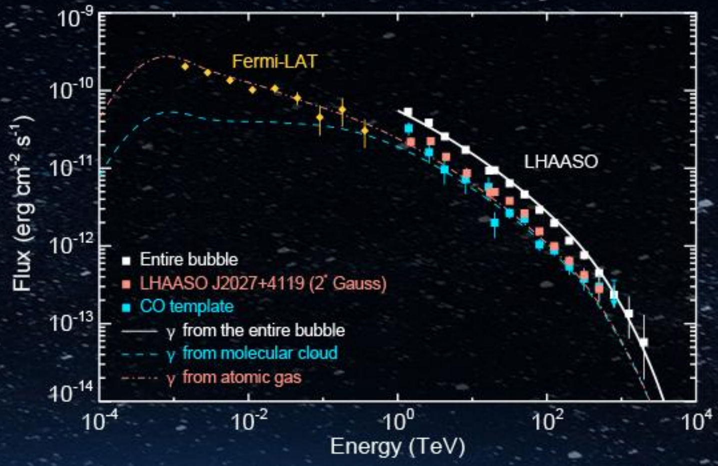
The extreme Universe viewed in very-high-energy gamma rays 2023

Modelling the Ultrahigh-energy Emission of Cygnus Bubble



Ruo-Yu Liu (for LHAASO Collaboration)
School of Astronomy and Space Science,
Nanjing University

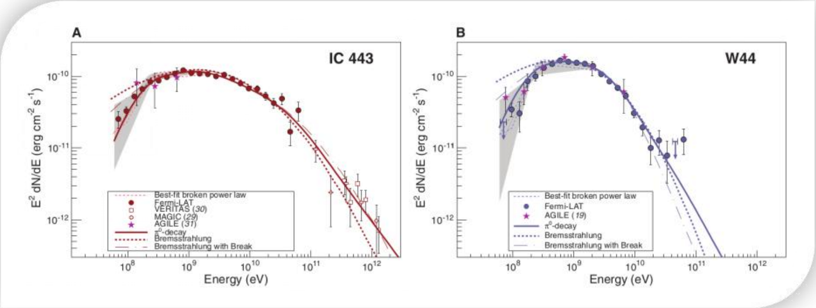
20.02.2024, CTA-Japan Workshop 2023, Tokyo, Japan (Online)

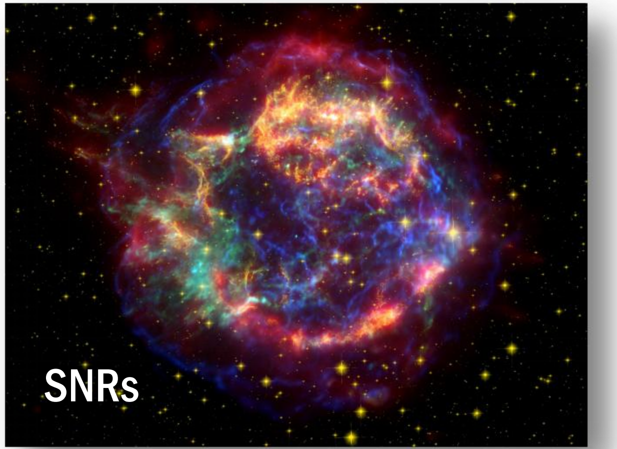
Outline

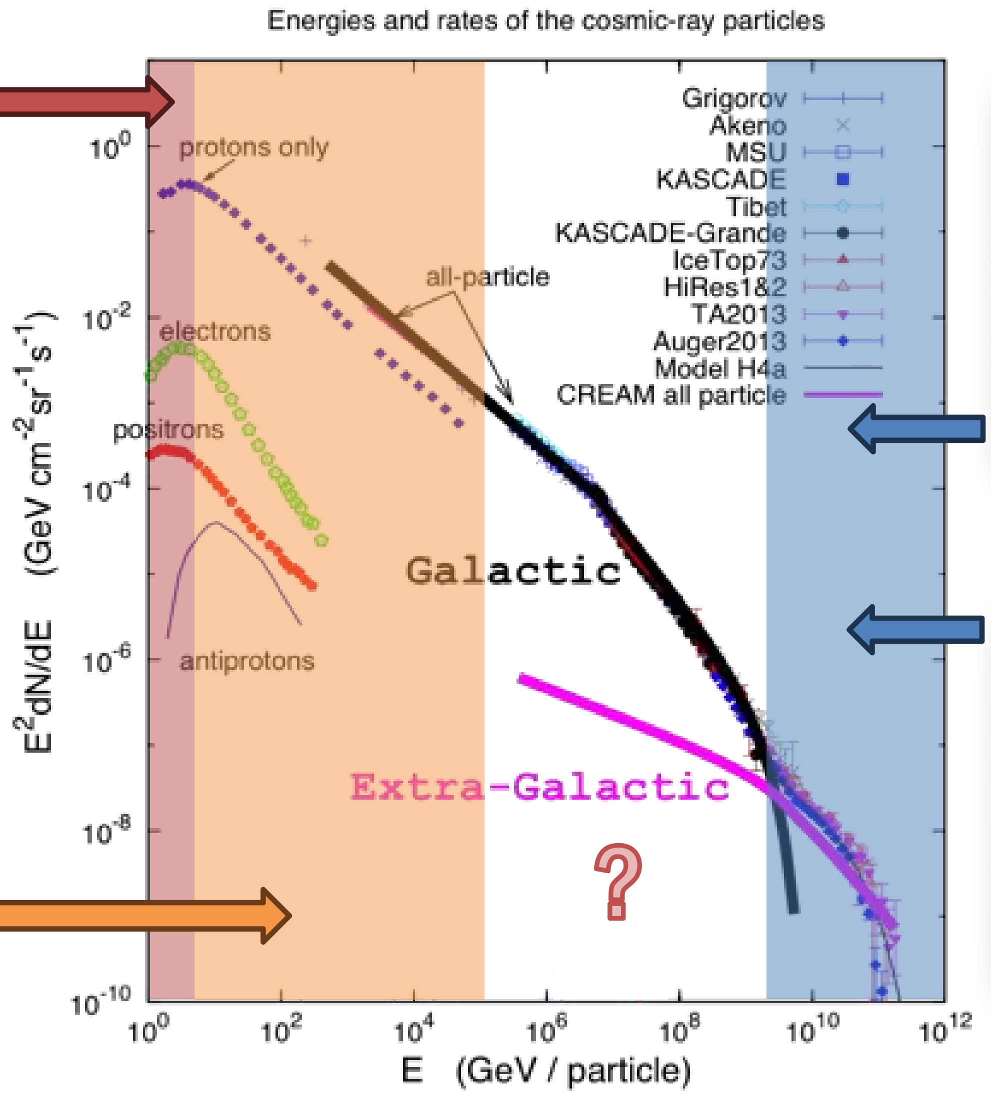
- A Brief Review of Previous Studies (observational & theoretical)
- Observation of Cygnus Bubble by LHAASO and Modelling
- Discussion & Summary

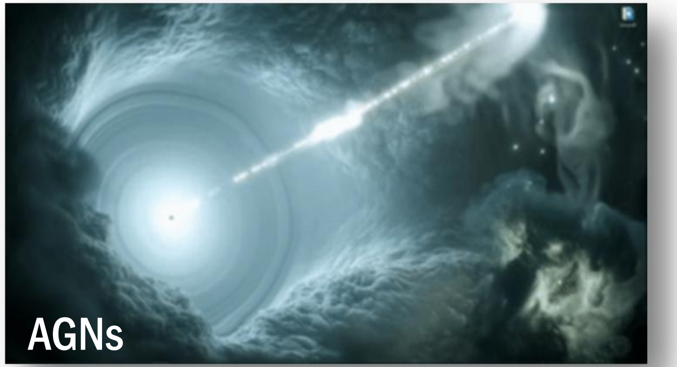
Introduction

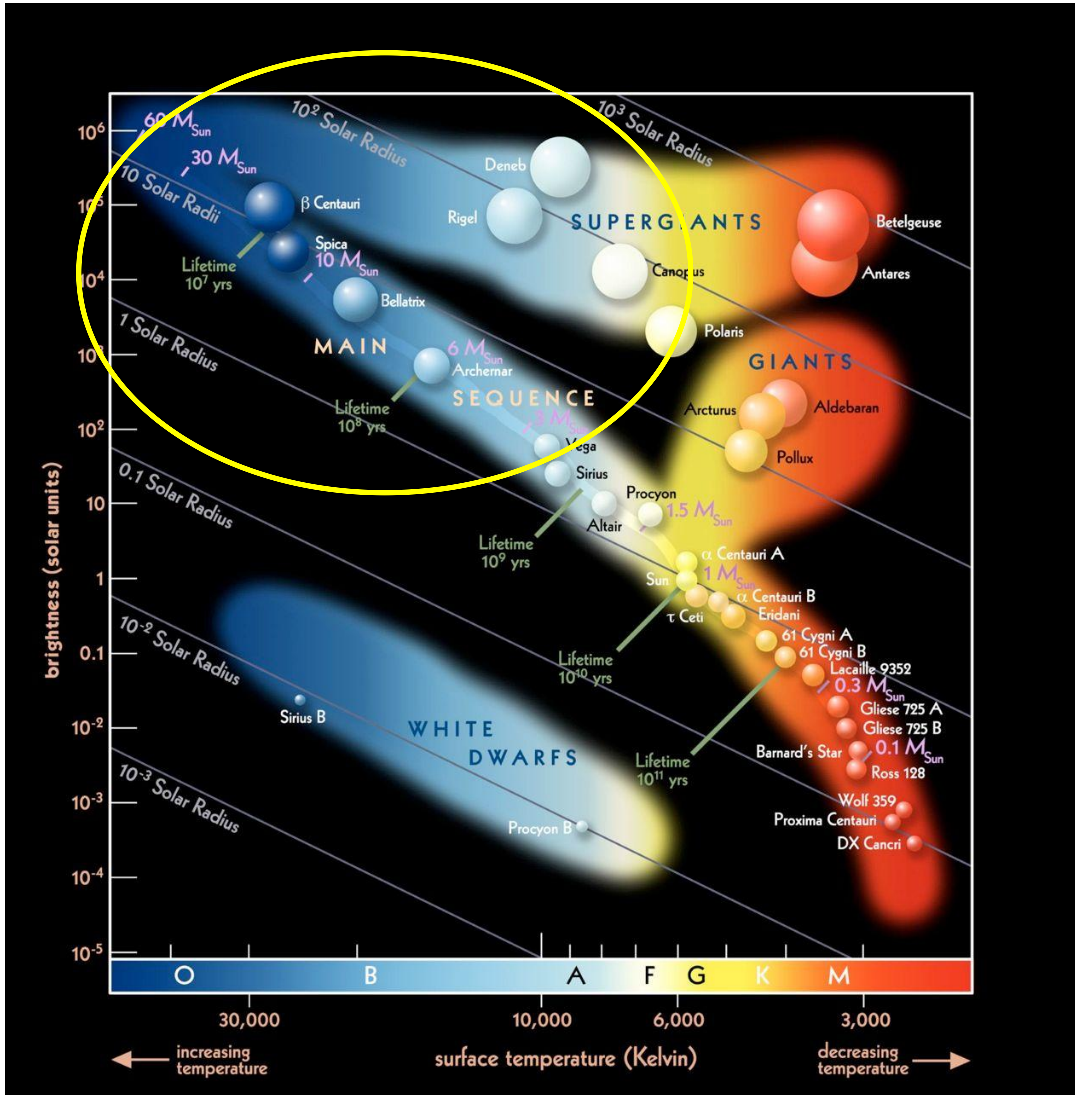
Origin of Cosmic Rays











Massive stellar winds as CR accelerators

Casse & Paul 1980

TABLE 1

DISTANCES BETWEEN THE SHOCK AND THE STAR FOR DIFFERENT KINDS OF STARS IN DIFFERENT ENVIRONMENTS

Distance between the shock and the star (pc)	18	5.2	5.7	1.6
Star:				
Mass loss rate ($M_\odot$ yr^{-1})	10^{-5}	10^{-5}	10^{-6}	10^{-6}
Wind velocity (km s^{-1})	2000	2000	2000	2000
Surrounding medium:				
Density n (particles cm^{-3})	1	10^3	1	10^3
Temperature[a] (K)	10^4	20	10^5	20
Magnetic field strength (μG)	3	30	3	30
Cosmic ray energy density (eV cm^{-3})	1	1	1	1
Pressure (10^{-12} dynes cm^{-2}):				
Due to gas: p_G	2.8	2.8	2.8	2.8
Due to magnetic field: p_B	0.36	36	0.36	36
Due to cosmic rays: p_{CR}	0.15	0.15	0.15	0.15
Total due to ISM: p_i	3.3	39	3.3	39

Provided the acceleration is not intermittent, and in the optimum case, the highest energies that cosmic rays of charge Z can attain at stellar wind terminal shock are:

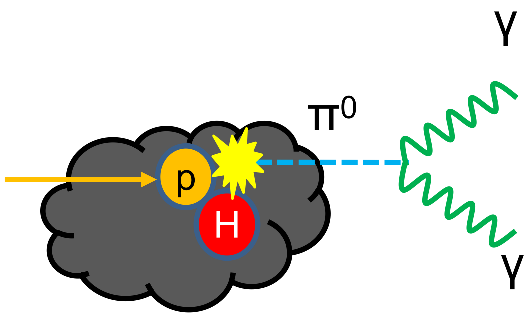
$$E_{\max} = 4 \times 10^6\, Z(B/10^{-5}\ \mathrm{G})\,(w/2.5 \times 10^8\ \mathrm{cm\ s^{-1}})^2\ \mathrm{GeV}$$

whereas for supernova shocks, under similar conditions:

$$E_{\max} < 10^5\, Z(B/10^{-6}\ \mathrm{G})\ \mathrm{GeV}\,,$$

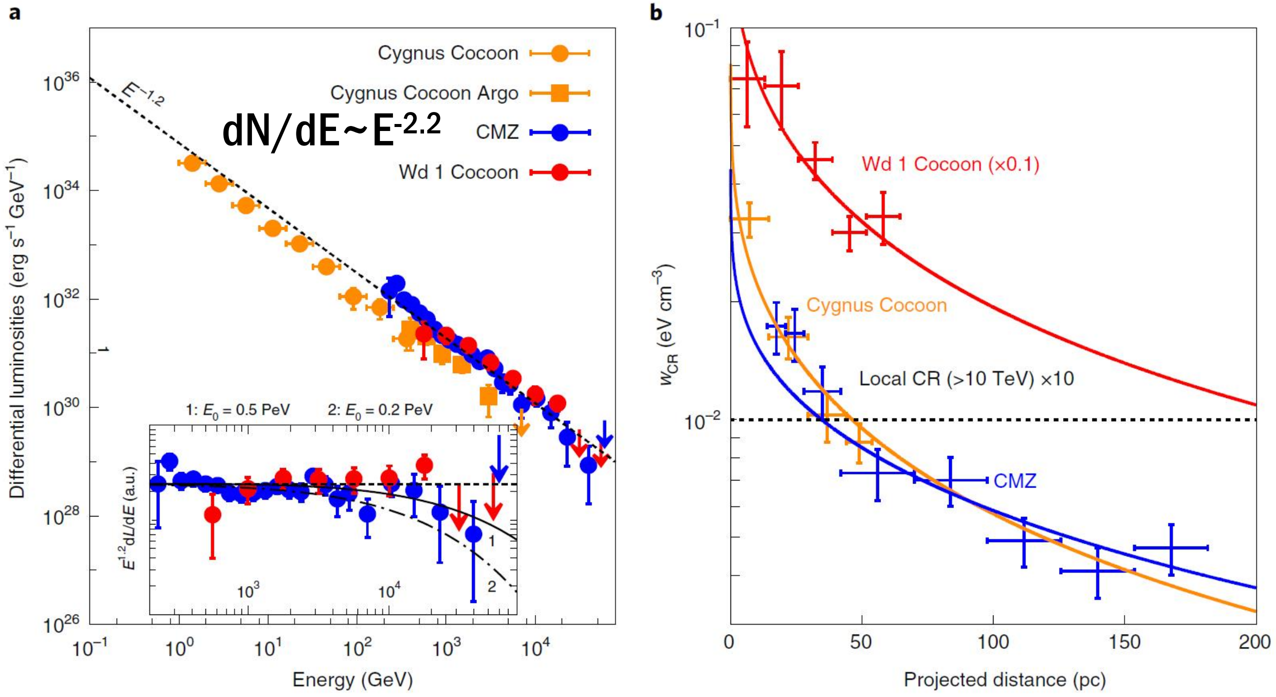
Cesarsky & Montemerle 1983

Gamma-ray as Probes of Hadronic CR Accelerators

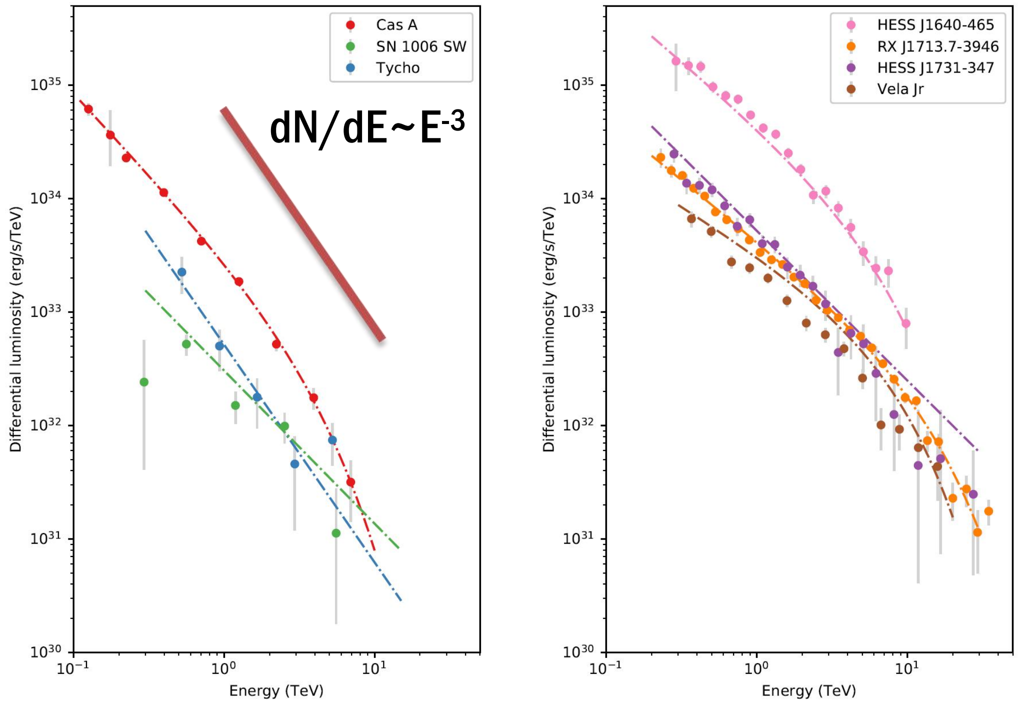


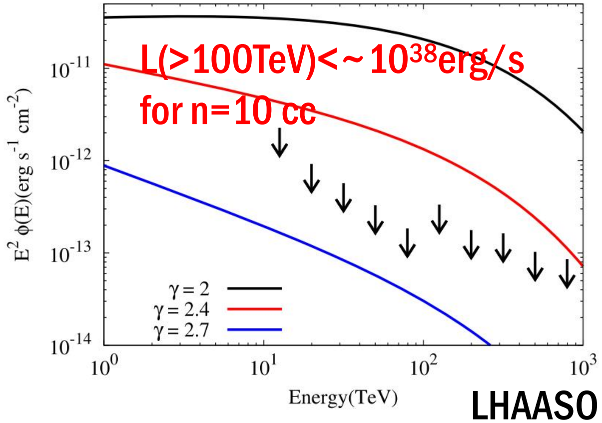
CR Spatial distribution

$u_{cr} \sim L/r$ Diffusion



Aharonian et al. 2019





Cas A: ~340yr

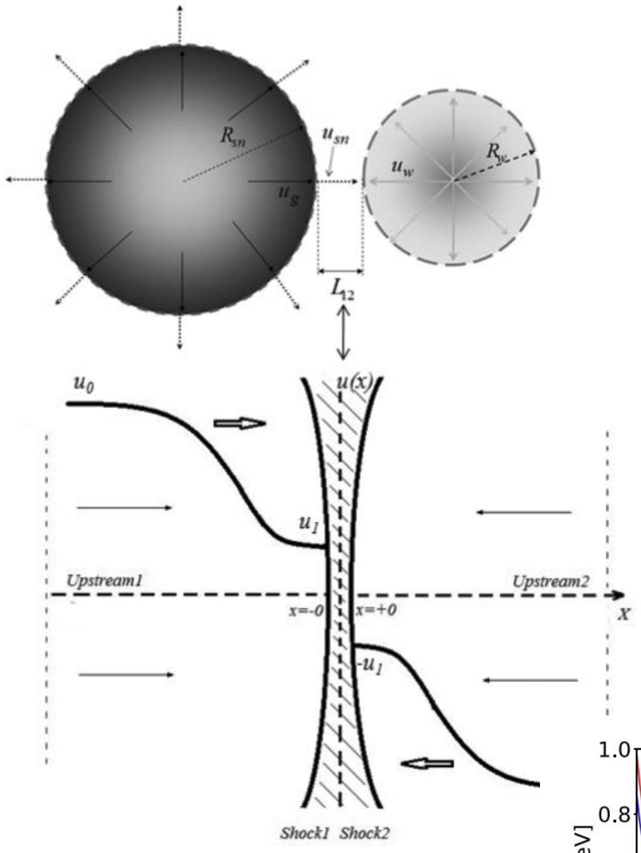
c*340yr ~ 110pc=1.8deg

Non-detection of signal within 1.8 deg of Cas A put a strong upper limit on the PeV CR energy budget

LHAASO Collaboration 2024

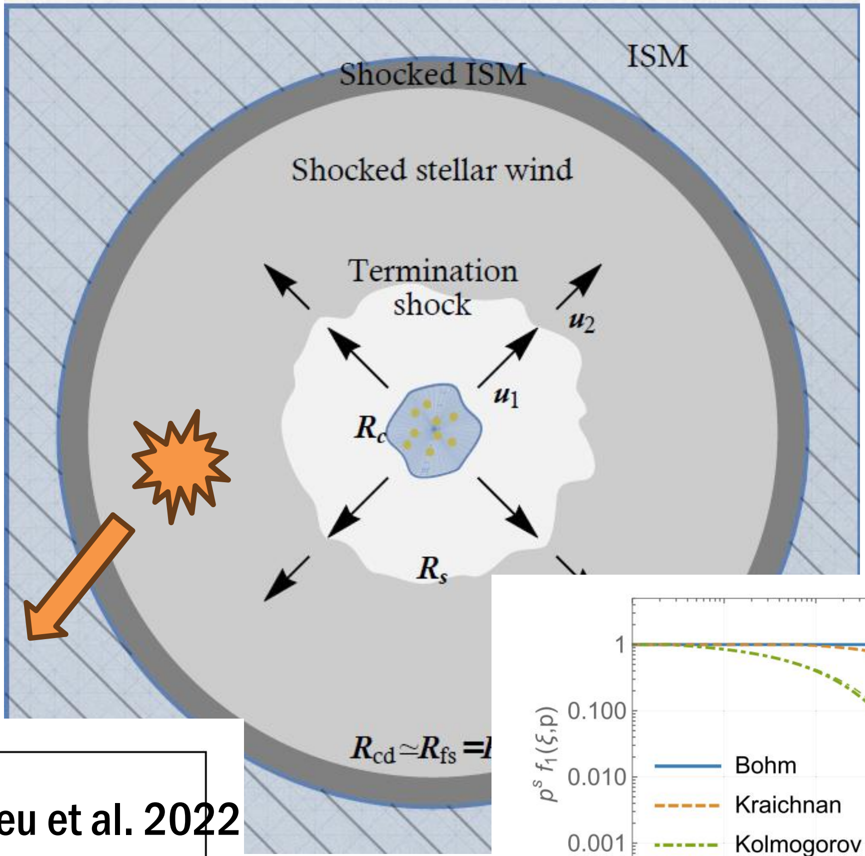
Particle acceleration in star clusters

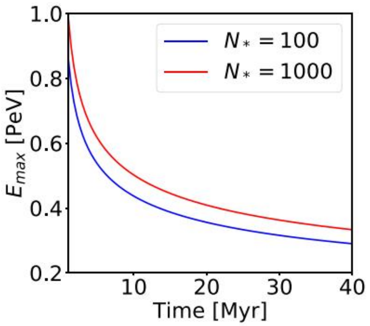
Colliding shocks

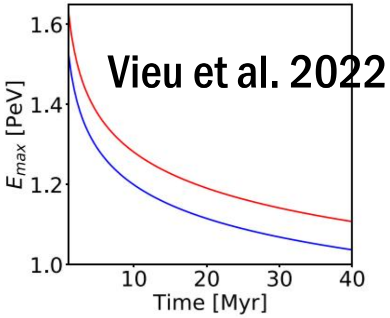


Bykov et al. 2013

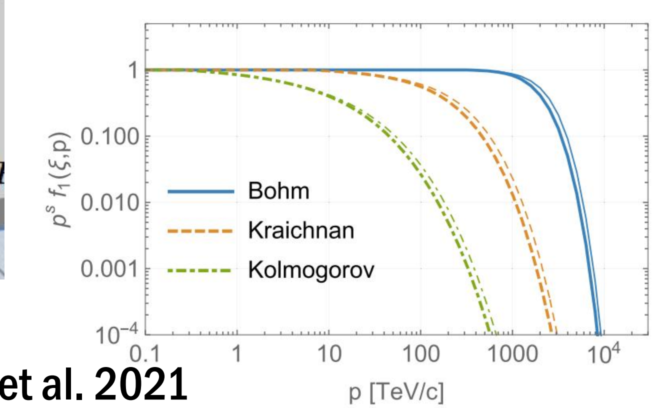
Collective wind termination shocks







Vieu et al. 2022



Morlino et al. 2021

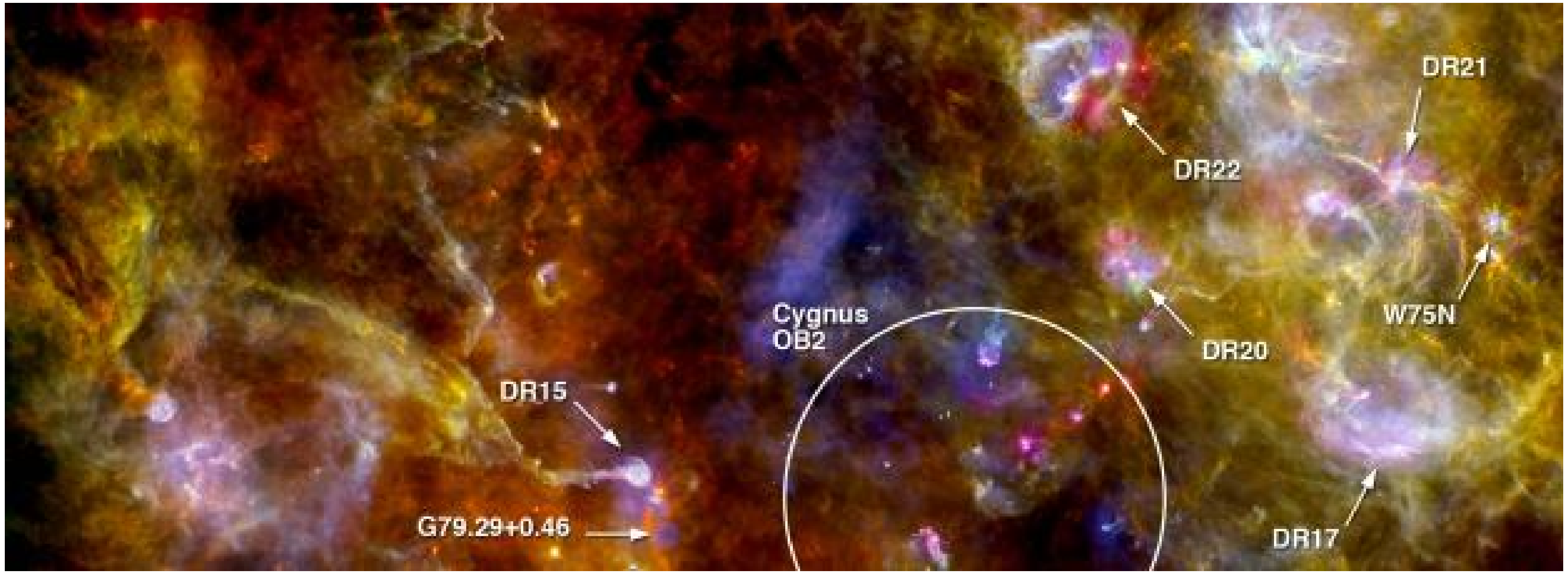
Previous Gamma-ray Observation of Cygnus Star-forming region

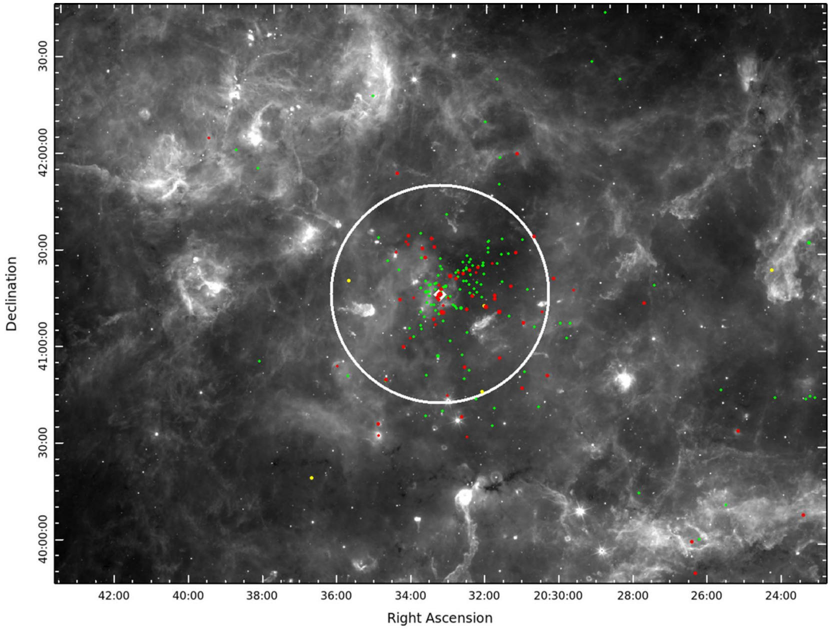
Cygnus X: an intense star-forming region close to Earth (1.4-1.7 kpc)

extension ~ 200 pc

hundreds of O stars, thousands of B stars

several x10^6 $M_\odot$ solar mass in gas

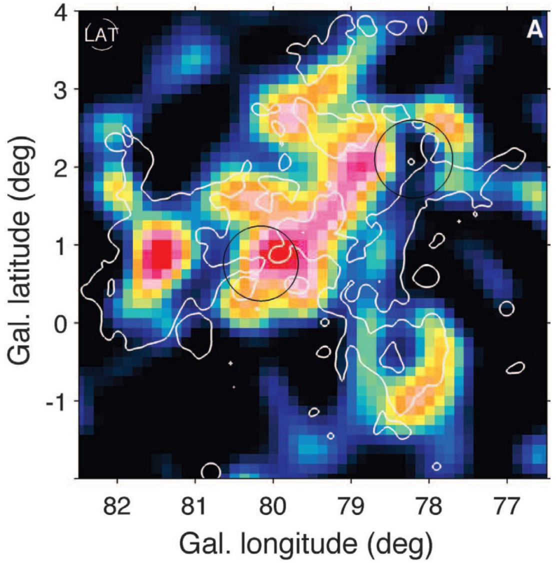


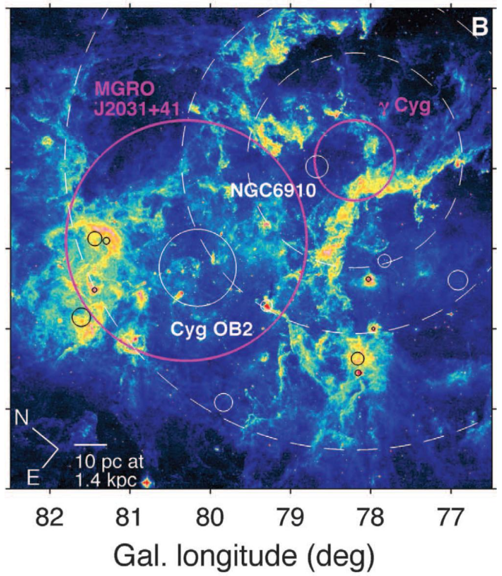


Credit： ESA/Herschel Space Observatory

Wright et al. 2015

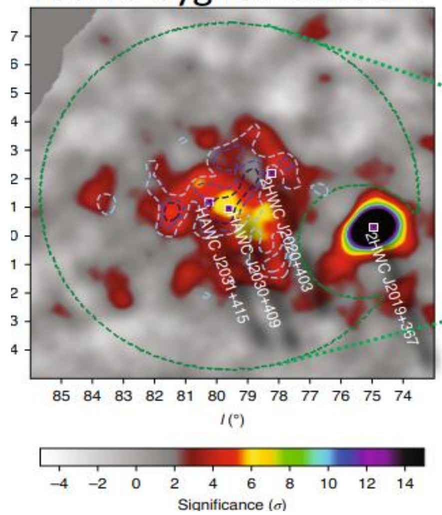
Fermi-LAT Collaboration 2011



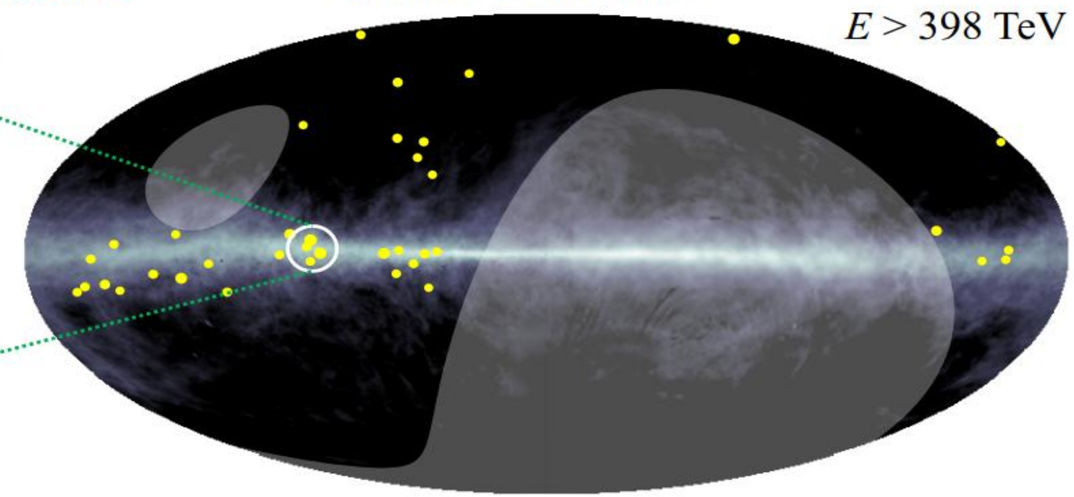


[Abeysekara et al., Nature Astronomy (2021)]

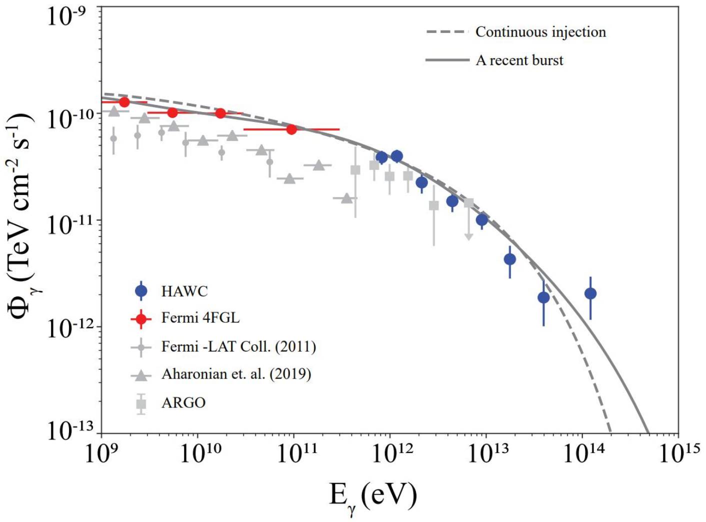
HAWC Cygnus Cocoon

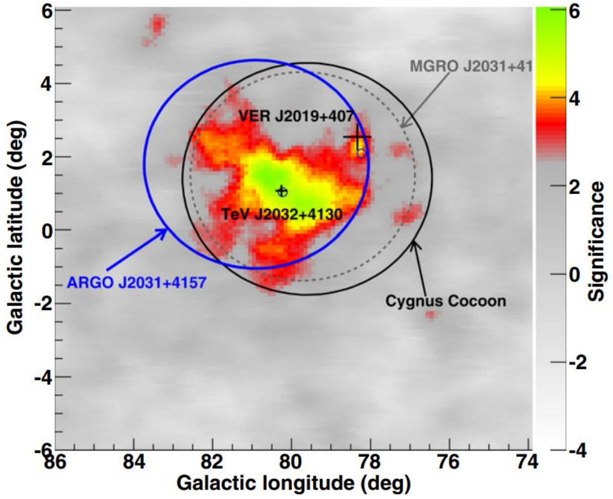


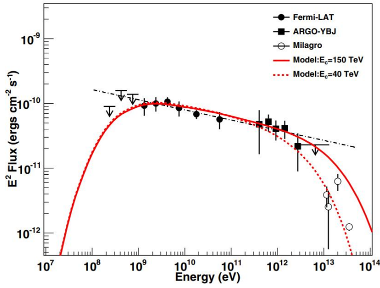
Galactic Coordinates



Asgamma Collaboration 2021







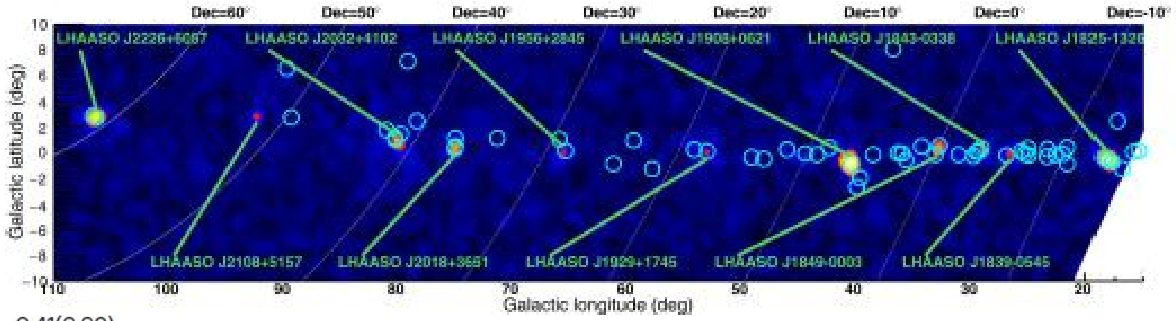
ARGO Collaboration 2014

LHAASO's Observation and Model

LHAASO’s Observation

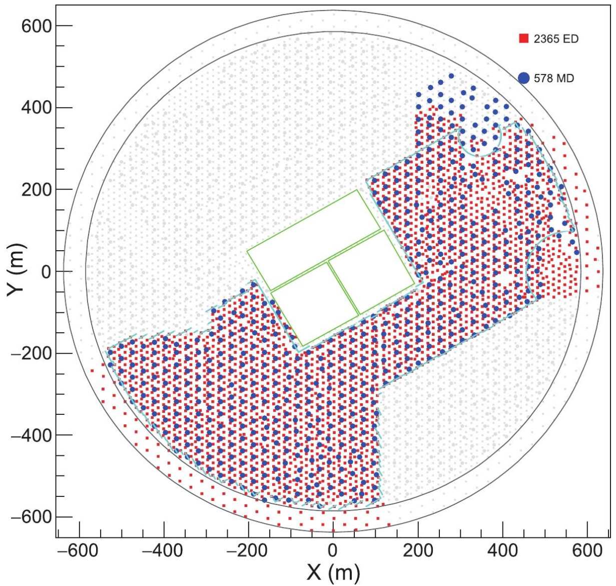
Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 -0.10^{+0.16}$	
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 -0.07^{+0.16}$	
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)

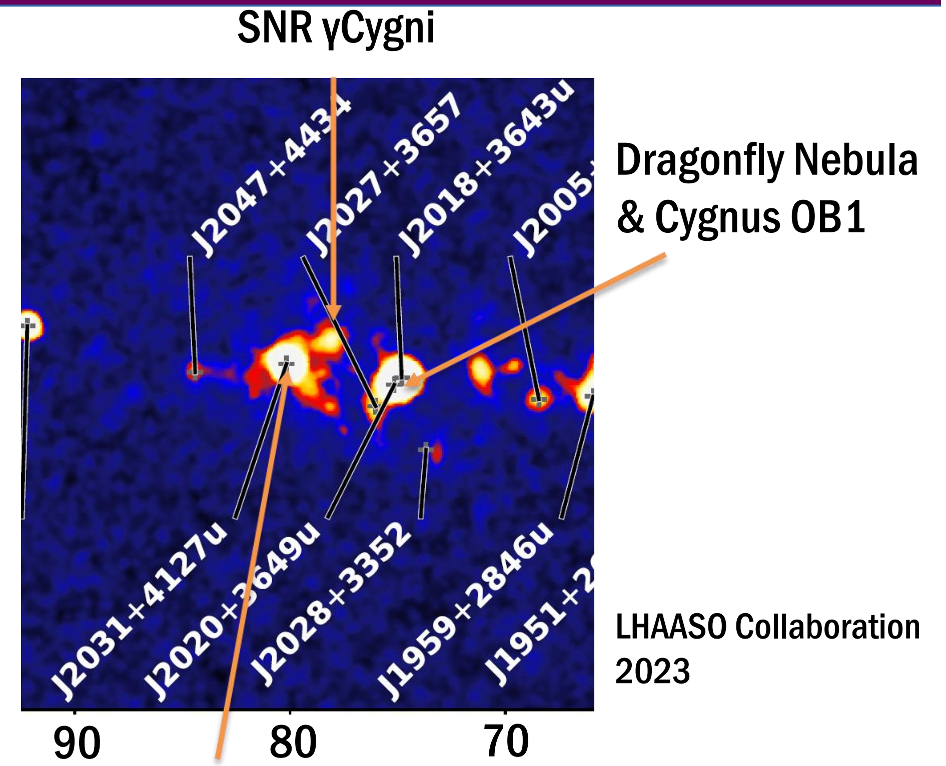
Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimated as the boundary values of the area that contains ±34.14% of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the error is 1σ.

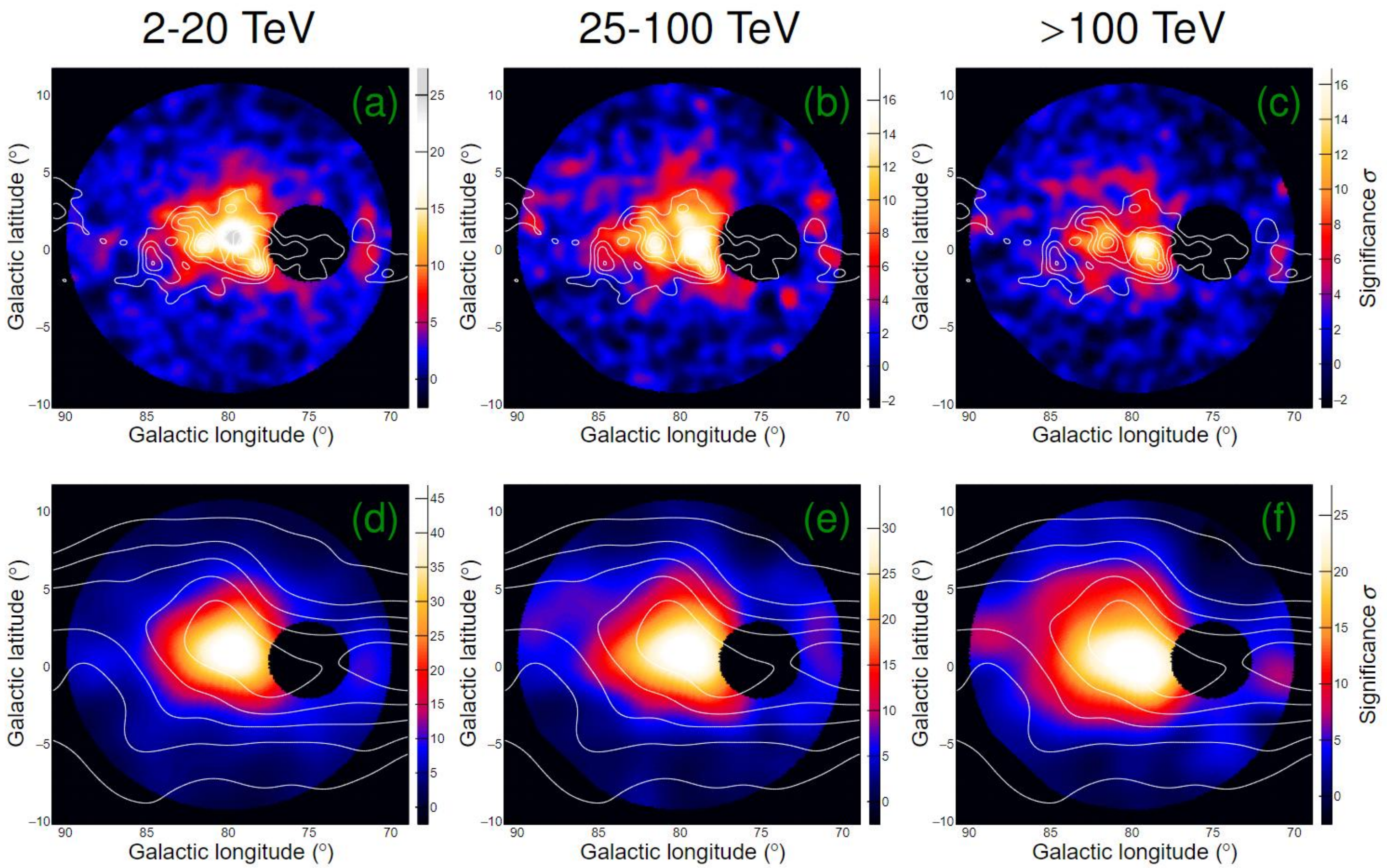


0.54 Crab flux @ 100TeV within 0.3deg of the best-fit position

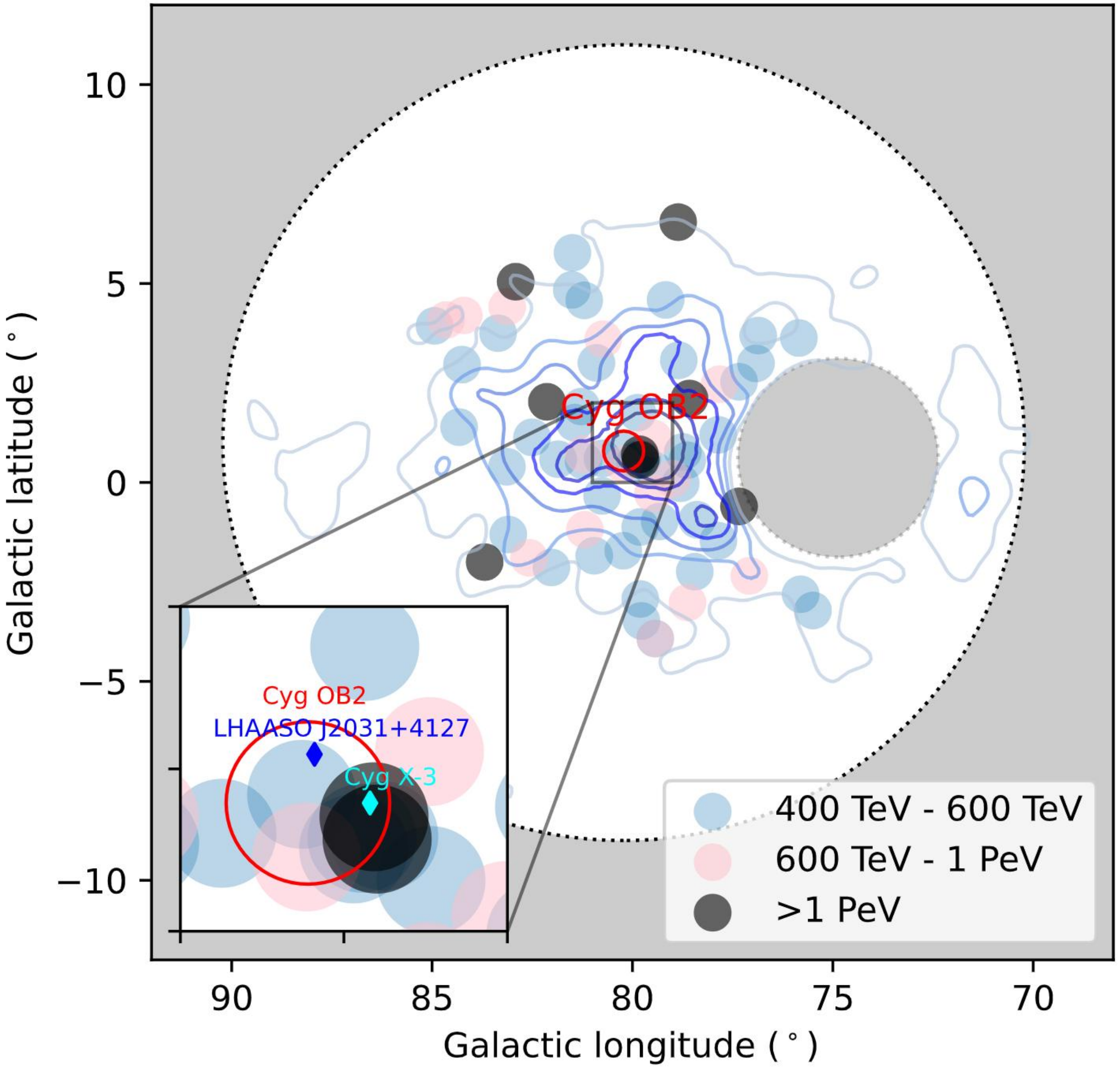
Half array over 11 months







Source	Components	$\alpha_{2000}(\circ)$	$\delta_{2000}(\circ)$	$r_{39}(\circ)$	TS	$N_0(TeV^{-1}m^{-2}s^{-1})$	Γ
LHAASO J2027+4119	KM2A	307.43 ± 0.16	41.05 ± 0.13	2.17 ± 0.10	145	$(0.62 \pm 0.05) \times 10^{-15}@50TeV$	-2.99 ± 0.07
	WCDA	306.90 ± 0.23	41.33 ± 0.16	2.28 ± 0.14	251.44	$(1.27 \pm 0.14) \times 10^{-9}@7TeV$	-2.63 ± 0.08
HI	KM2A				108	$(0.69 \pm 0.10) \times 10^{-15}@50TeV$	-2.94 ± 0.12
	WCDA				60.77	$(1.43 \pm 0.26) \times 10^{-9}@7TeV$	-2.66 ± 0.12
MC	KM2A				88	$(0.46 \pm 0.06) \times 10^{-15}@50TeV$	-2.87 ± 0.14
	WCDA				67.47	$(1.08 \pm 0.19) \times 10^{-9}@7TeV$	-2.73 ± 0.13
LHAASO J2031+4057	WCDA	307.89 ± 0.09	40.96 ± 0.16	0.33 ± 0.08	115.40	$(0.11 \pm 0.06) \times 10^{-9}@7TeV$	-2.75 ± 0.17



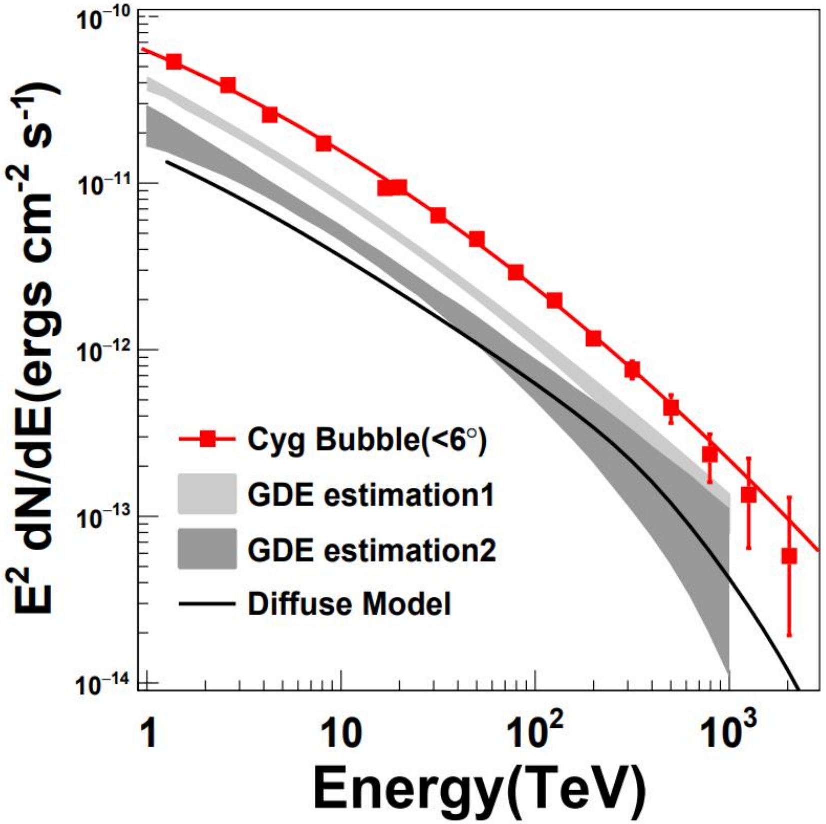
66 photon-like events within a radius of 6 degree with an estimated background of 9.5

7/66 from central 0.5 deg region v.s. $66*(0.5/6)^2 \approx 0.5$

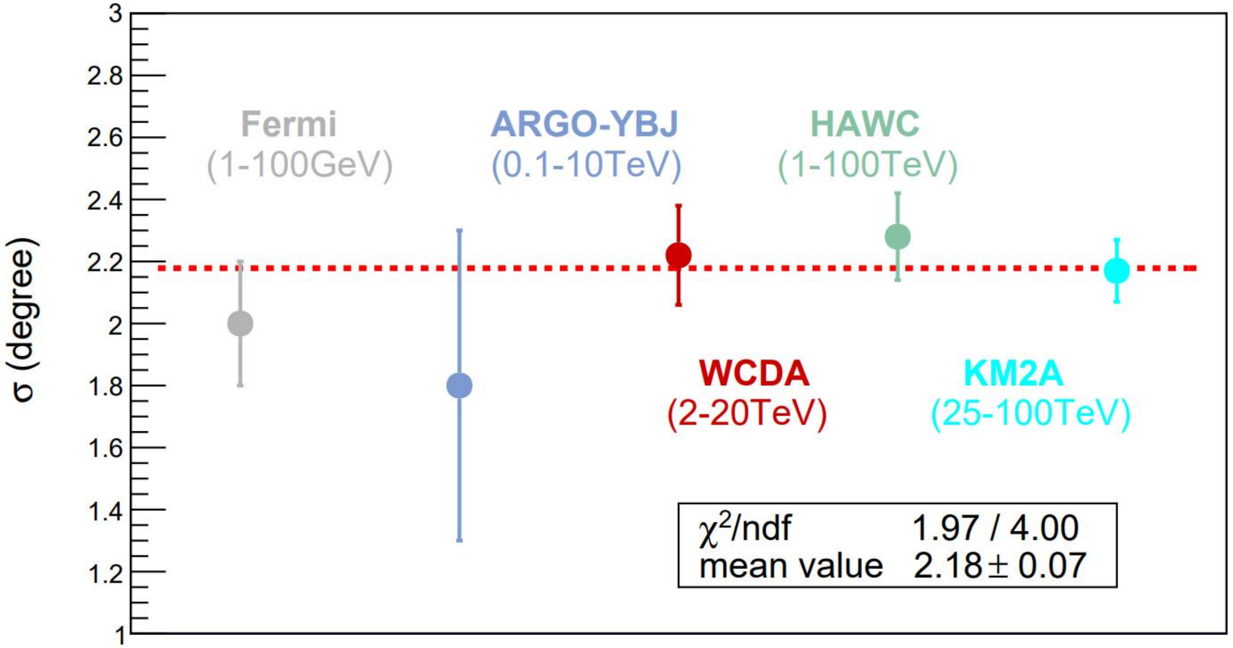
2/8 PeV event from central 0.5 deg region

Overdensity at the centre – injection!

E (PeV)	δE (PeV)	N_e	N_μ	$\theta(^\circ)$	$D_{edge}(m)$	$\psi(^\circ)$
1.08	0.16	5904	13.0	19.4	143	4.7
1.19	0.18	5480	14.1	34.4	73	0.2
1.20	0.18	6939	12.6	14.2	132	5.8
1.35	0.20	6938	8.4	27.1	43	2.9
1.38	0.20	6469	8.9	17.4	52	2.6
1.42	0.21	6258	6.6	12.7	57	0.1
1.78	0.27	6665	12.8	18.0	41	1.8
2.48	0.37	13815	29.1	33.0	99	5.2



Spectrum goes up to 2.5 PeV, without significant softening or cutoff feature



Energy-independent size

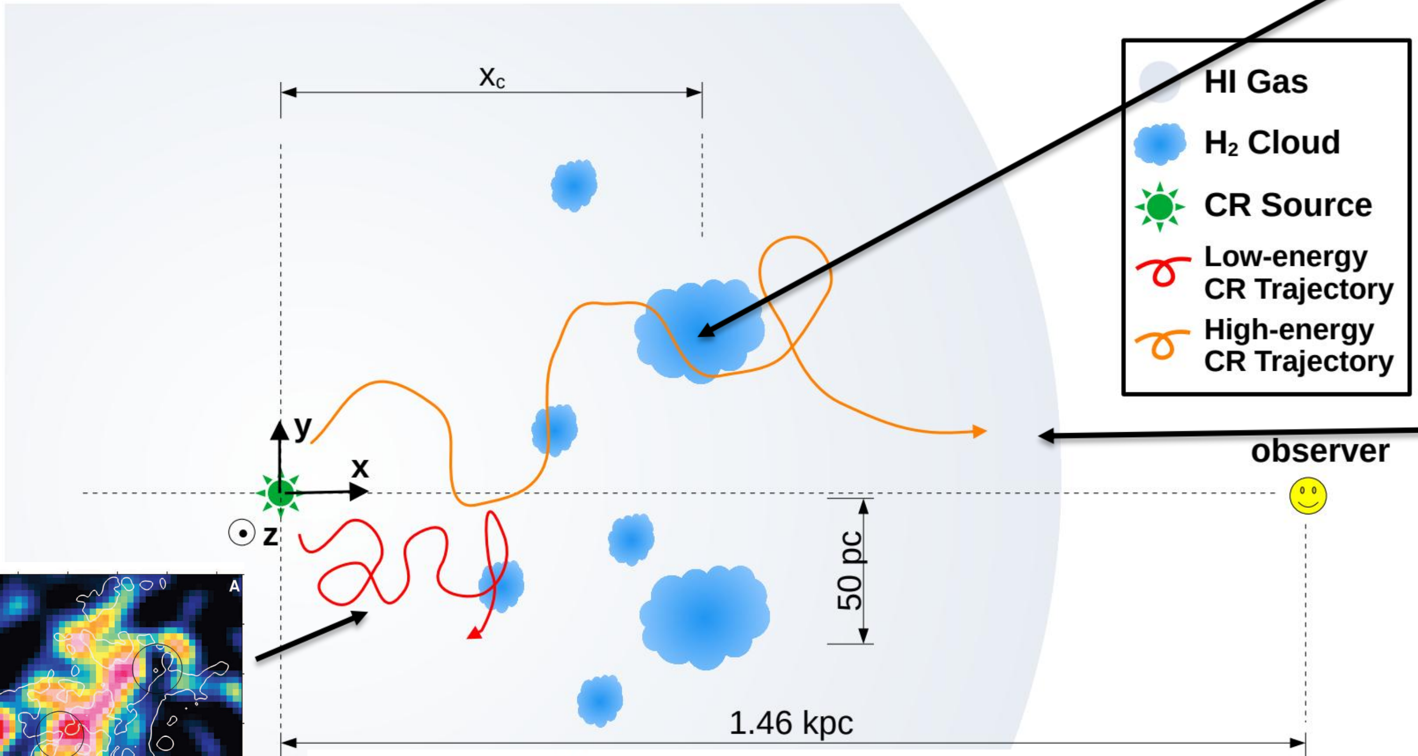
Leptonic scenario: $r \sim (Dt_c)^{1/2} \sim$ decrease with E increase

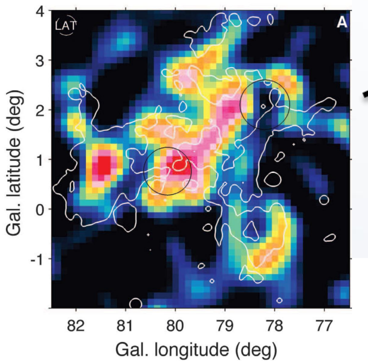
Favor hadronic origin

$$\Gamma(E) = (2.71 \pm 0.02) + (0.11 \pm 0.02) \times \log_{10}(\mathrm{E}/10\ \mathrm{TeV})$$

Physical Picture

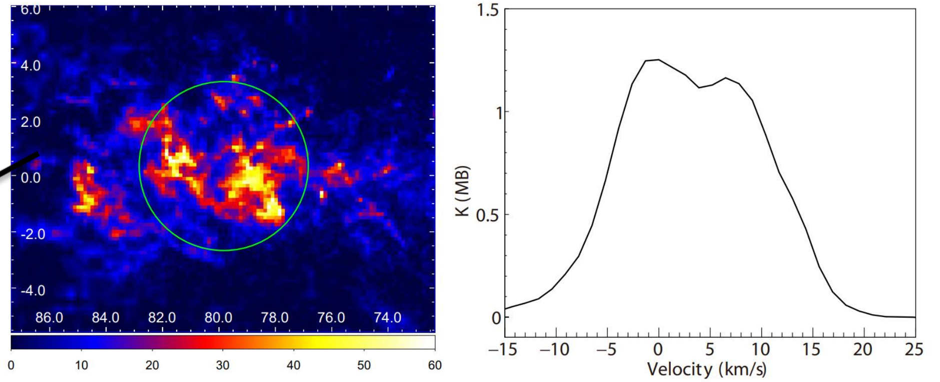
Spectra of different components
Radial surface brightness profile
Cygnus Cocoon measured by Fermi-LAT
Gas distribution

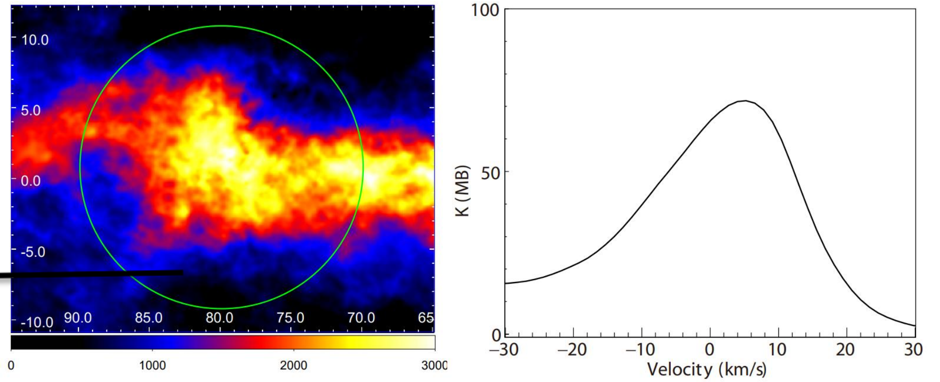


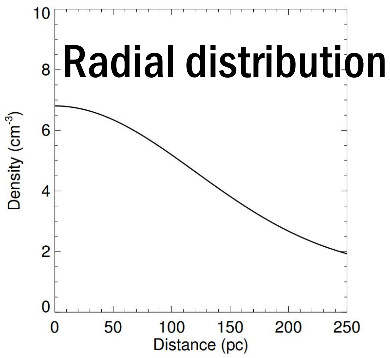


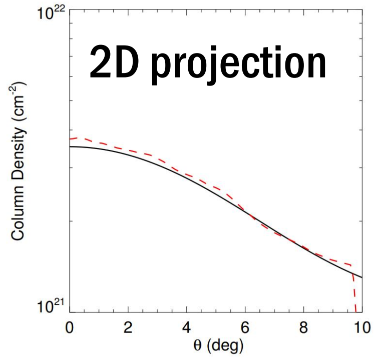
$$n_{\rm HI}(x,y,z) = \frac{M_{\rm HI}}{(2\pi)^{3/2}\sigma_{\rm HI}^3 m_{\rm H}} \exp\left\{-[x^2+y^2+z^2]/2\sigma_{\rm HI}^2\right\} + n_0$$

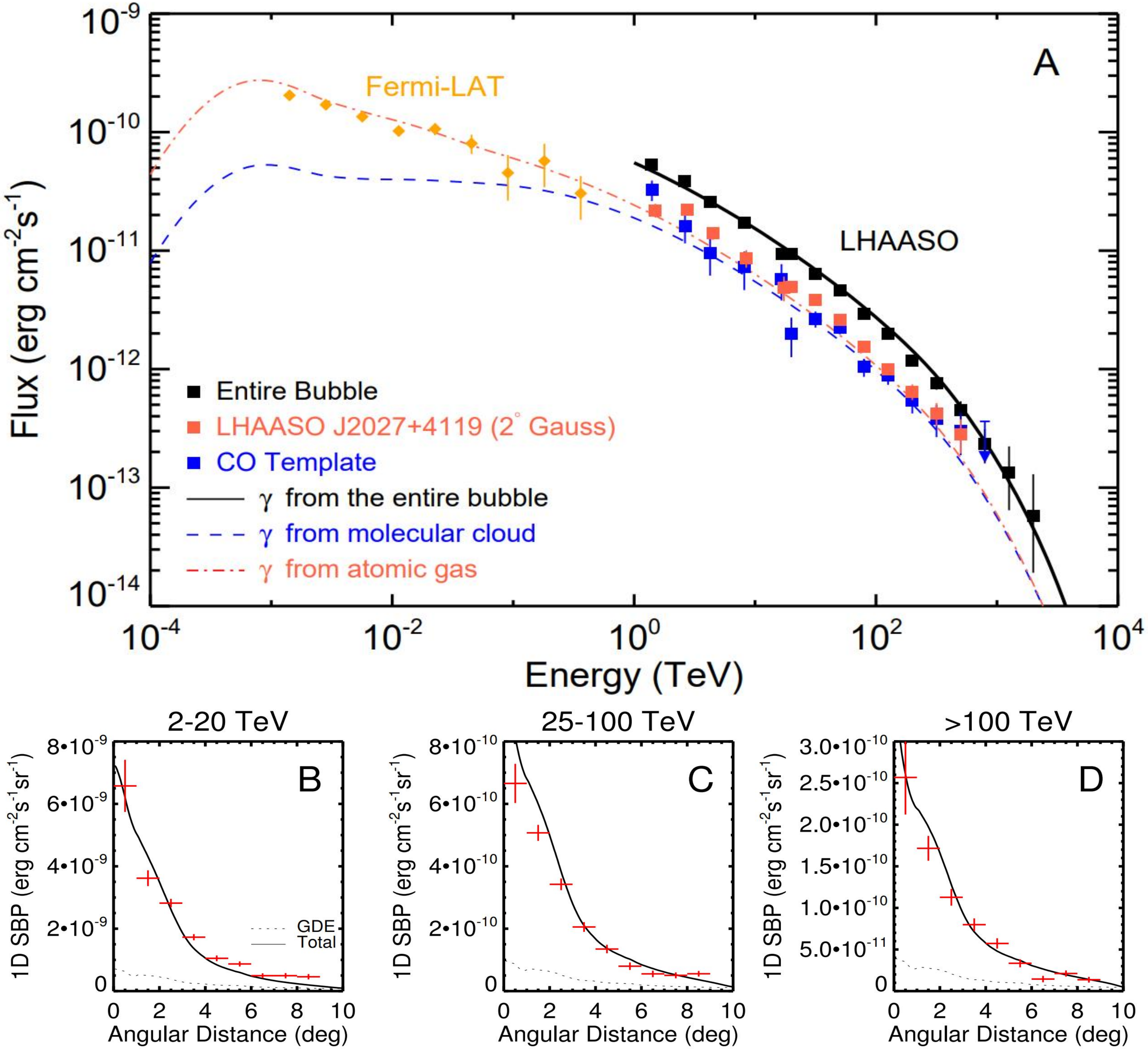
$$n_{\rm MC}(x,y,z) = \frac{M_{\rm MC}}{(2\pi)^{3/2}\sigma_{\rm MC}^3 m_{\rm H}} \exp\left\{-[(x-x_{\rm MC})^2+(y-y_{\rm MC})^2+z^2]/2\sigma_{\rm MC}^2\right\} + n_1$$









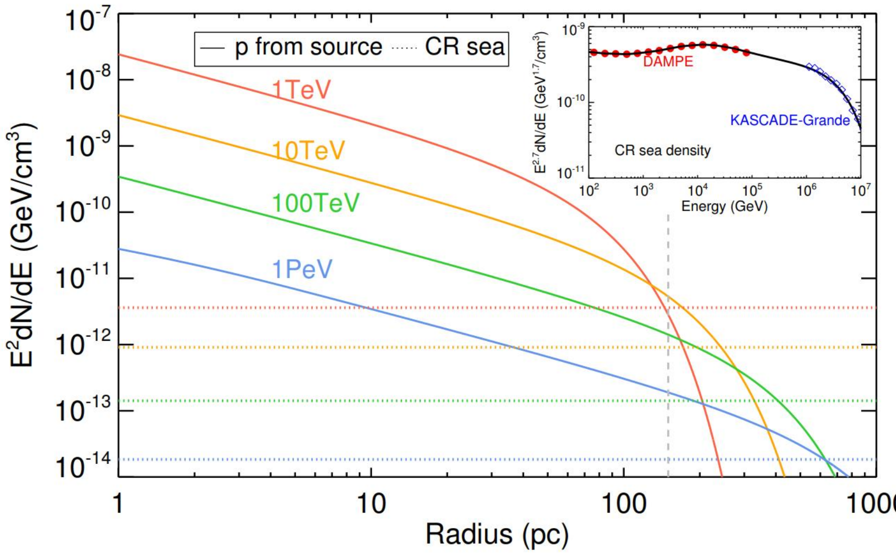


$$D(E_p) = 3 \times 10^{26}(E_p/1\mathrm{TeV})^{0.7}\ \mathrm{cm^2 s^{-1}}$$

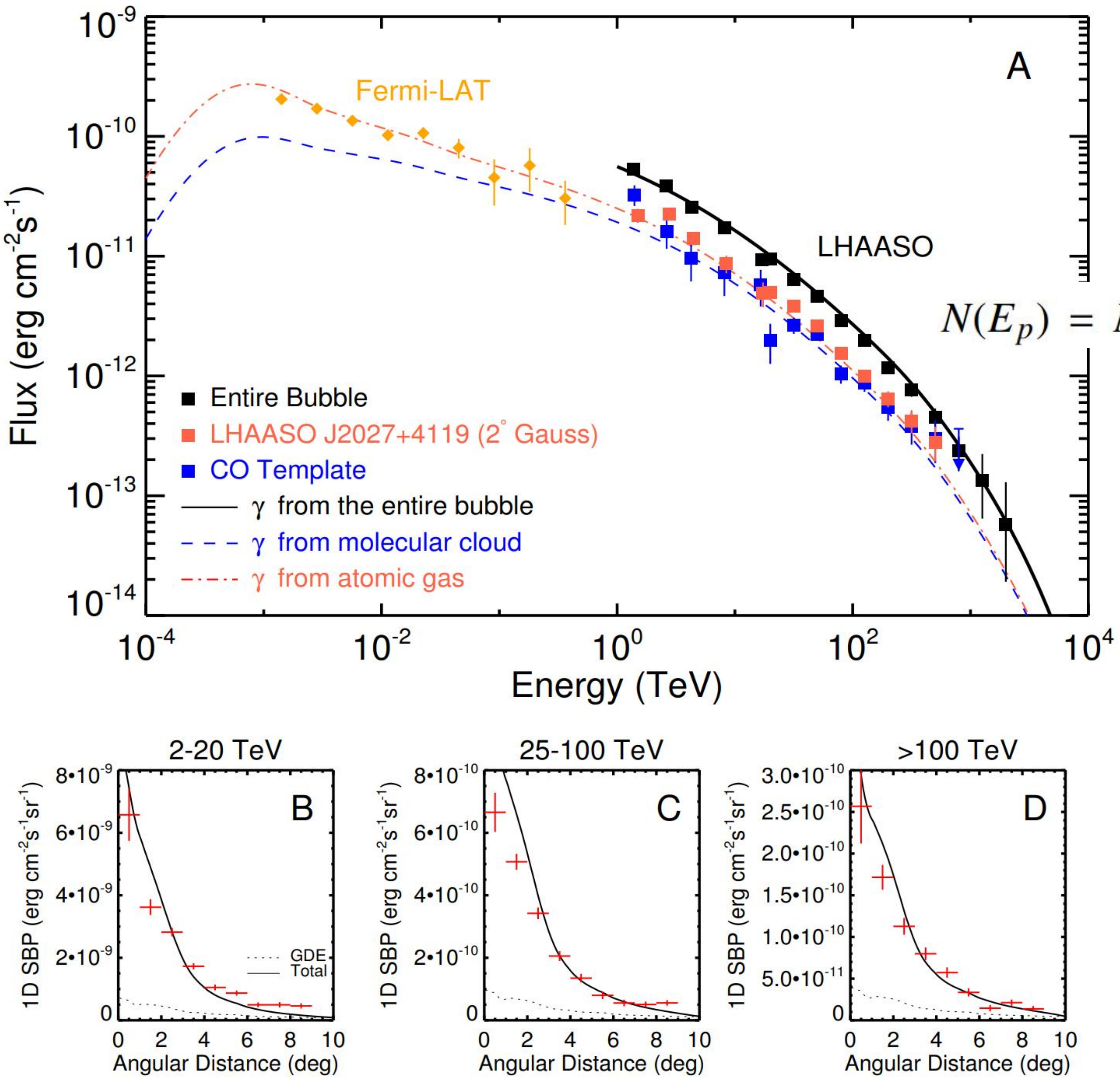
$$N(E_p) = N_0 E_p^{-2.25} \exp(-E_p/5\,\mathrm{PeV})$$

$$L_p \simeq 10^{37}\ \mathrm{erg/s}$$

1% of mechanical power of OB2



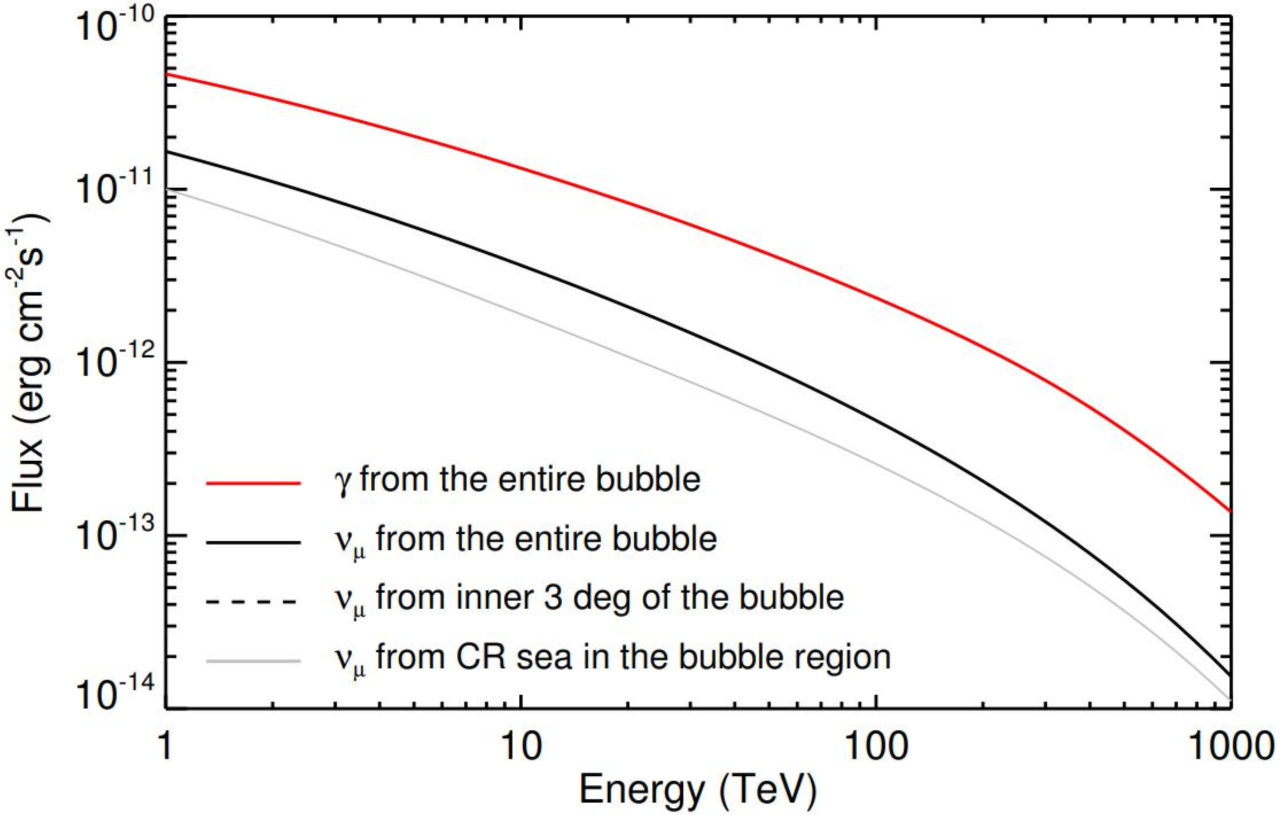
Excess of CR density up to 600 pc at 1PeV

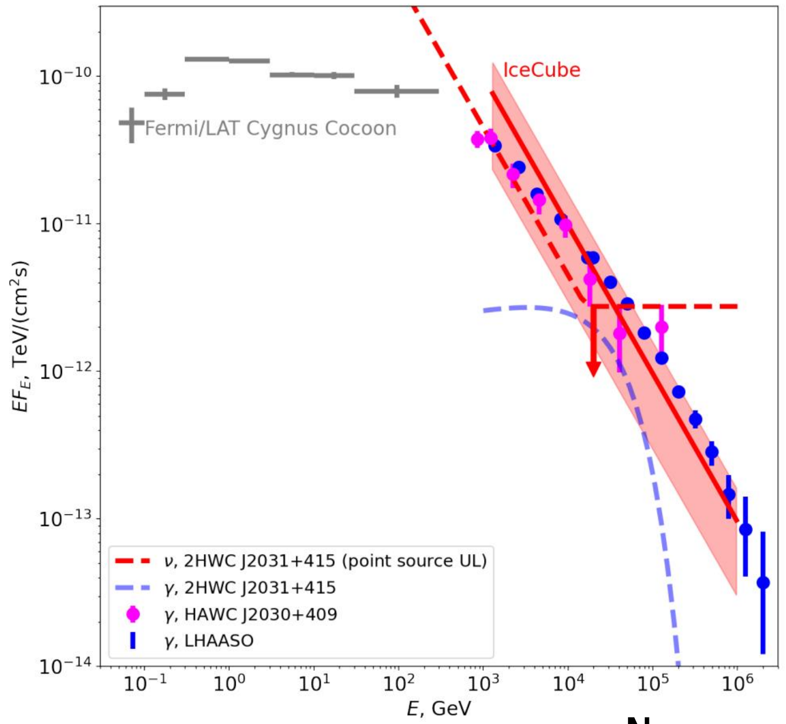


$D(E_p) = 5 \times 10^{26} (E_p / 1\mathrm{TeV})^{1/3}\ \mathrm{cm^2/s}$

$$N(E_p) = N_0 E_p^{-2.25} (1 + E_p/30\mathrm{TeV})^{-0.5} \exp(-E_p/10\mathrm{PeV}).$$

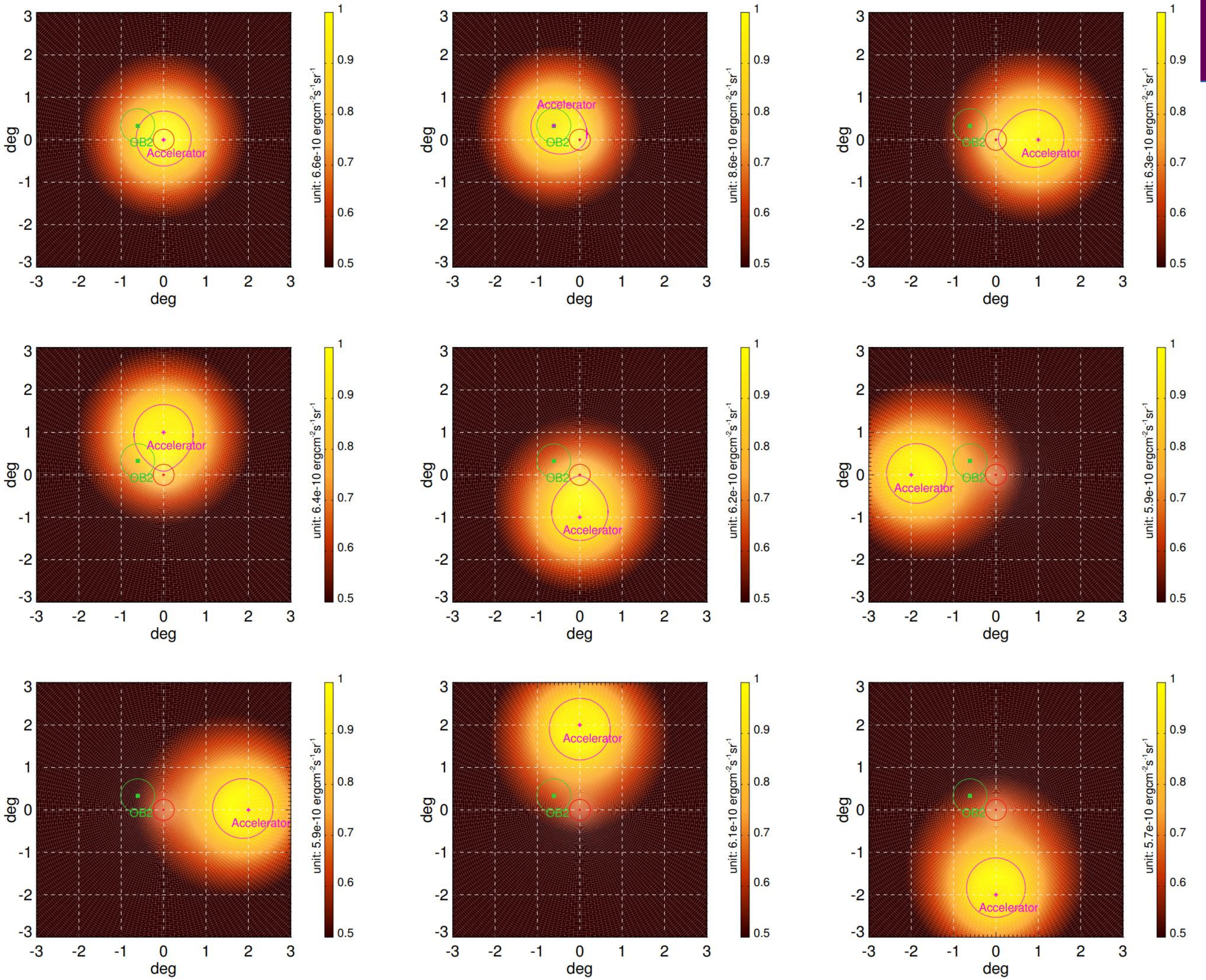
$$L_p \simeq 10^{37}\ \mathrm{erg/s}$$





Neronov et al. 2023

29/7.7/0.36 (anti-)muon neutrino events above 1/10/100 TeV for 10-yr IceCube operation the position of the bubble centroid basically follow that of the accelerator / injection point



Discussion and Summary

Could other sources power the bubble?

Cygnus X-3

Unlikely.

Distance: 7.4
$L \sim d^2 \sim 25 \uparrow$

Much Less gas target at 7.4 kpc

$L_{EDD} \sim 10^{39}$erg/s

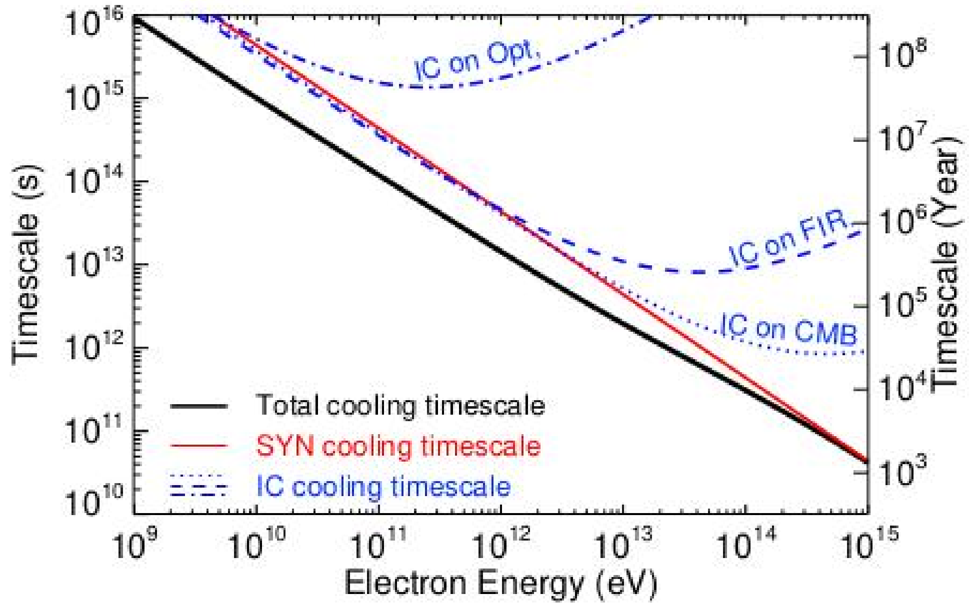
Required $L_p >> L_{EDD}$

PSR J2032+4127 / MT91 213

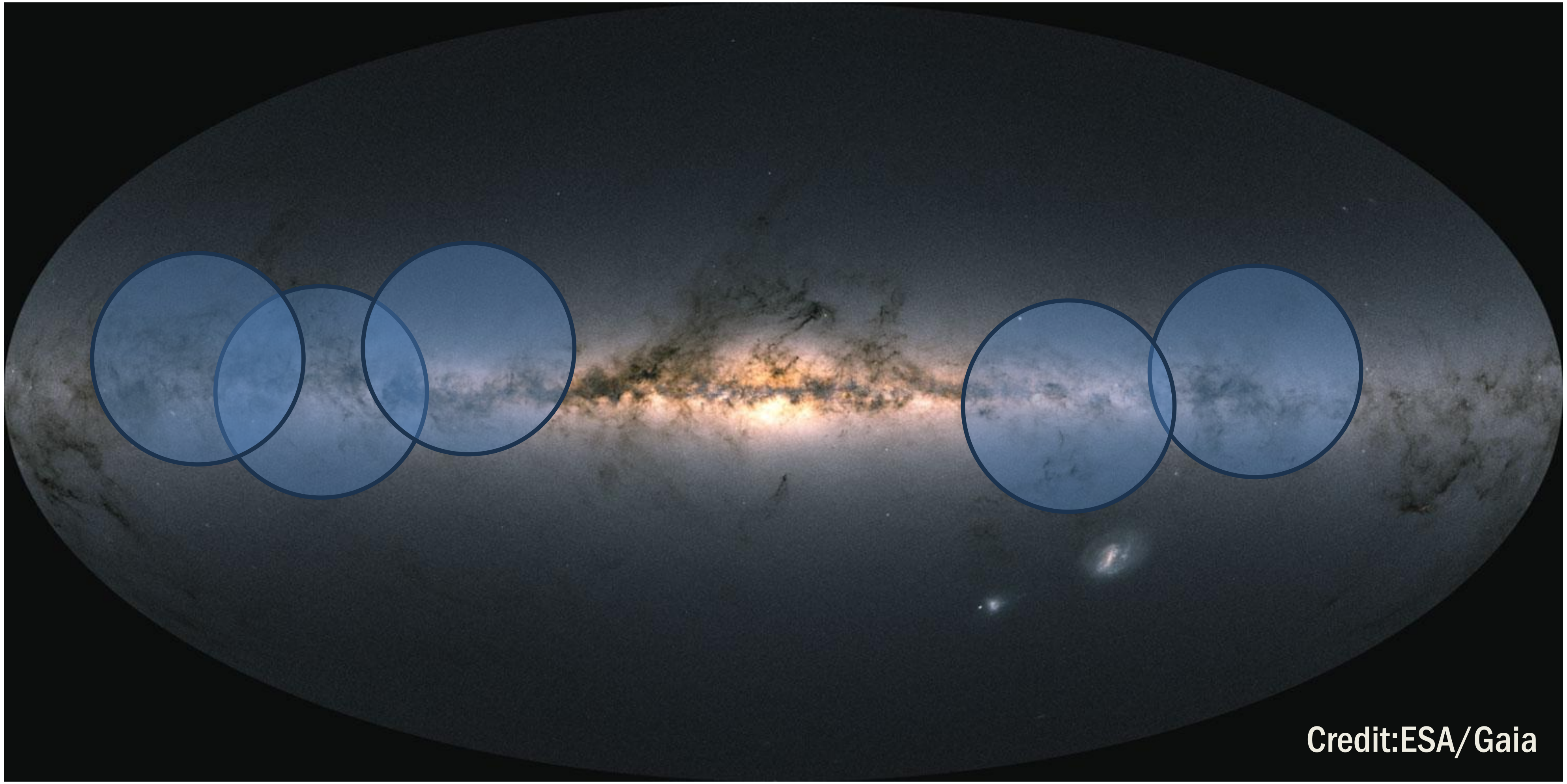
Unlikely.

$L_{sd} \sim 1.7 \times 10^{35}$ erg/s << required L_p

Binary emission – variable as measured by MAGIC & VERISTAS



Influences on global CR transport in our Galaxy



$D_{ISM} \sim 10(E/1GeV)^{1/2}$ from secondary-to-primary CR ratio

How common could such giant slow-diffusion bubble appear in Galaxy?

Summary

- LHAASO has detected a giant ultrahigh-energy gamma-ray bubble in Cygnus star-forming region, extending a radius of at least 6 deg
- Spectra and morphology of the bubble support the origin of UHE emission to be hadronic interactions of diffusing protons injected from the centra accelerator and surrounding gas
- Protons need be accelerated well beyond PeV in the central source. Cygnus OB2 is the best candidate of the super PeVatron, and the first-ever located source of CR at 10 PeV
- Observations of IACT with higher angular resolution toward the core region can reveal more physics.

Thank you for your attention!