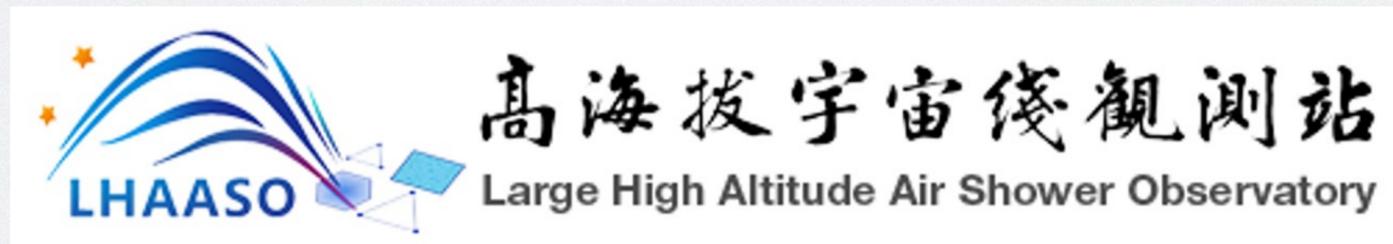# YOUNG MASSIVE CLUSTERS AS COSMIC RAY SOURCES

Ruizhi Yang
on behalf of LHAASO collaboration

outline

- Star forming regions/Young star clusters as gamma-ray and cosmic ray sources

- Gamma-ray observations

- Confinement of Cosmic rays near sources

- GCR distribution reveals a similar peak as that for OB stars.

- Isotope measurement favor a superbubble origin. (W.R Binns 2016)

- Most of OB stars exist in associations or clusters, stellar wind can accelerate CRs (Cesarsky & Montmerle 83).

- Efficiency may even better than SNR (high speed wind lasts much longer than SNR shock)

- Sufficient wind power (10^{38} - 10^{39} erg/s for each cluster, more than -10^{41} erg/s in the Galaxy) to account for CRs

- Could be visible in gamma-ray due to CR-gas interaction.

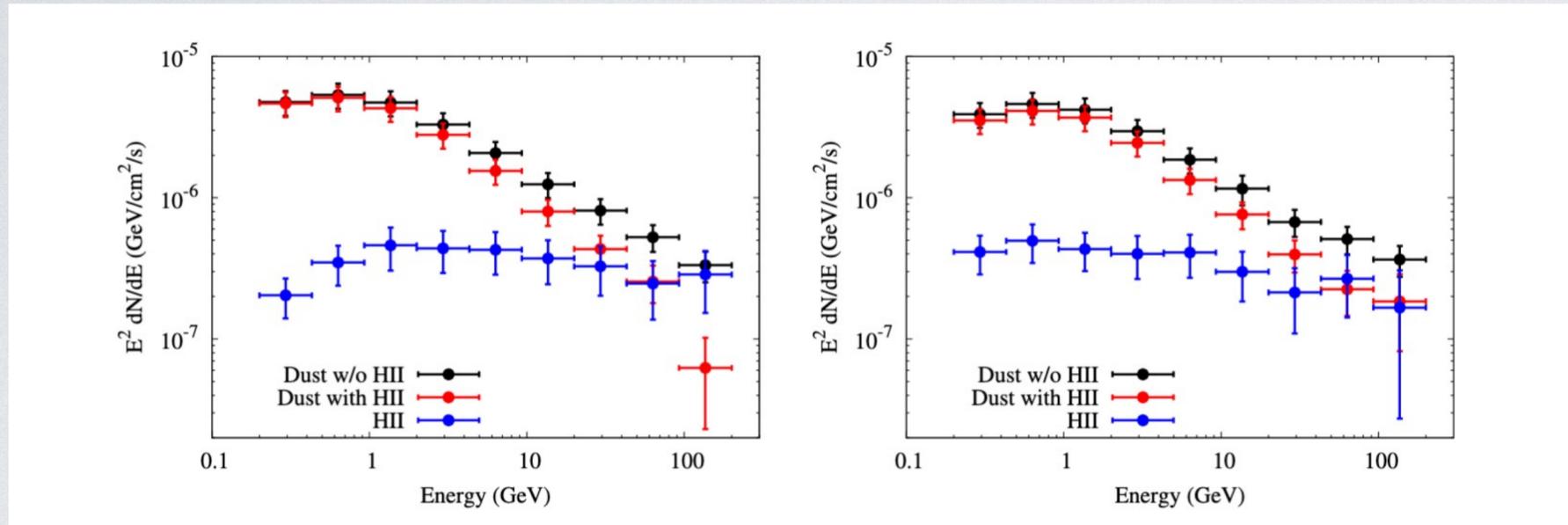# CR DISTRIBUTION VS SOURCE DISTRIBUTIONS IN THE GALAXY
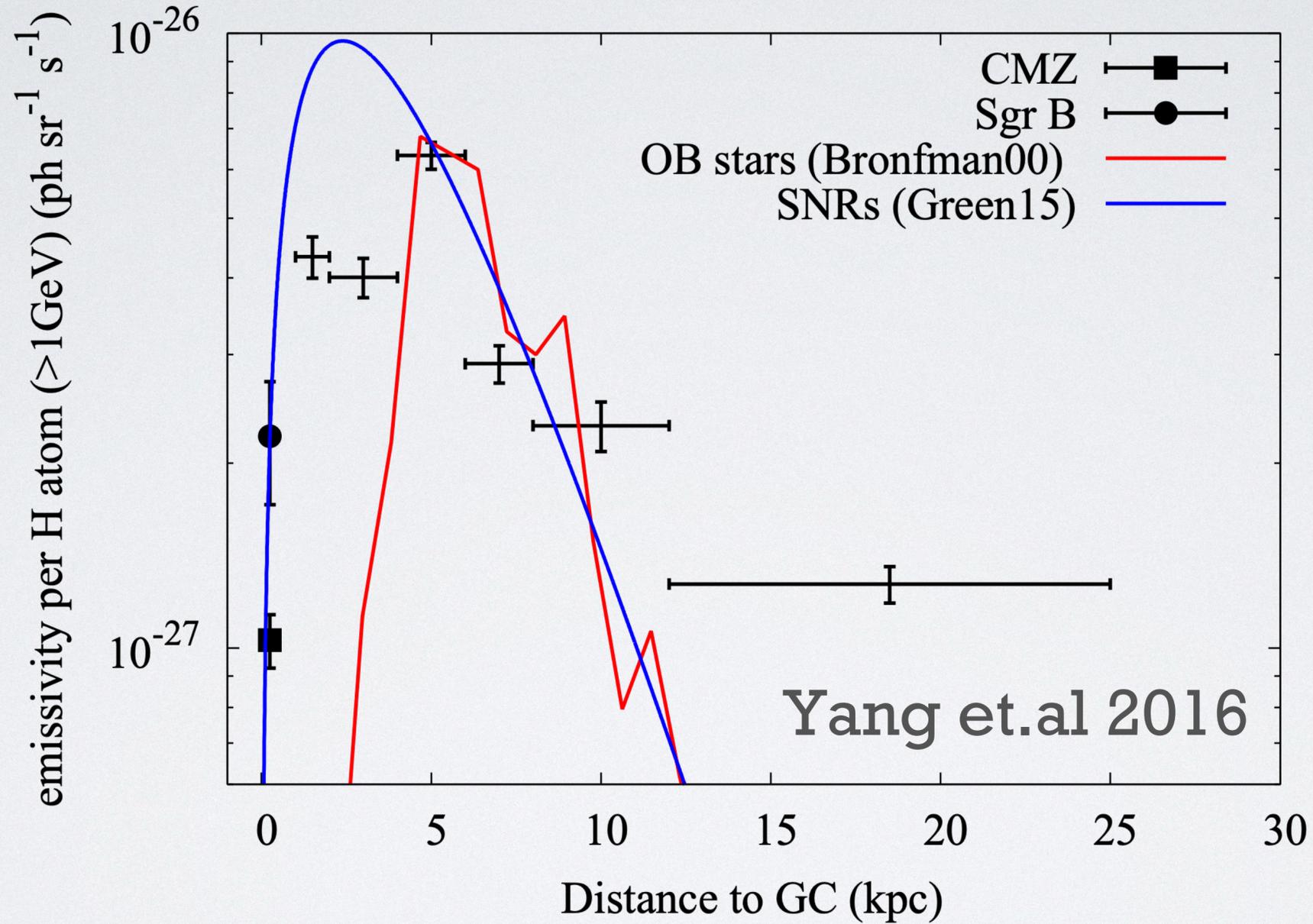
Peak of CR radial profile coincide with that of OB stars (massive star clusters) rather than SNRs
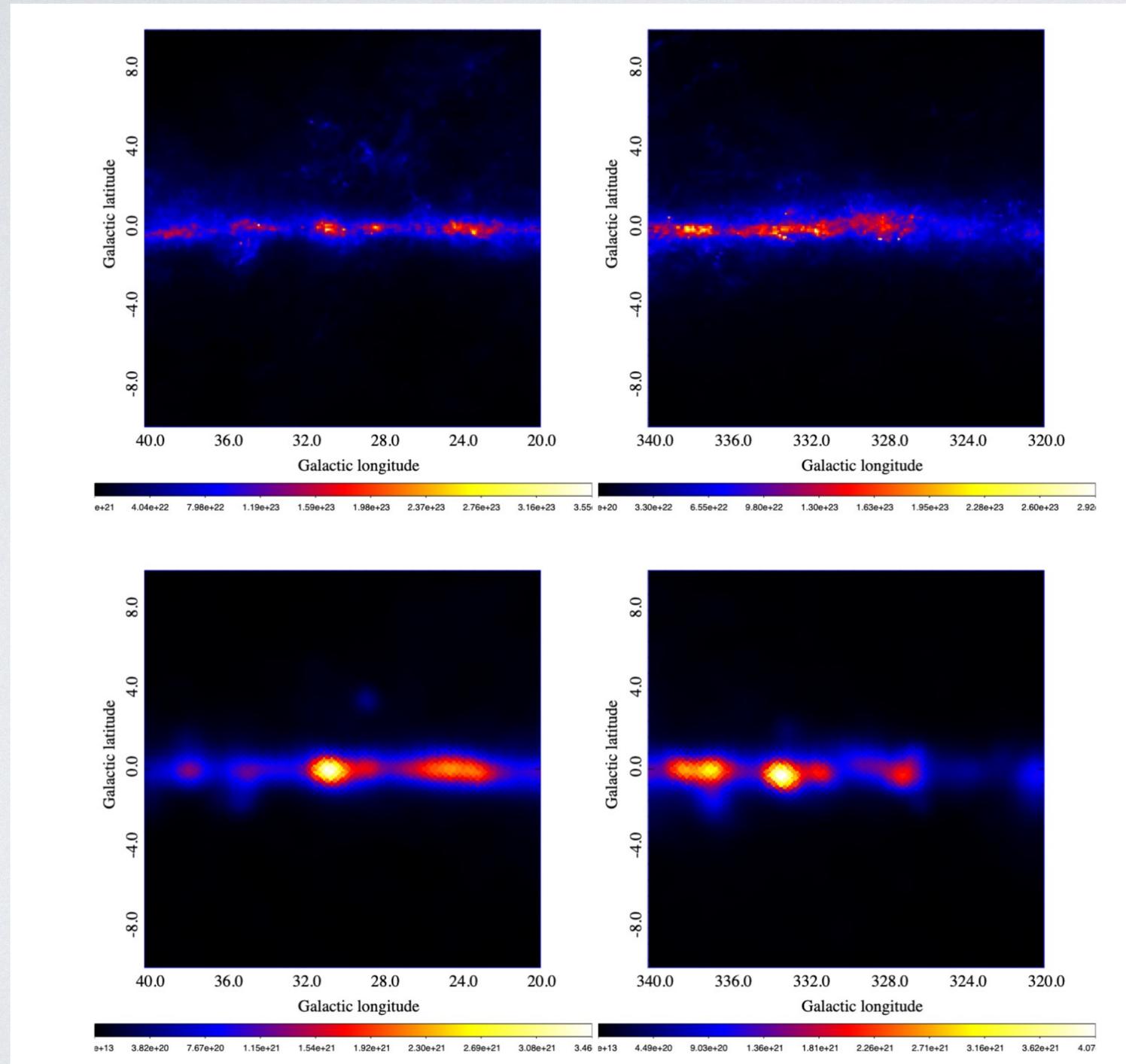
- HII gas were ignored in former modeling

- HII can trace star forming activity, may related to CR sources (such as cocoons near YMCs).

- Different Morphology in HII and total gas column can be used to separate different component
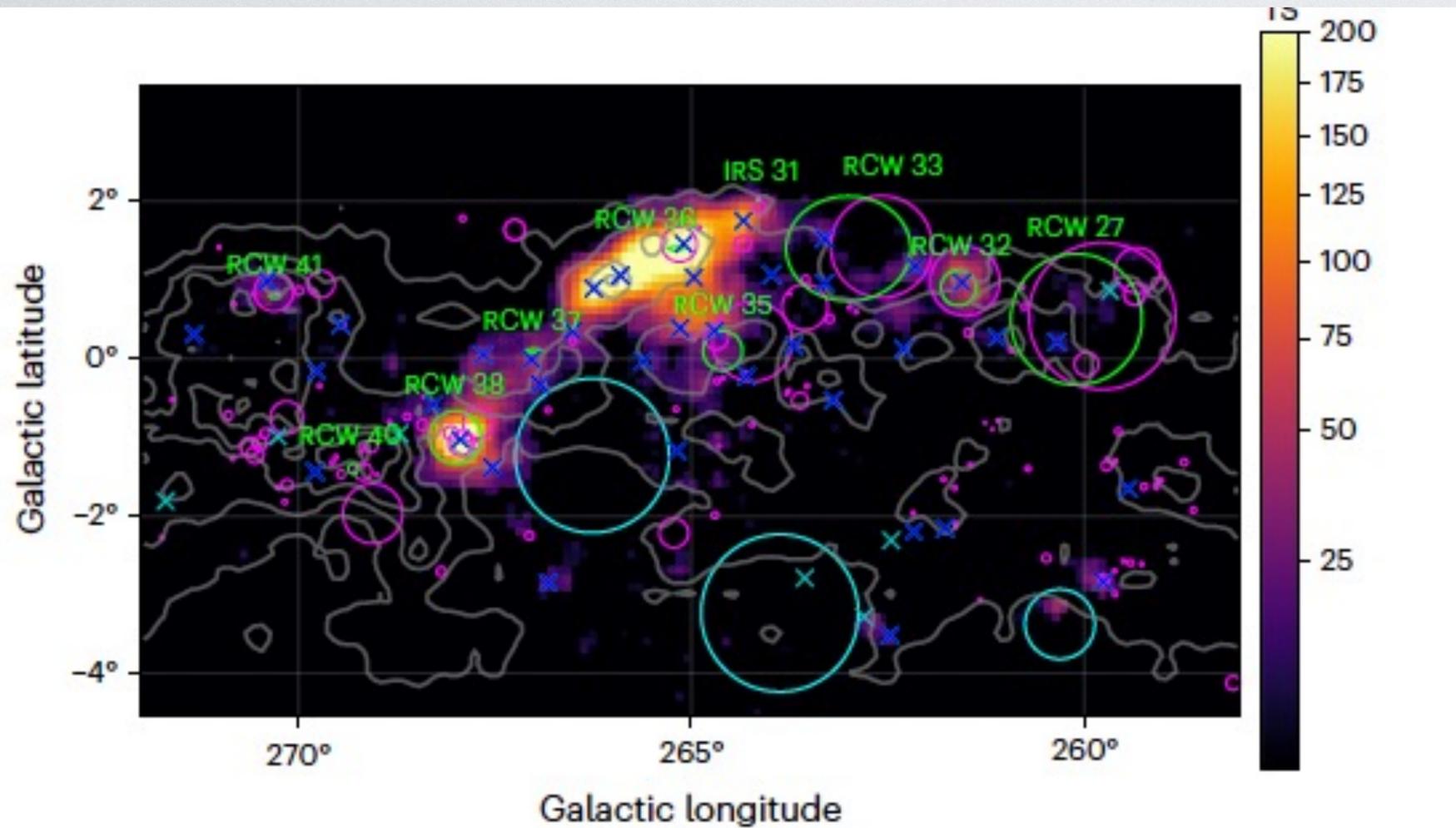
Liu et.al A&A 659, A101 (2022)

Liu et.al A&A 659, A101 (2022)

- After considering HII component the CR distributions looks "more homogeneous"

- The former inhomogeneity is simply due to the mixing of "true" diffuse (sea) component with hard "source" (island) regions
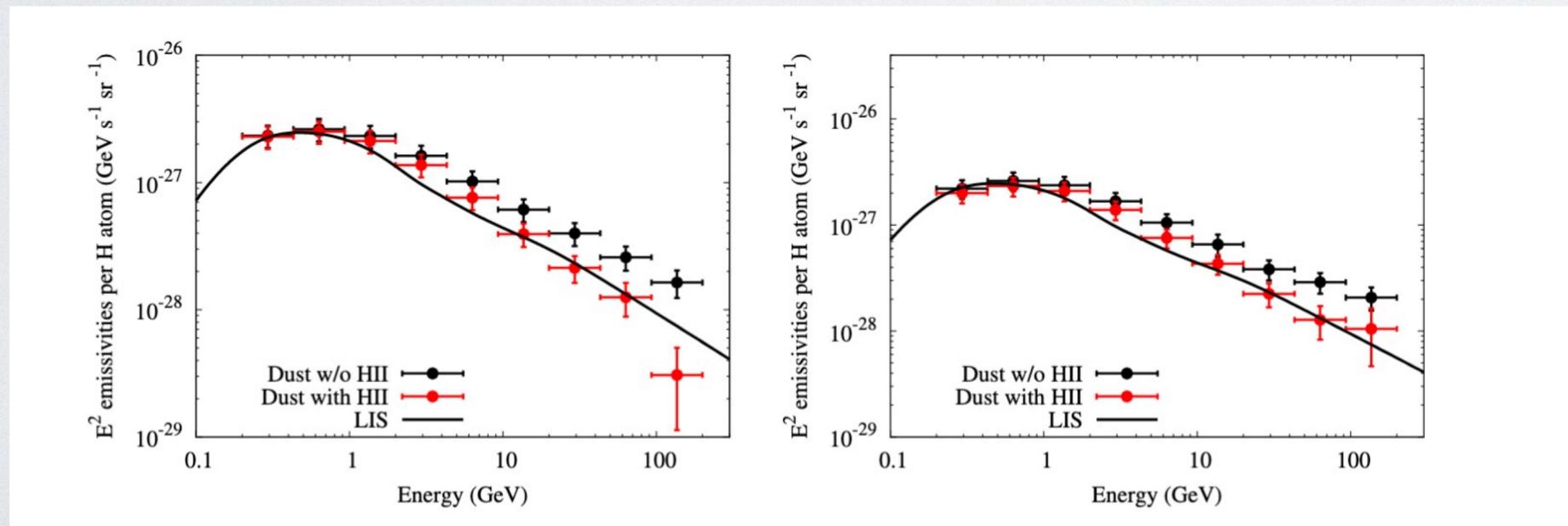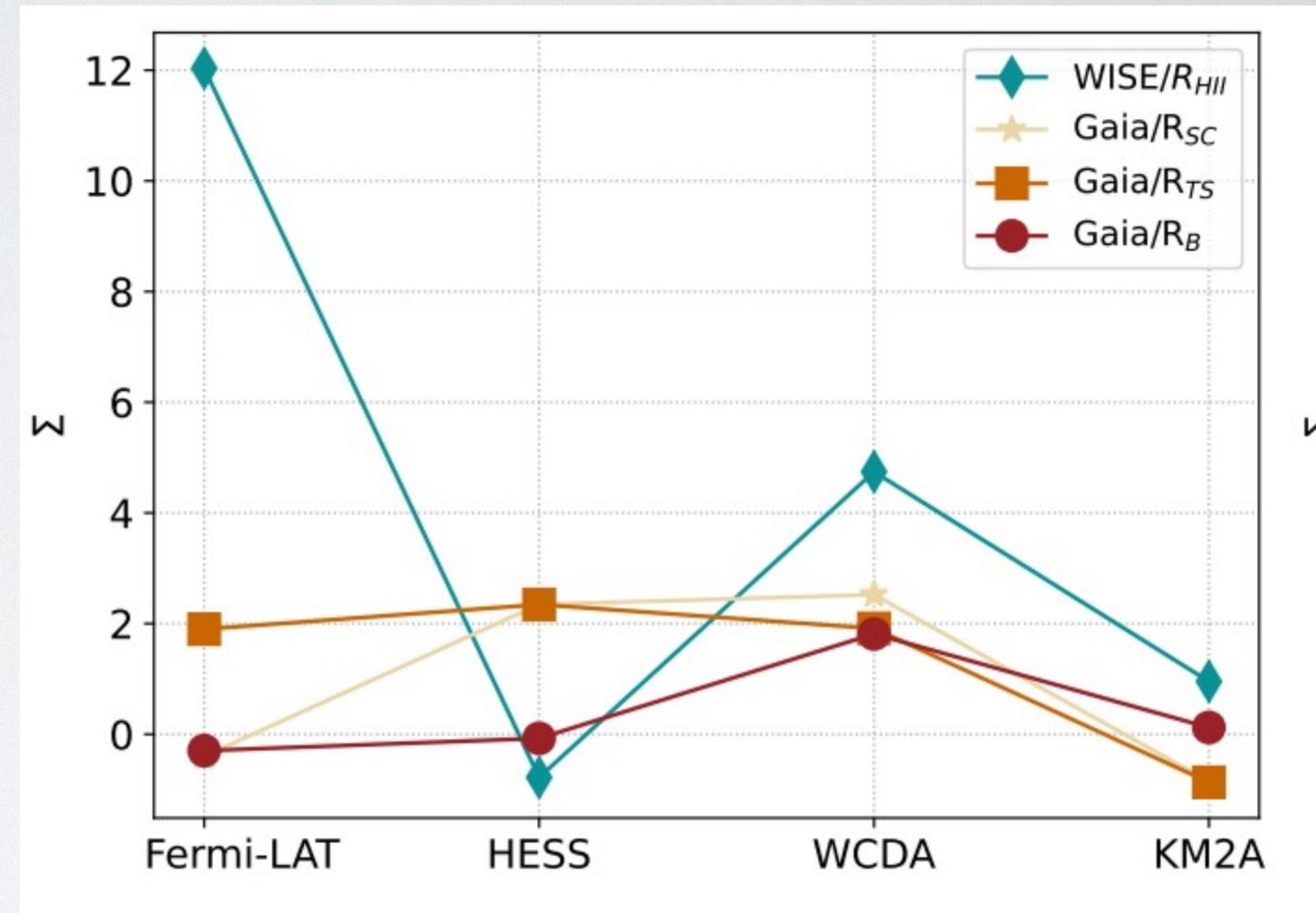
GAMMA-RAY EMISSIONS FROM HII REGIONS

Significant gamma-ray emission in Vela GMC associated with HII gas
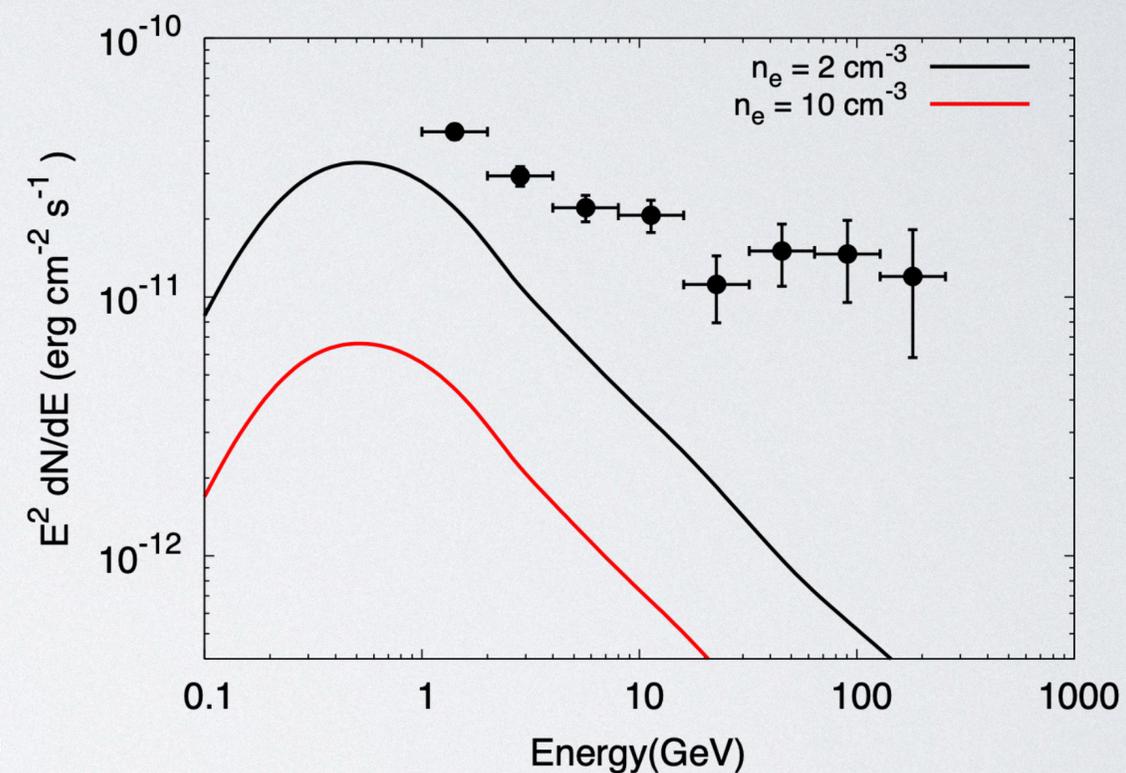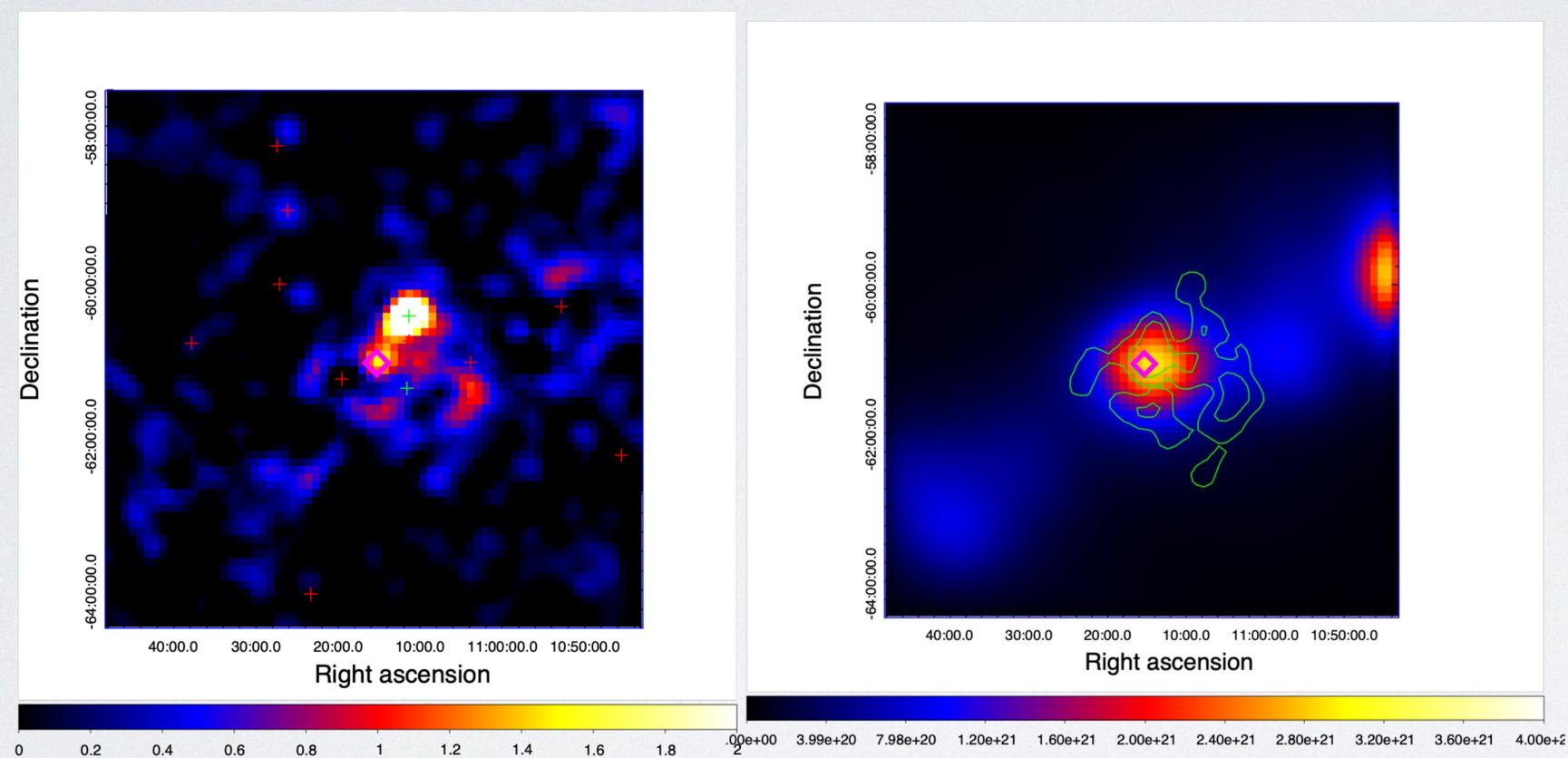
Peron et.al 2024a

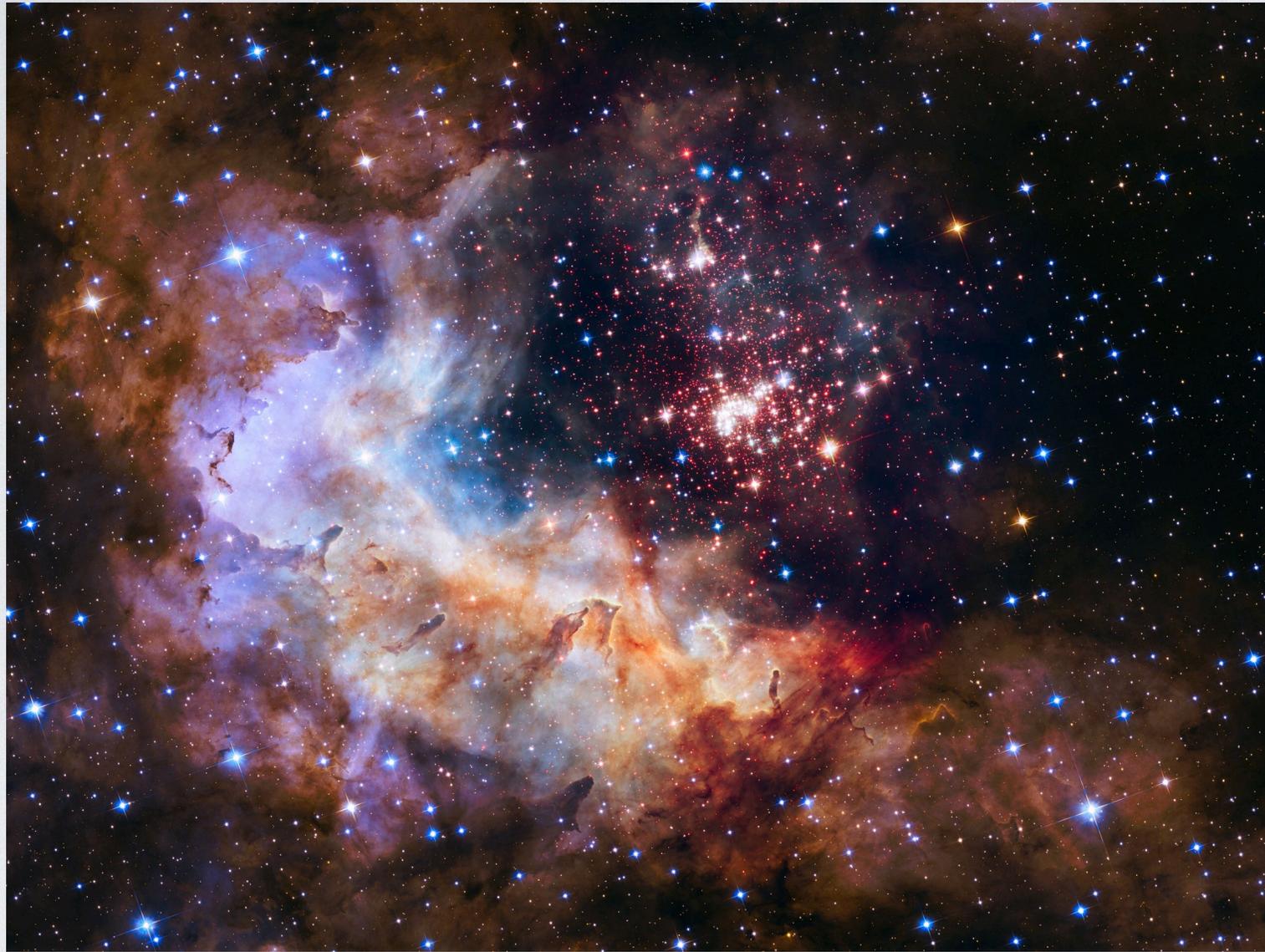Correlation of HII region with GeV unidentified sources

Peron et.al 2024b

The giant HII regions are linked naturally to the young massive star clusters (YMCs)

example is the case for NGC 3603. left :gamma, middle: HII
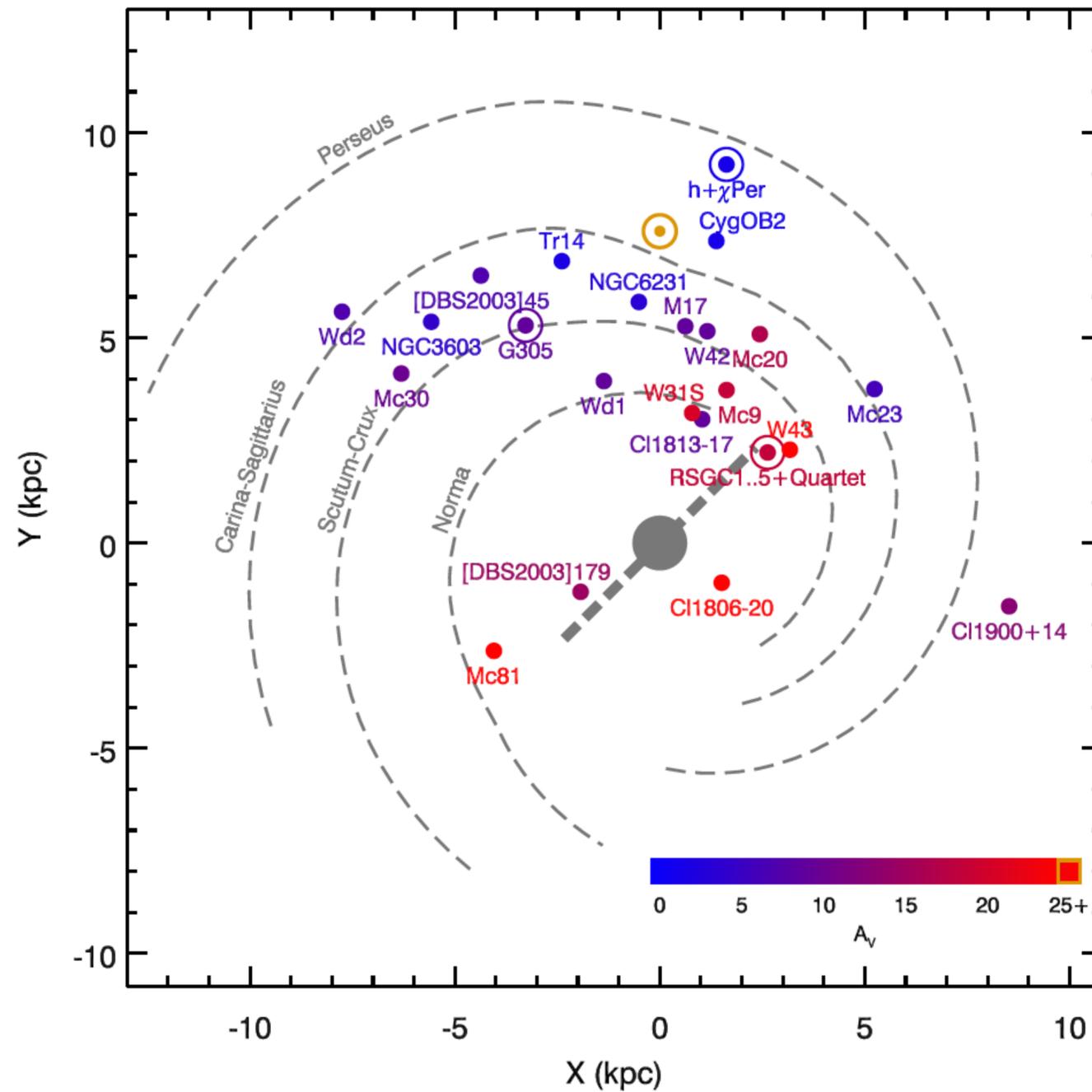
Yang & Aharonian 2017

YMCS

Westerlund 2 (HST image)

NGC 3603 (VLT image)

- More than dozens of OB stars and WRs
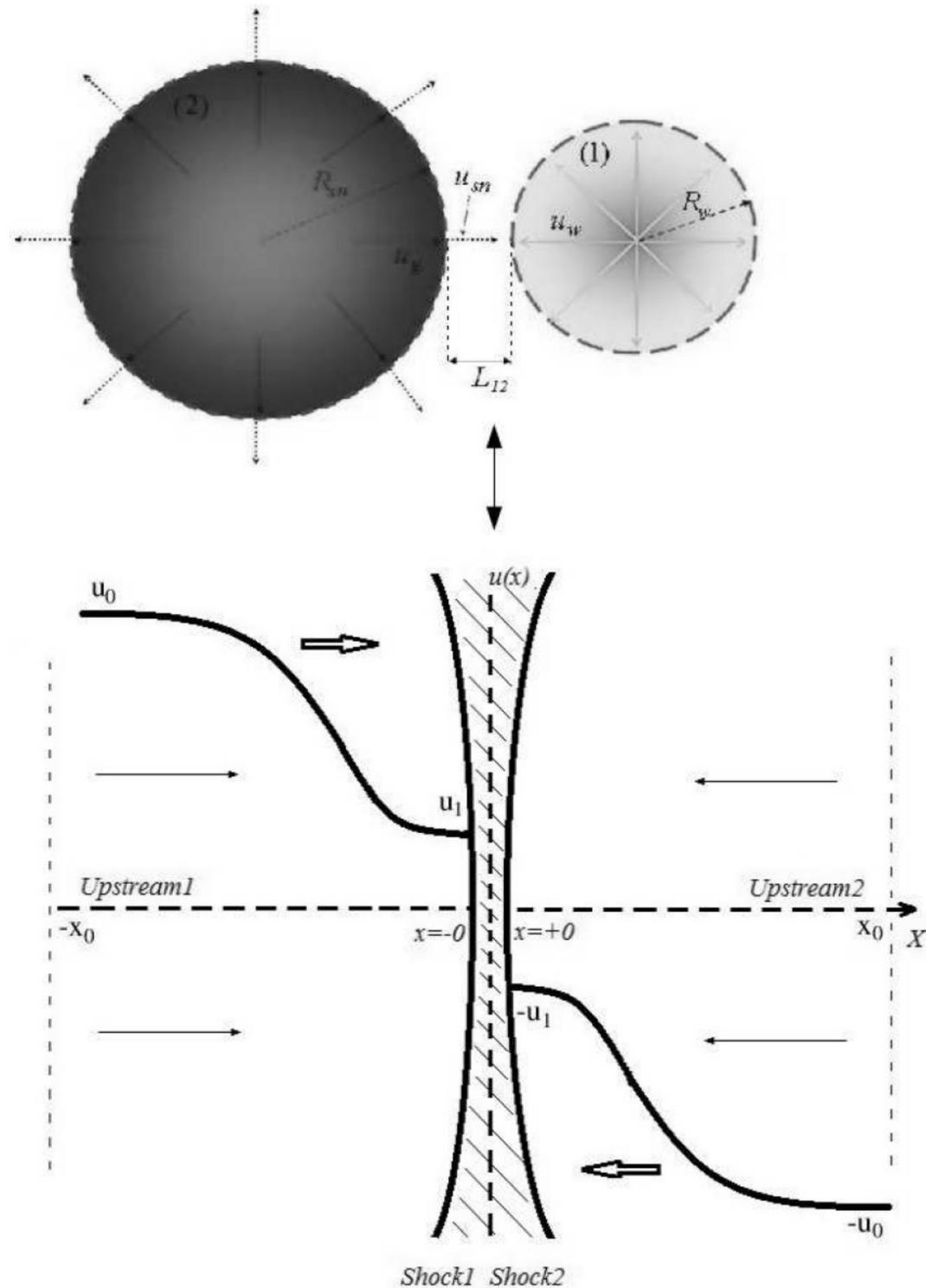- Compact structures (~ pc)

- ~20 in our Galaxy

- More to be discovered (high extinction in Galactic plane)

Davies et.al 2011

Stellar type	$\log[\dot{M}]$ $M_\odot \, yr^{-1}$	V_∞ [km s^{-1}]
WNL	-4.2	1650
WNE	-4.5	1900
WC6-9	-4.4	1800
WC4-5	-4.7	2800
WO	-5.0	3500
O3	-5.2	3190
O4	-5.4	2950
O4.5	-5.5	2900
O5	-5.6	2875

- The wind power of a single young star can be as high as 1e37 erg/s

Bykov et.al 2014
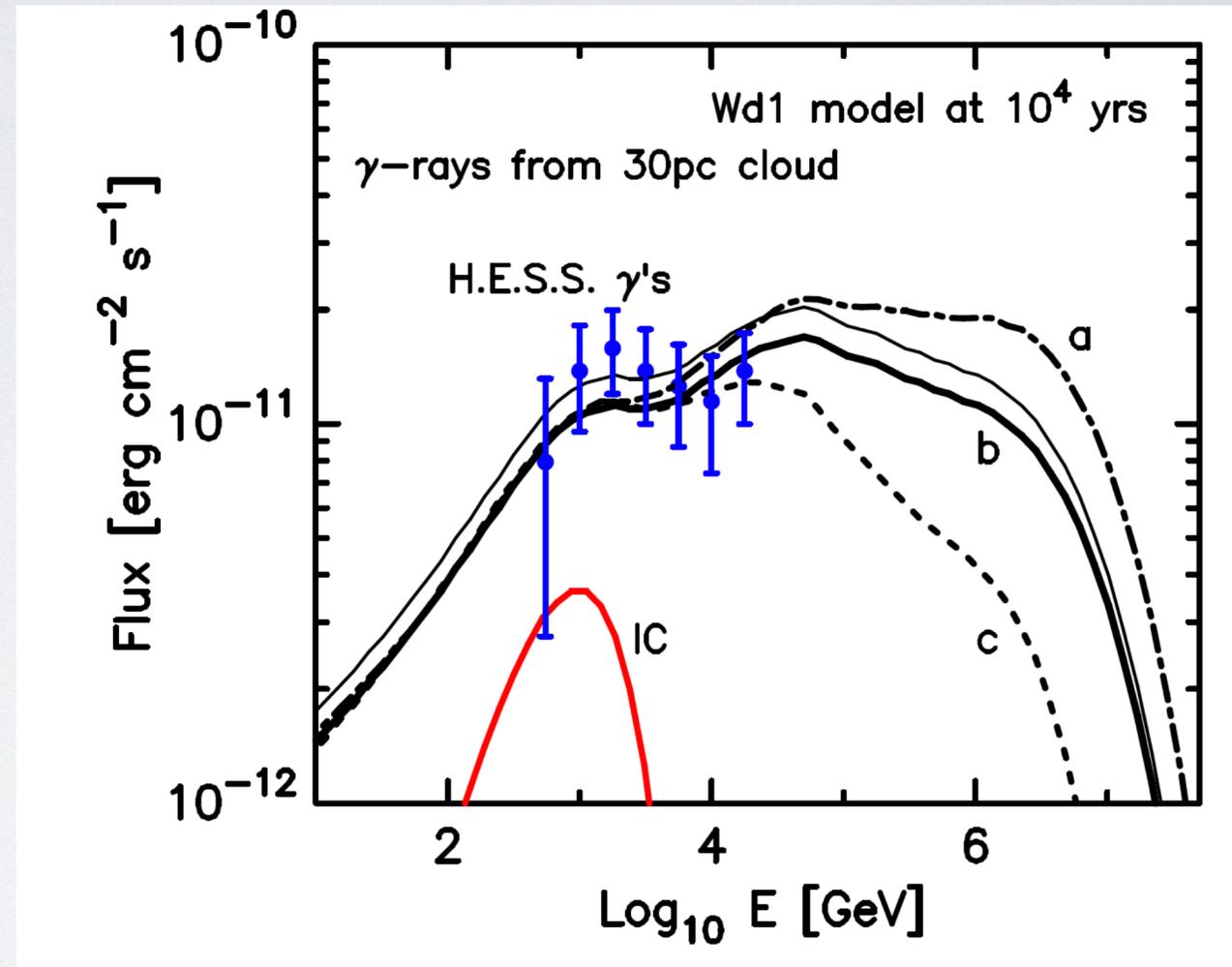
- One promising site: SNR shock colliding with wind termination
- Can accelerate to PeV

Cygnus Cocoon

30 Doradus C
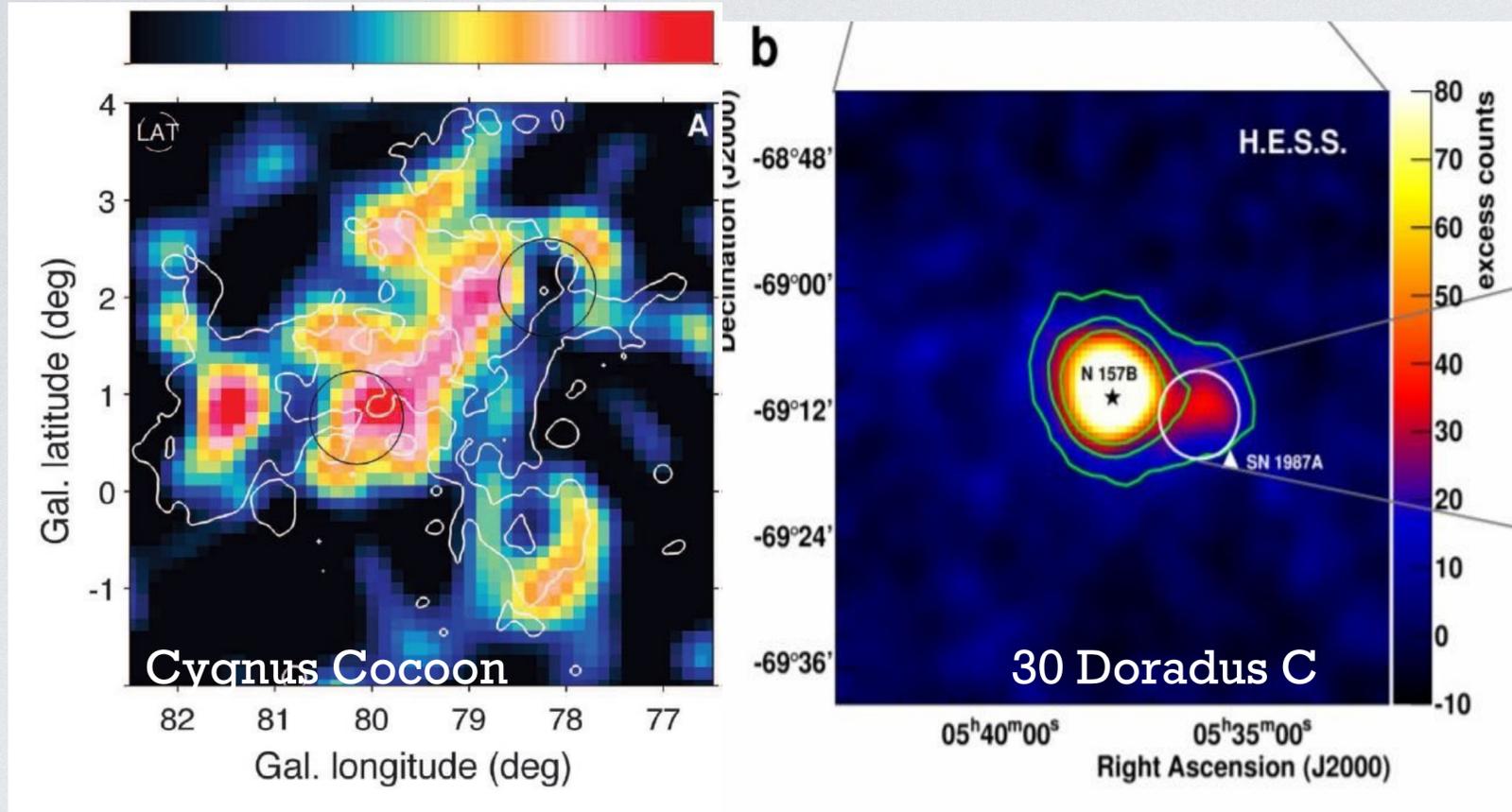
Westerlund 1

New GAMMA-RAY Source population:

Cygnus Cocoon(GeV-TeV)[Fermi 2012, HAWC2022]
Westerlund 1 (TeV) [HESS collaboration 2012]
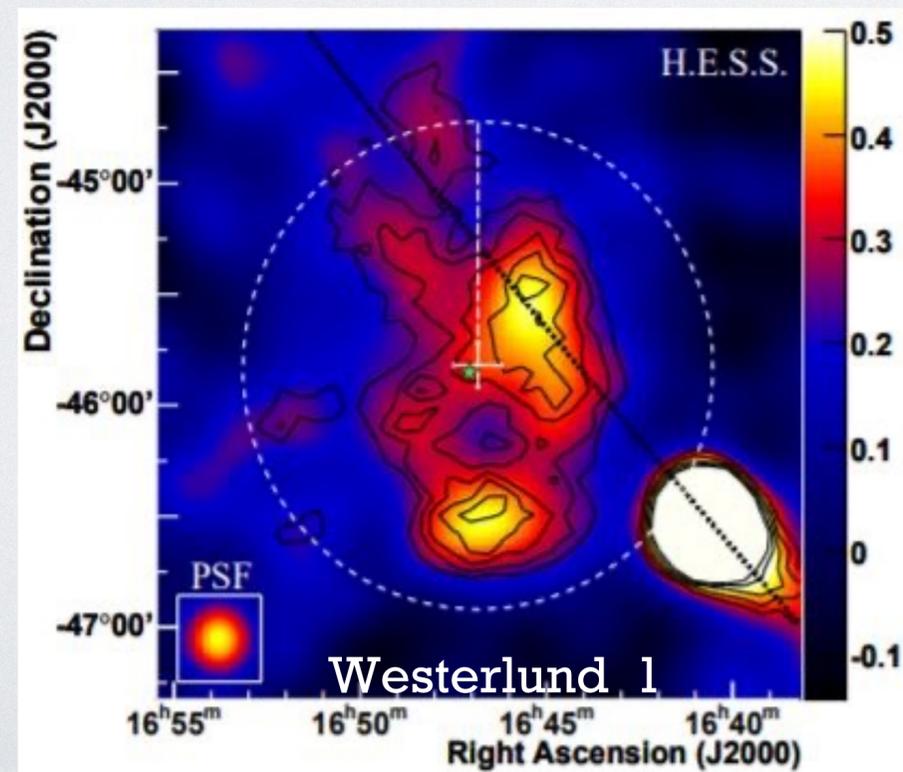Westerlund 2 (GeV, TeV?)[Yang et.al 2018]
NGC 3603 (GeV, TeV)[Yang et.al 2017]
W43 (GeV, TeV?) [Yang et.al 2020]
W40 (GeV) [Sun et.al 2019]
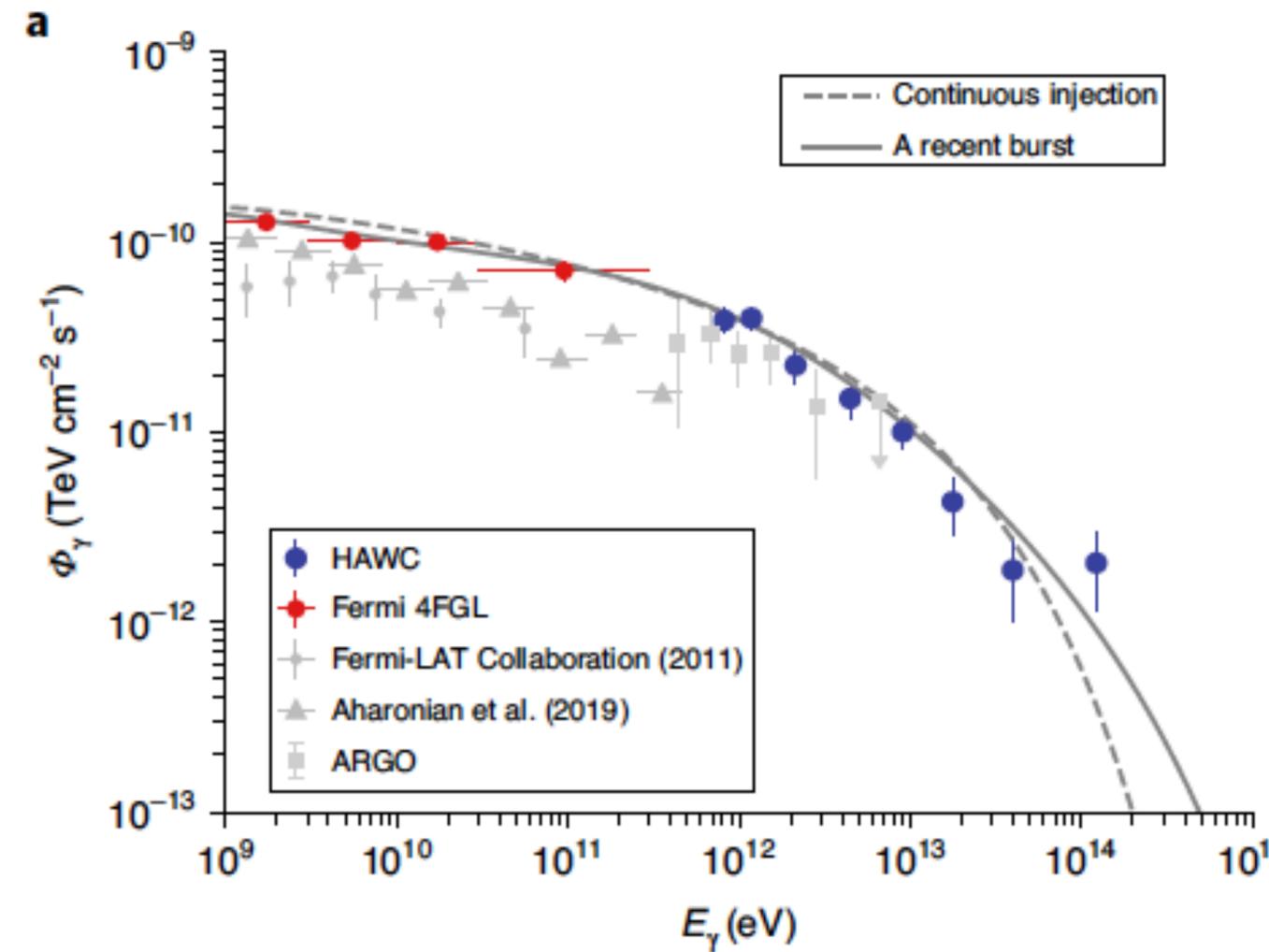G25/RSGC 1[Sun et.al 2020]
Carina nebular [Ge et.al 2022]
M17 [Liu et.al 2022]

CYGNUS COCOON
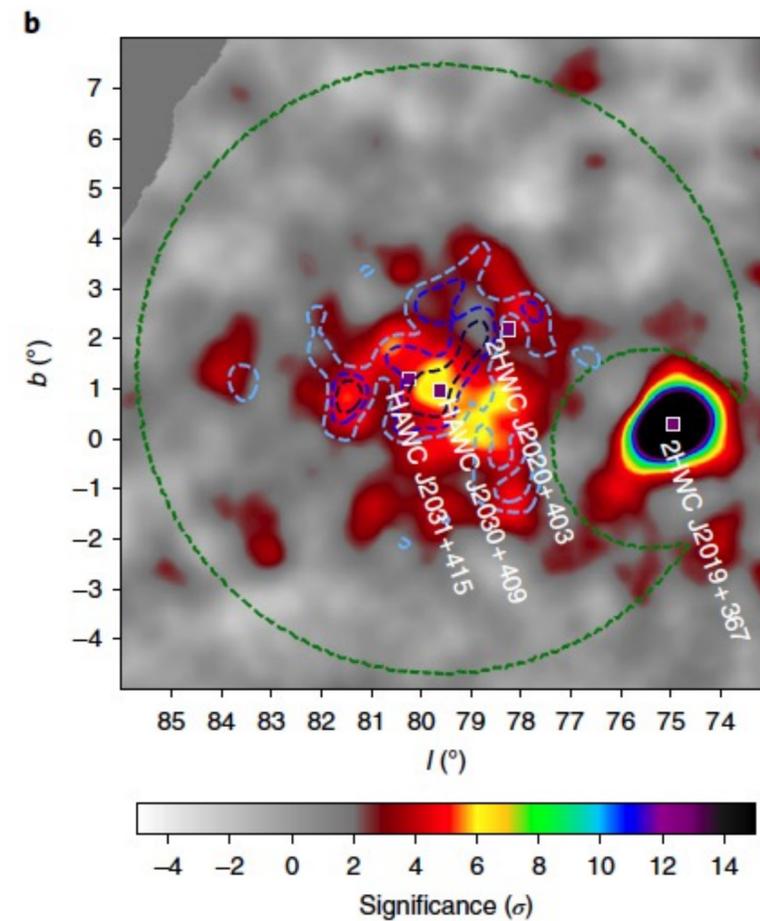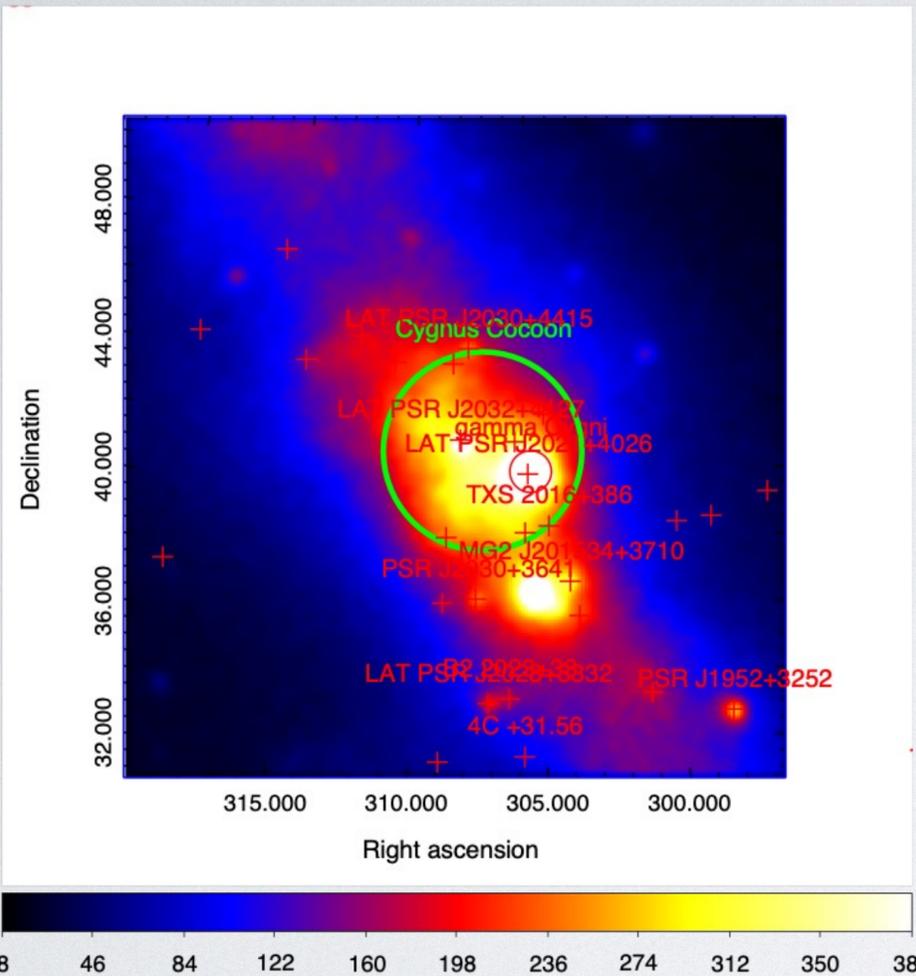
- Observed by Fermi LAT, ARGO-YBJ & HAWC
- extended emission up to more than 50 pc
- Hard spectrum in GeV band, softening above TeV
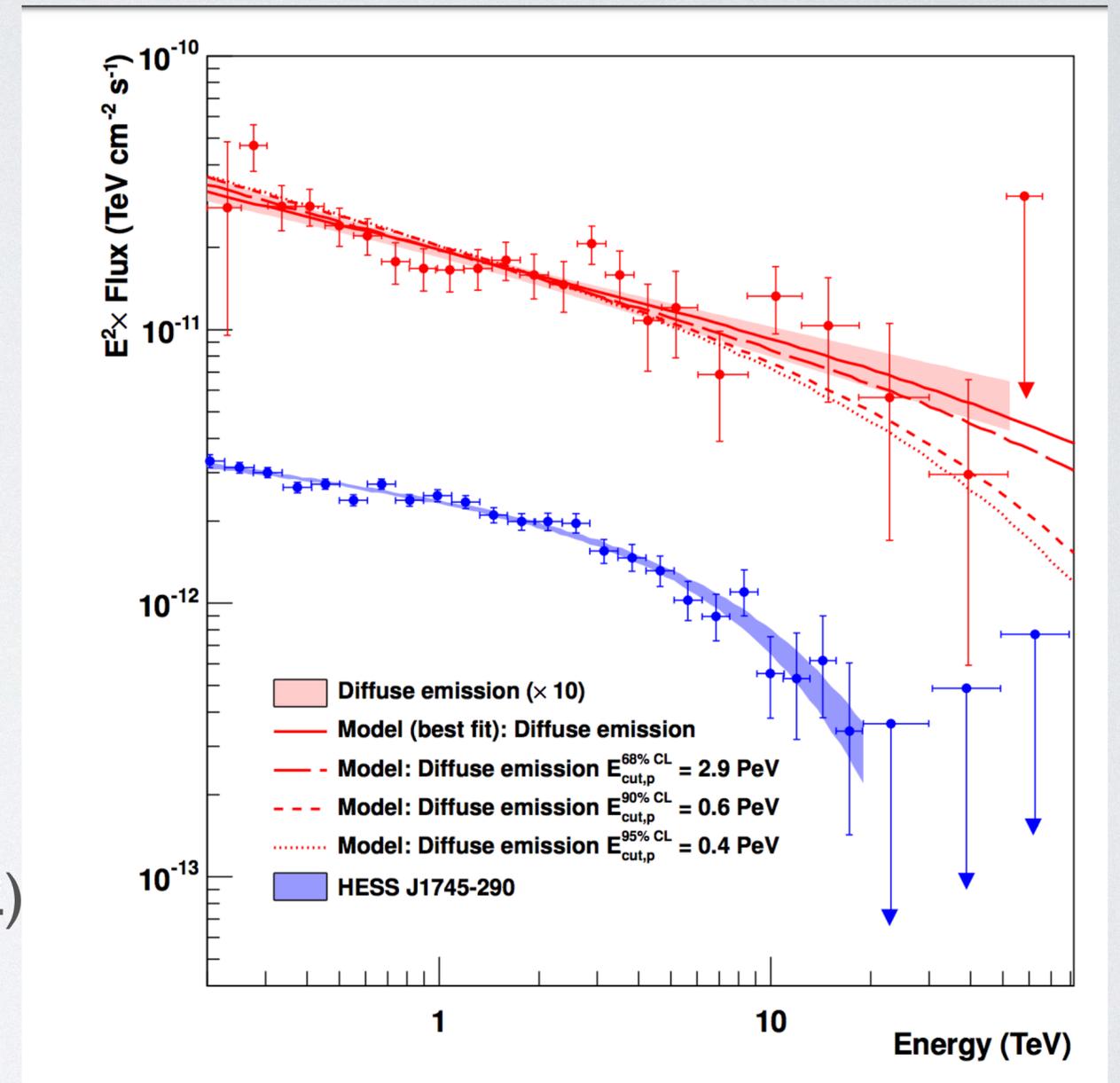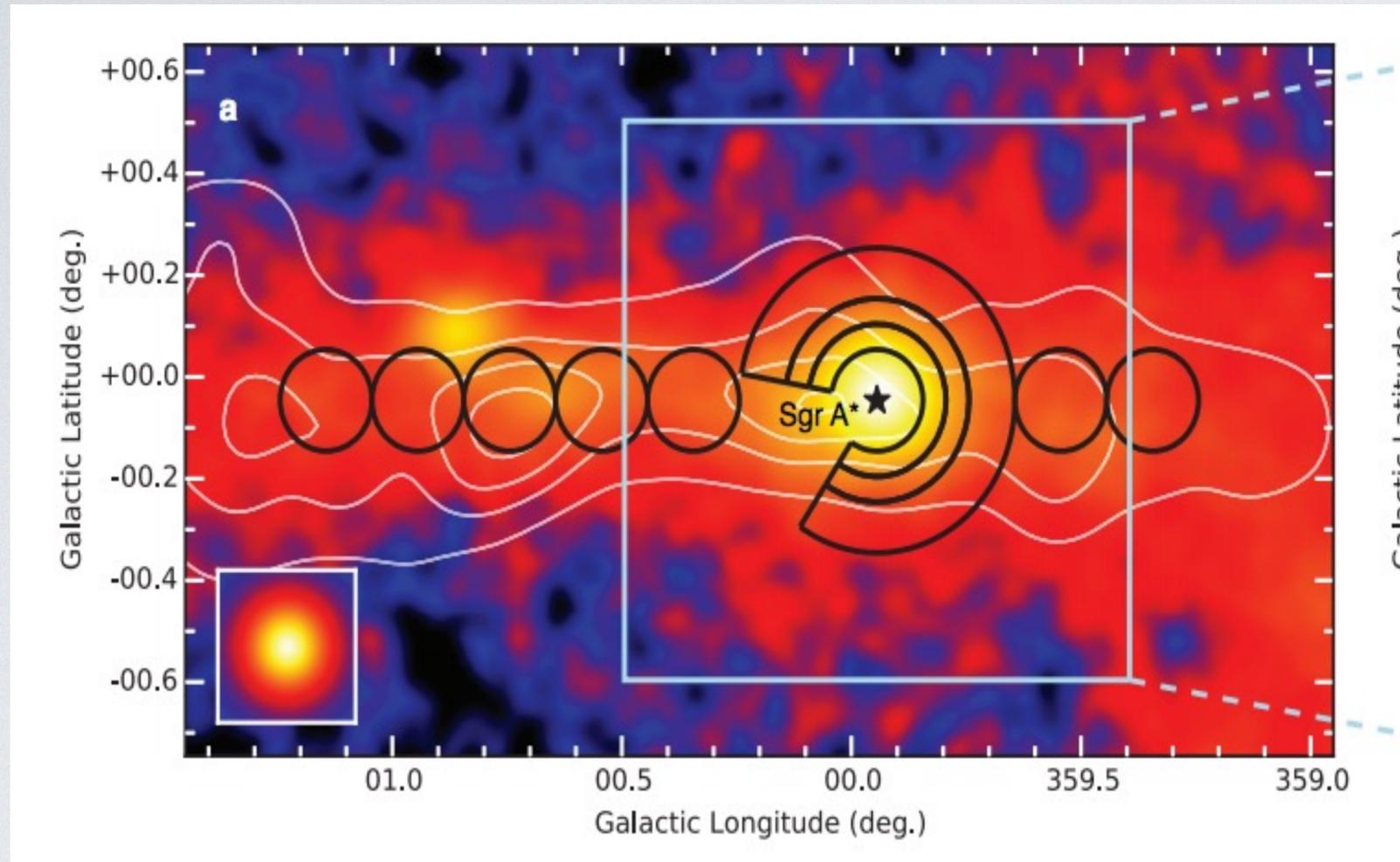
- Also reveal extended emission and hard spectrum (index ~ 2.2)
- Diffuse emission up to more than 150 pc
- GC region harbors Arches, Quintuplet and Nuclear cluster

HESS 2022
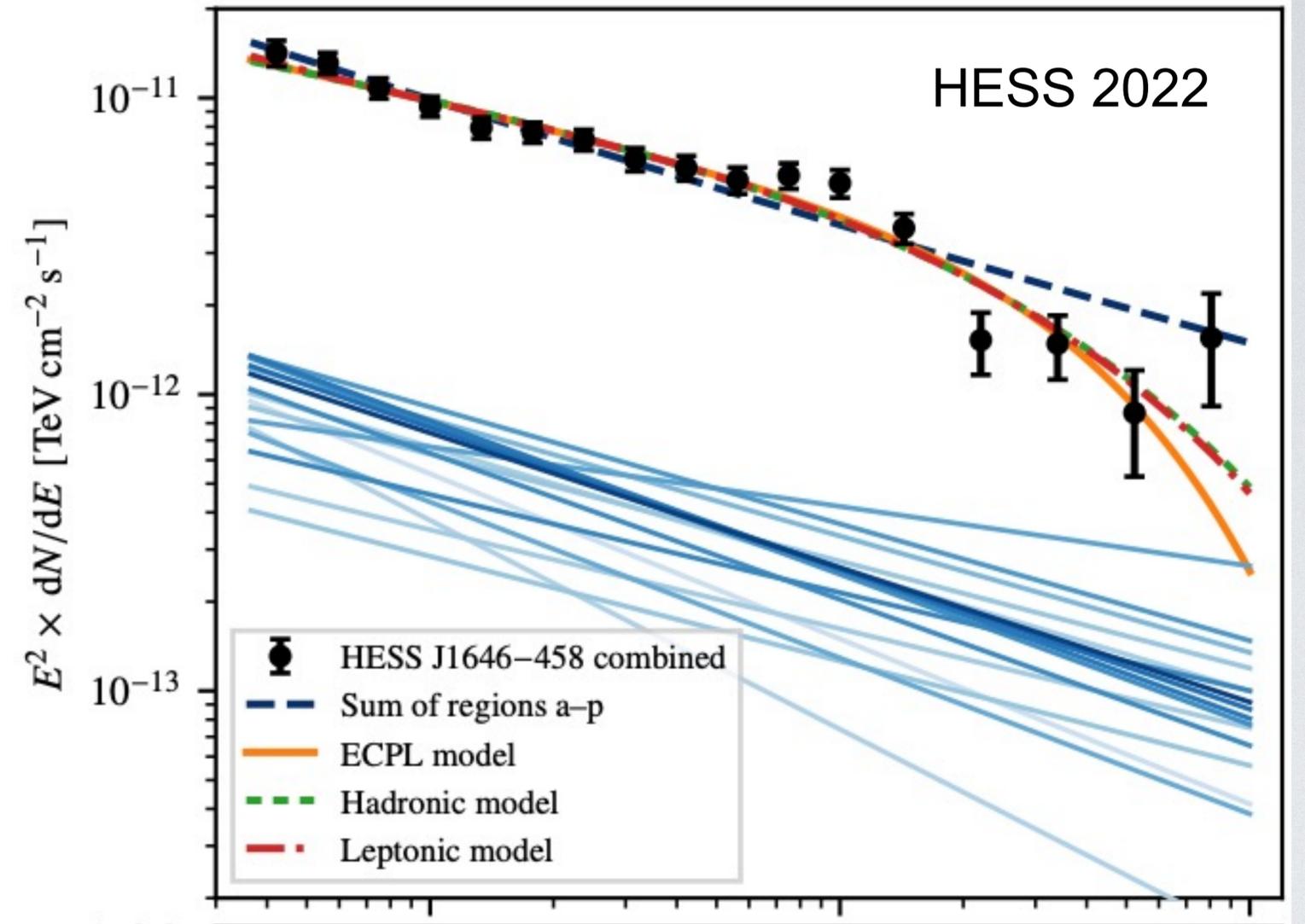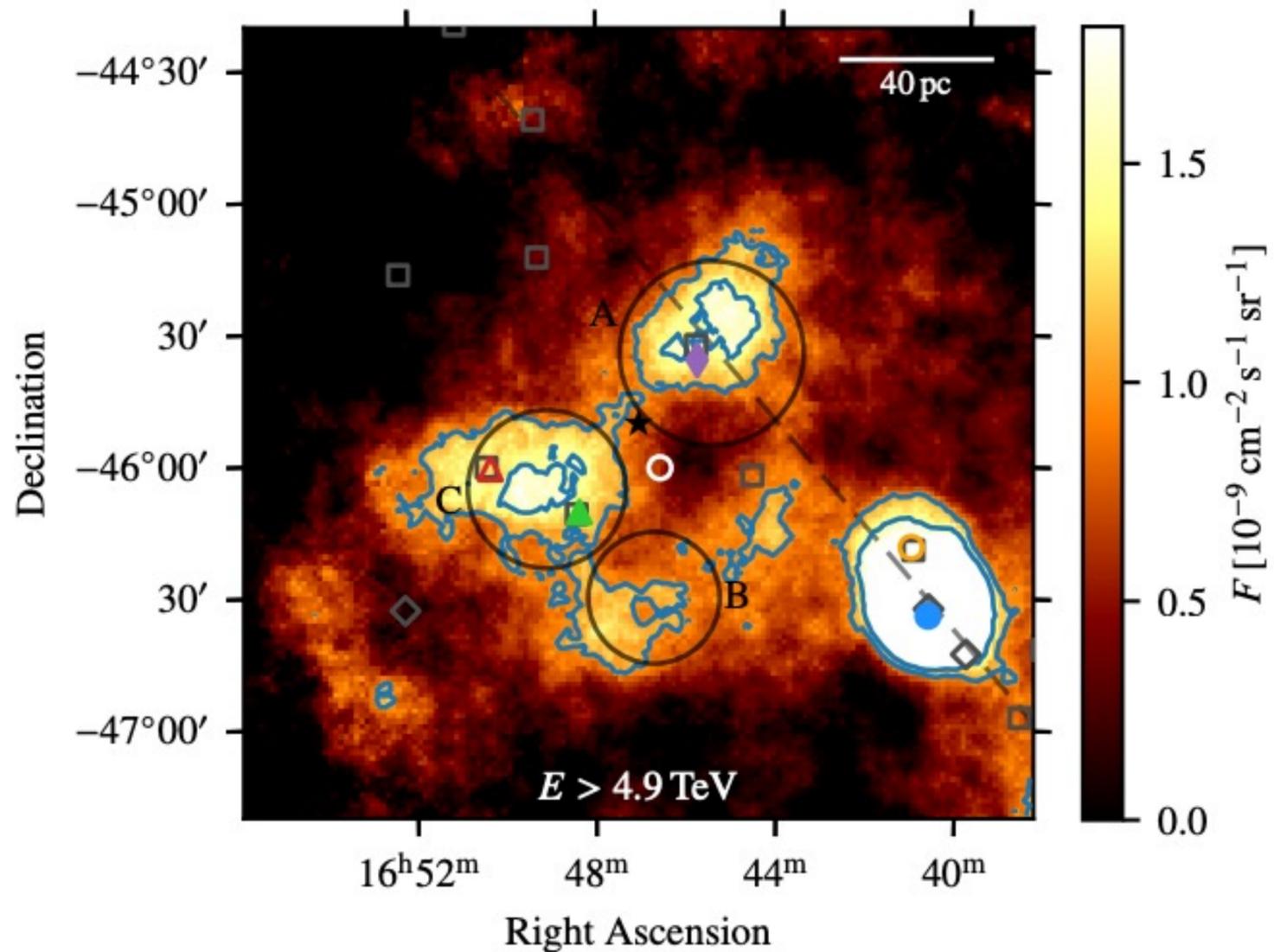
- extended emission up to more than 150 pc
- Hard spectrum up to 20 TeV
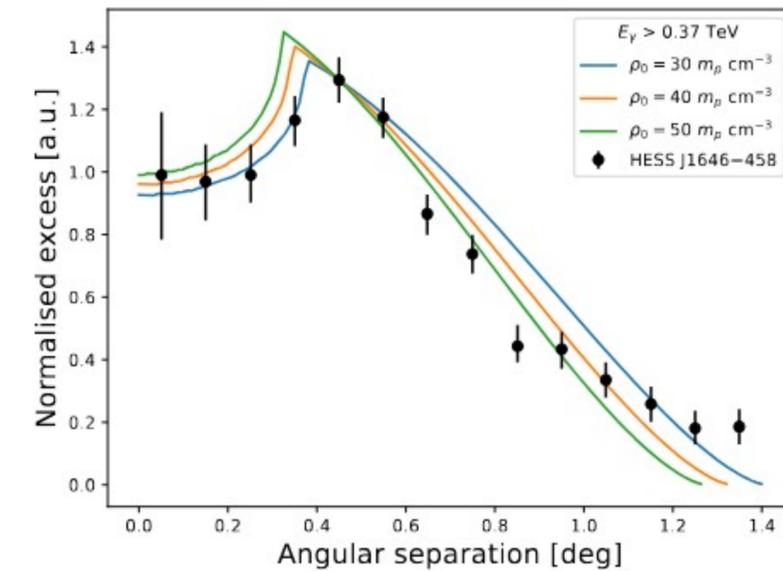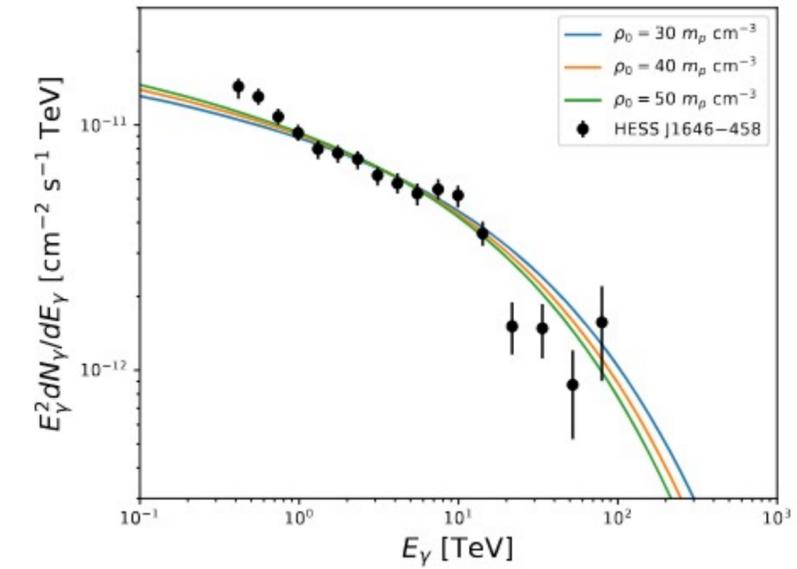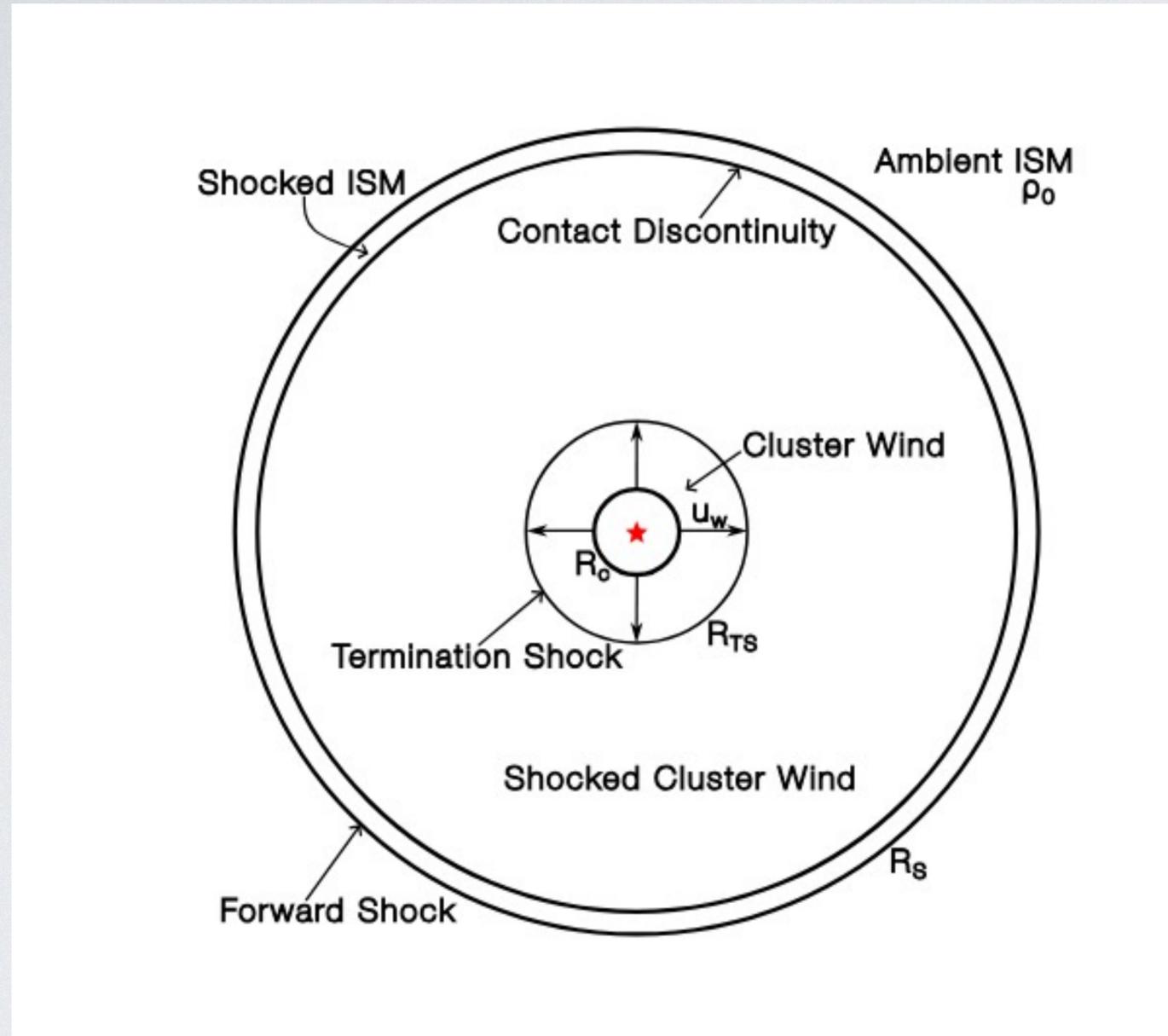
Shi & Yang JHEAP 2026

- Shell in gamma-rays
- Hadronic explanation possible when n > 20 cm^-3
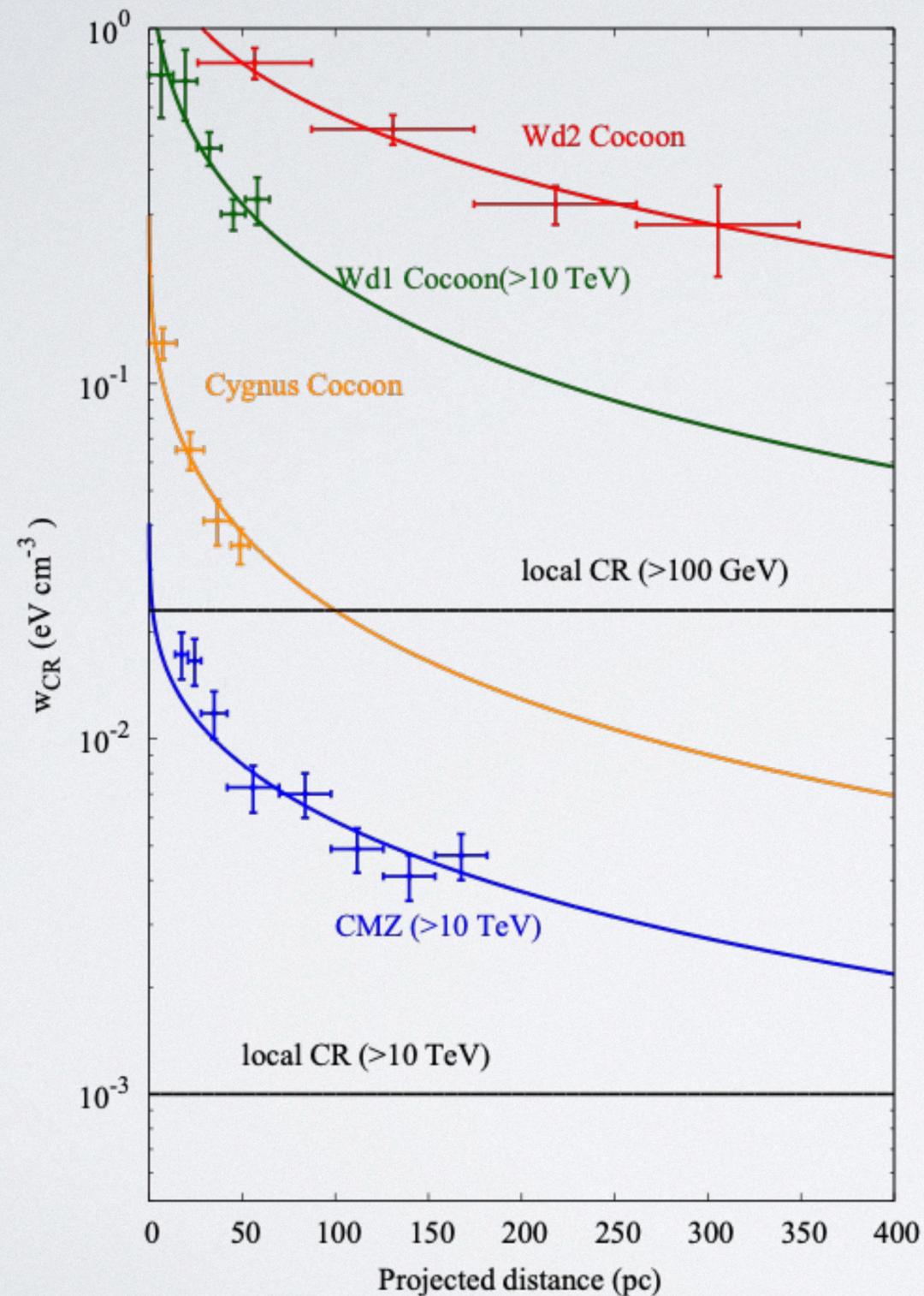
- CR distribution derived by gamma-ray profile and gas distributions

- All four sources (Wd1, Wd2, Cygnus cocoon, GC) show 1/r distribution of CRs

- In diffusion, 1/r profile implies a continuous injection (in the lifetime of clusters)

MASSIVE STAR CLUSTERS AS PEVATRONS?
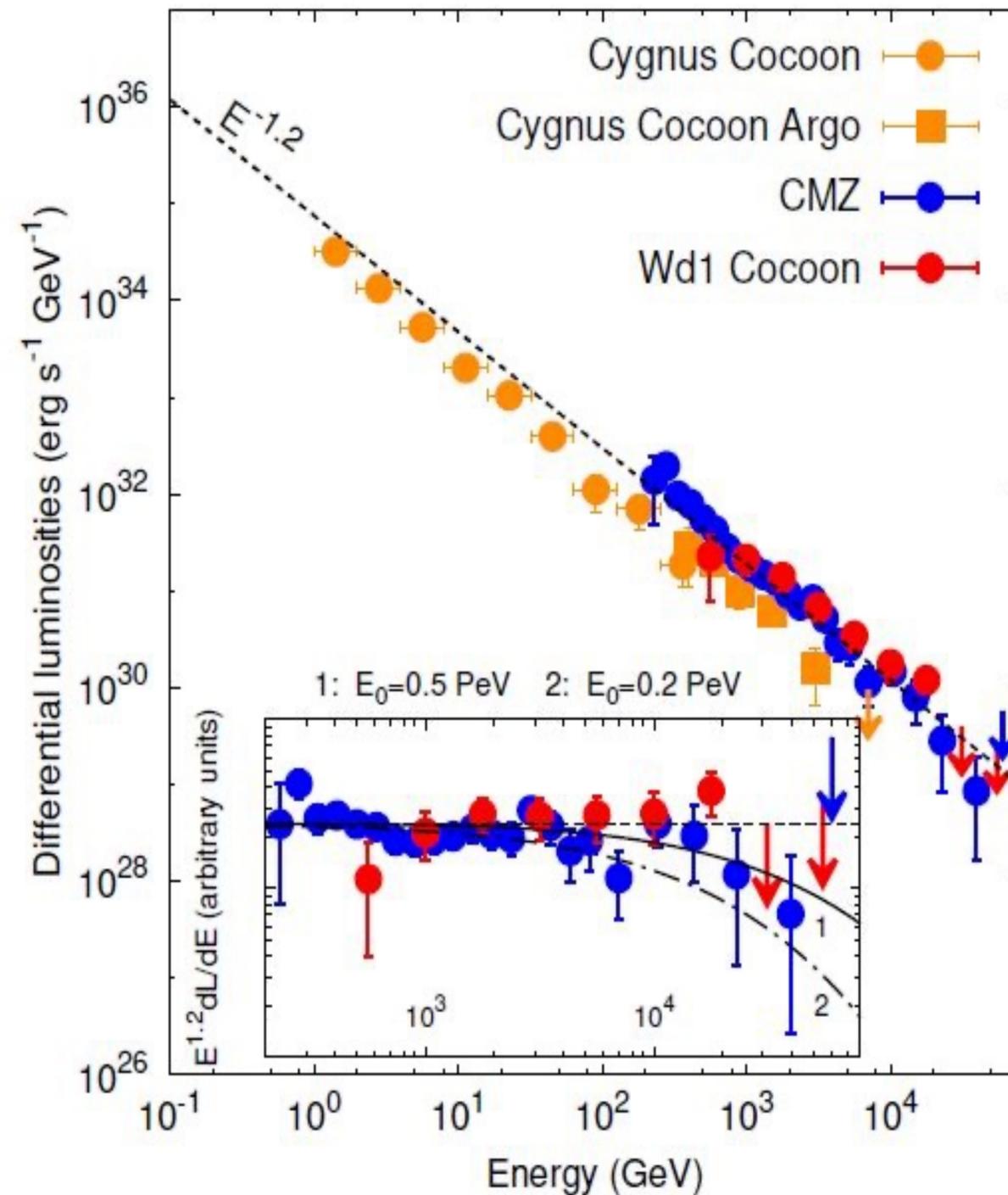
- Cygnus cocoon, Wd 1 and CMZ all emit multi-TeV gamma-ray.

- The spectrum of CMZ and Wd1 put lower limit of cutoff of parent proton spectrum to be several hundred TeV

- Difficult for IACT (large size, UHE)

- LHAASO is the ideal instrument!

LHAASO RESULTS

LHAASO ADVANTAGES
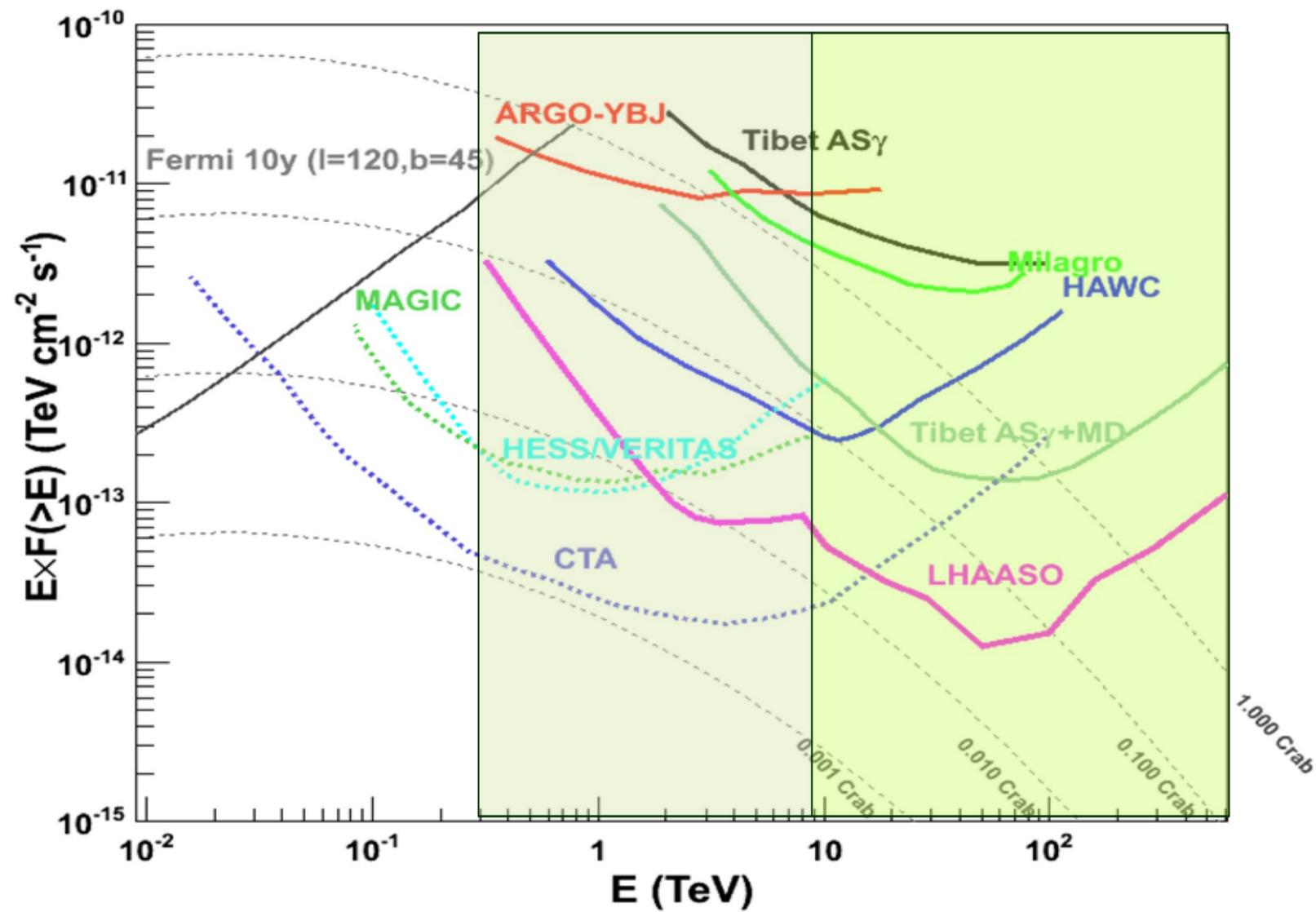
Unprecedented sensitivities above 20 TeV
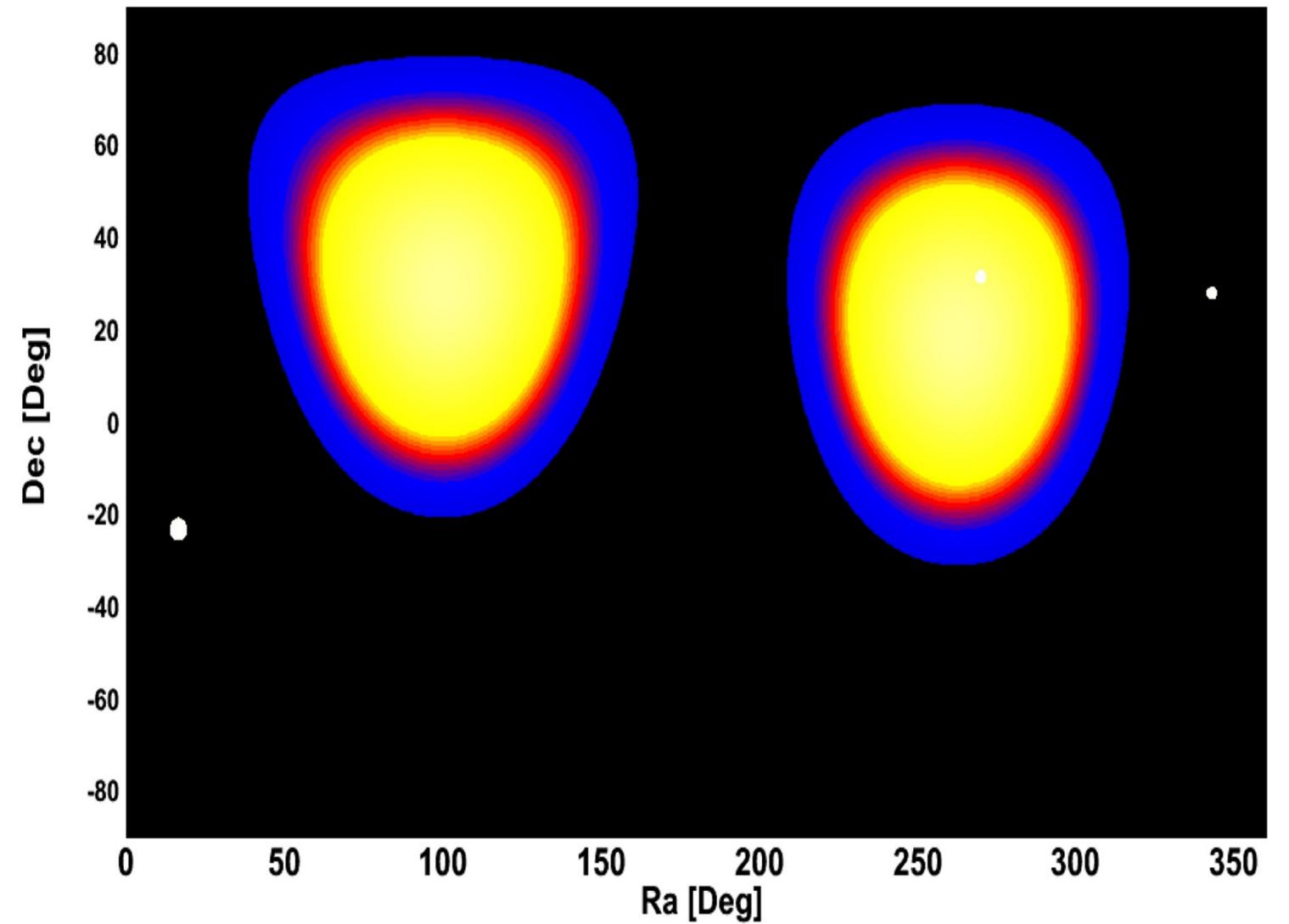
Large field of view

AN INCOMPLETE LIST FOR LHAASO

Name	RA	DEC	GeV counterpart	Former TeV observation
Cygnus Cocoon	20 33 12.0	+41 19 00	Yes	Argo detection
W43	18 47 32.4	-01 56 31	Yes	HESS J1848-018?
W40	18 31 26.5	-02 04 22	Yes	No
RSGC 1	18 37 58.0	-06 53 00	G25.0	2HWC 1837-065
h+χ Per	02 20 30.0	+57 08 00	No	No
Mc 9	18 34 08	−09 14 02	No	HESS J1834-087?
Mc 20	19 12 25	+09 57 40	No	HESS J1912+101?
Mc 23	19 30 13	+18 32 15	No	No
W49A	19 10 15	+09 06 05	W 49A?	No

Hints from first 12 sources

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	$\lesssim 2^f$	—	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	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	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	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

POSSIBLE ASSOCIATIONS IN FIRST CATALOG

| Source name	Components	Ra	Dec	$\sigma_{p,95,stat}$	r_{39}	TS
1LHAASO J1837−0654u	WCDA(8)*	279.39	-6.90	0.06	0.34±0.01	1049.8
	KM2A(10)	279.31	-6.86	0.09	0.33±0.04	331.2
1LHAASO J1929+1846u	WCDA(29)	292.34	18.77	0.10	0.49±0.02	416.2
	KM2A(34)	292.04	18.97	0.08	<0.21	130.0
1LHAASO J1834−0831	WCDA(7)	278.62	-8.53	0.22	0.40±0.07	96.0
	KM2A(9)	278.44	-8.38	0.28	0.40±0.07	68.9

RSGC 1

MC 23

MC 9

Caveats :
- YMCs lie in very dense regions
- All the current catalogs are far from completeness
- New YMC catalog using GAIA data (within 3 kpc)
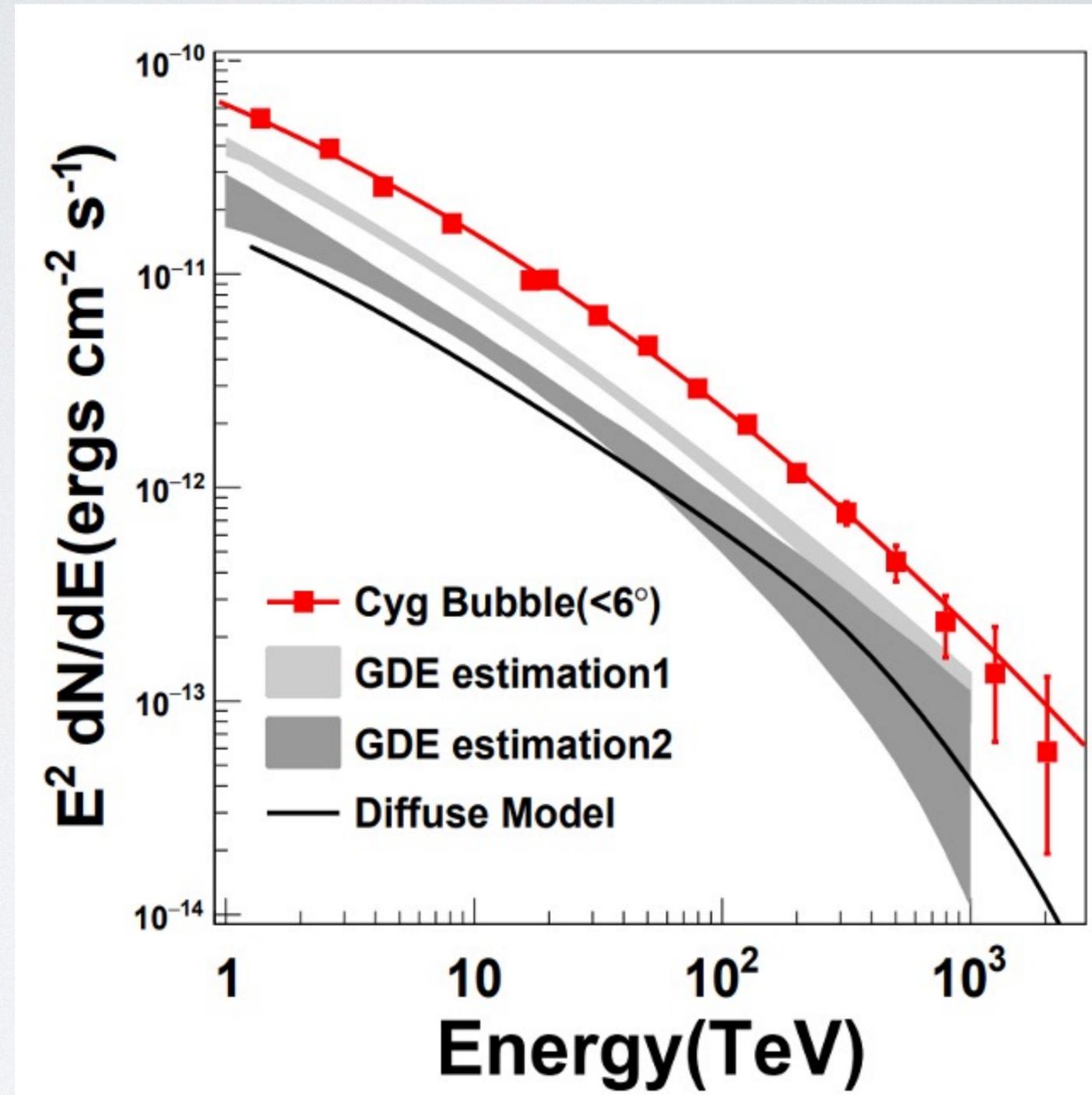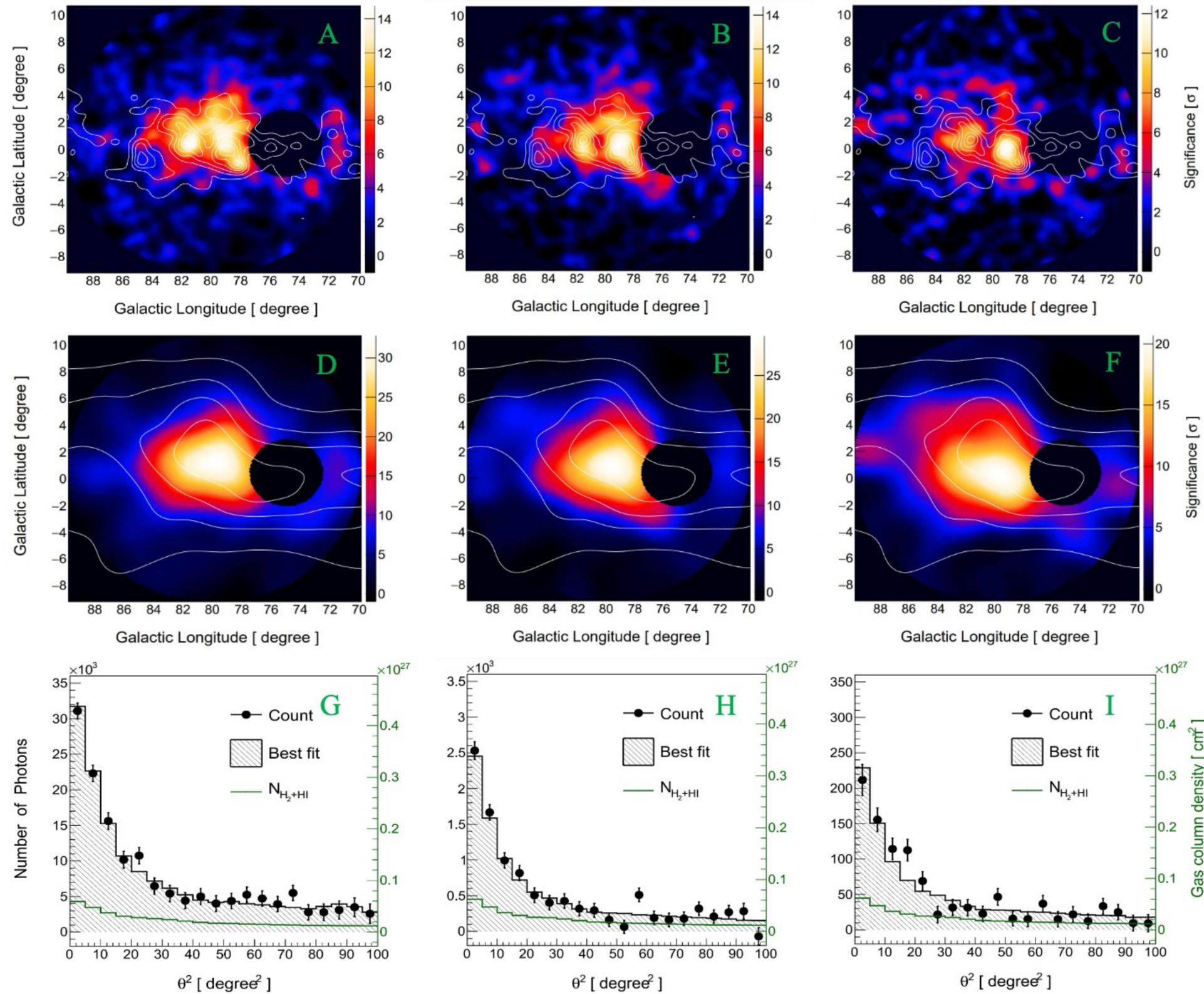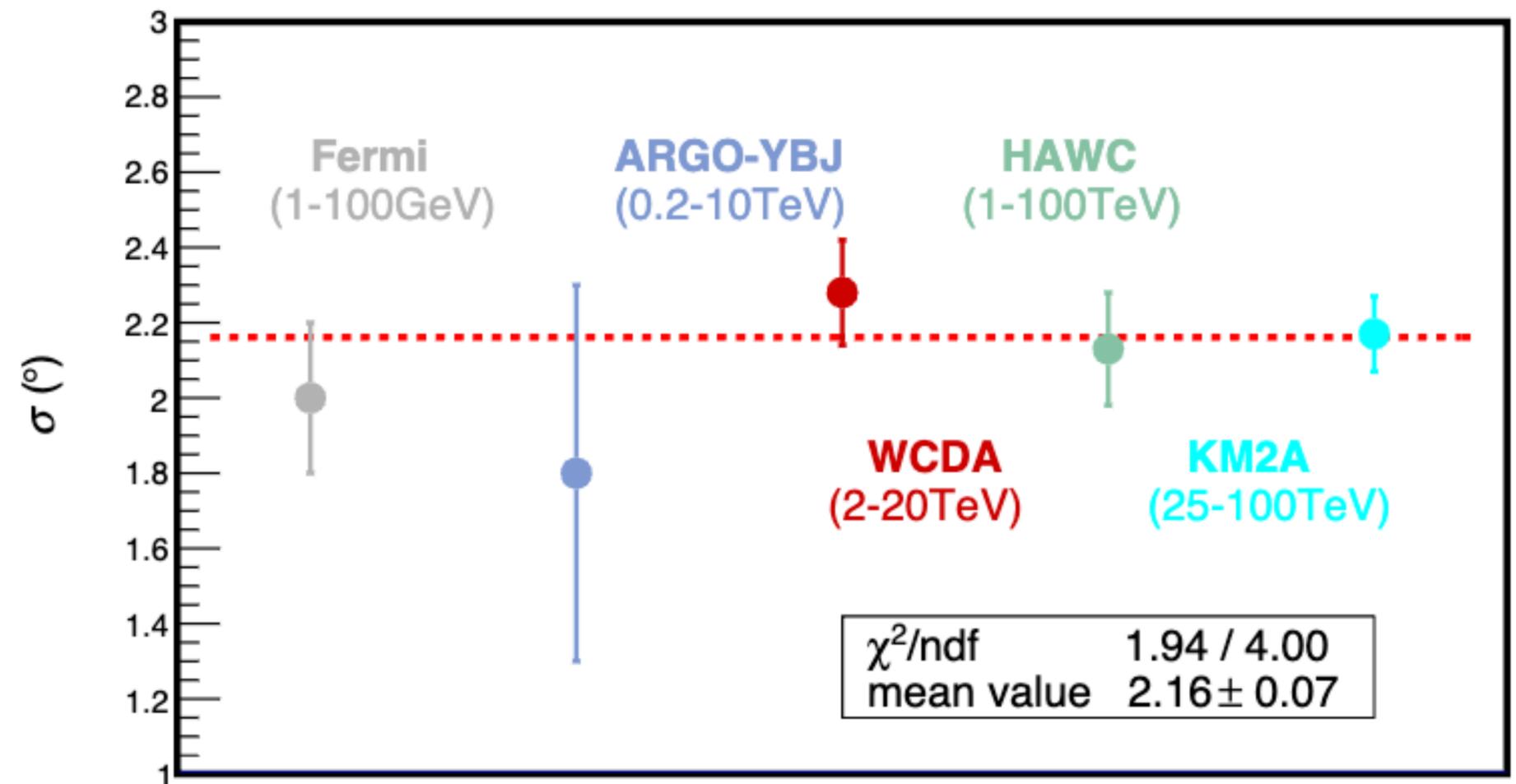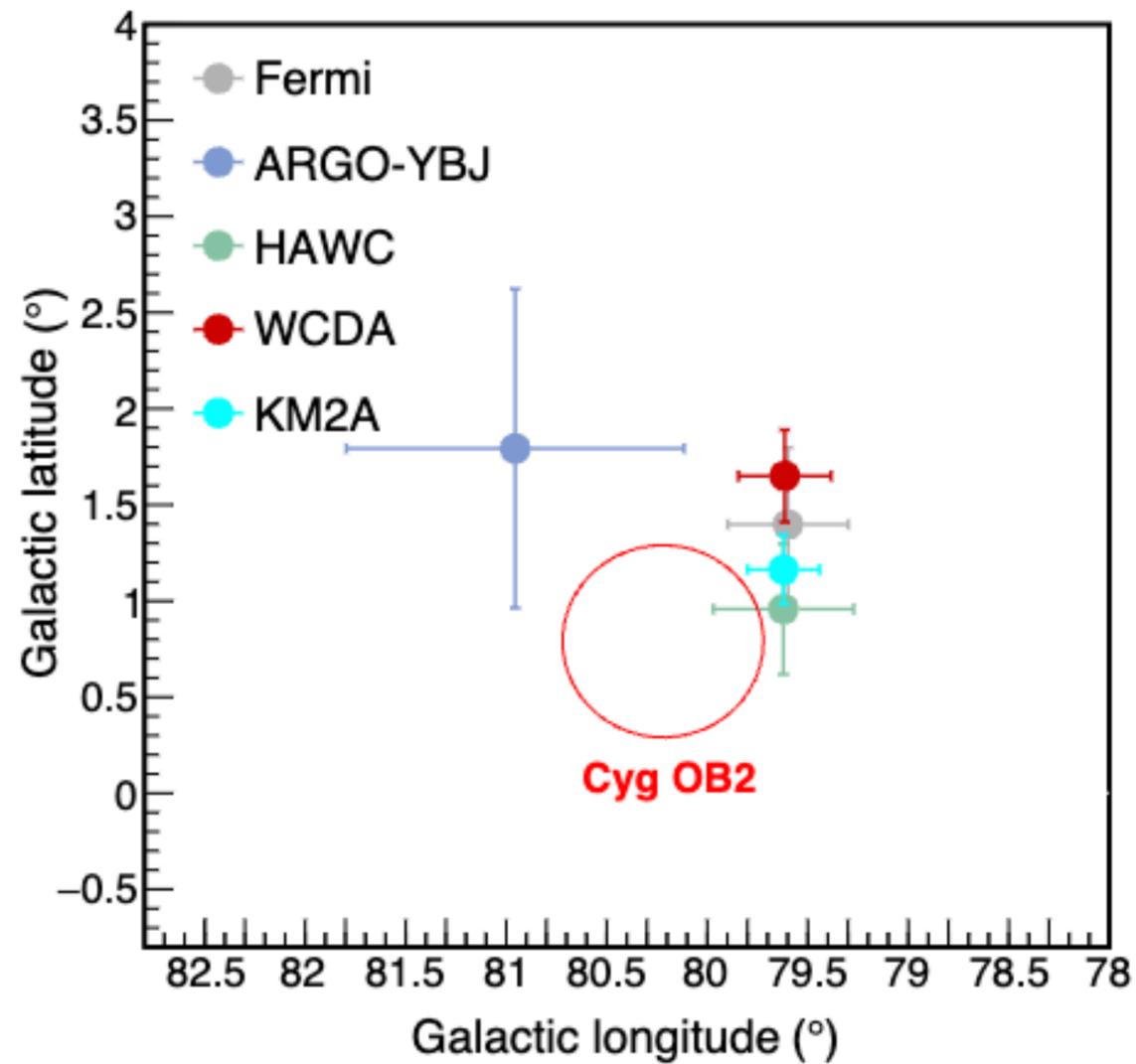- FAST radio recombination line to search new YMCs
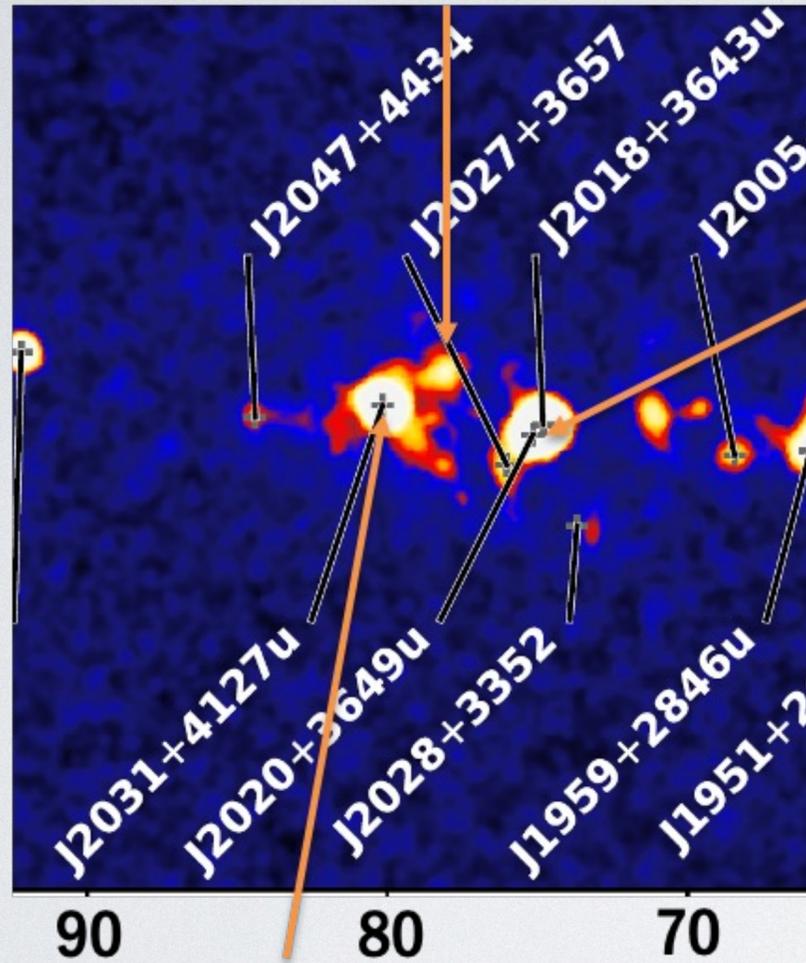
Galactic diffuse gamma-ray background (GDE) must be taken into account

Huge bubble beyond ~10 degrees (200 pc)

Energy independent morphology
Favor hadronic origin

| 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
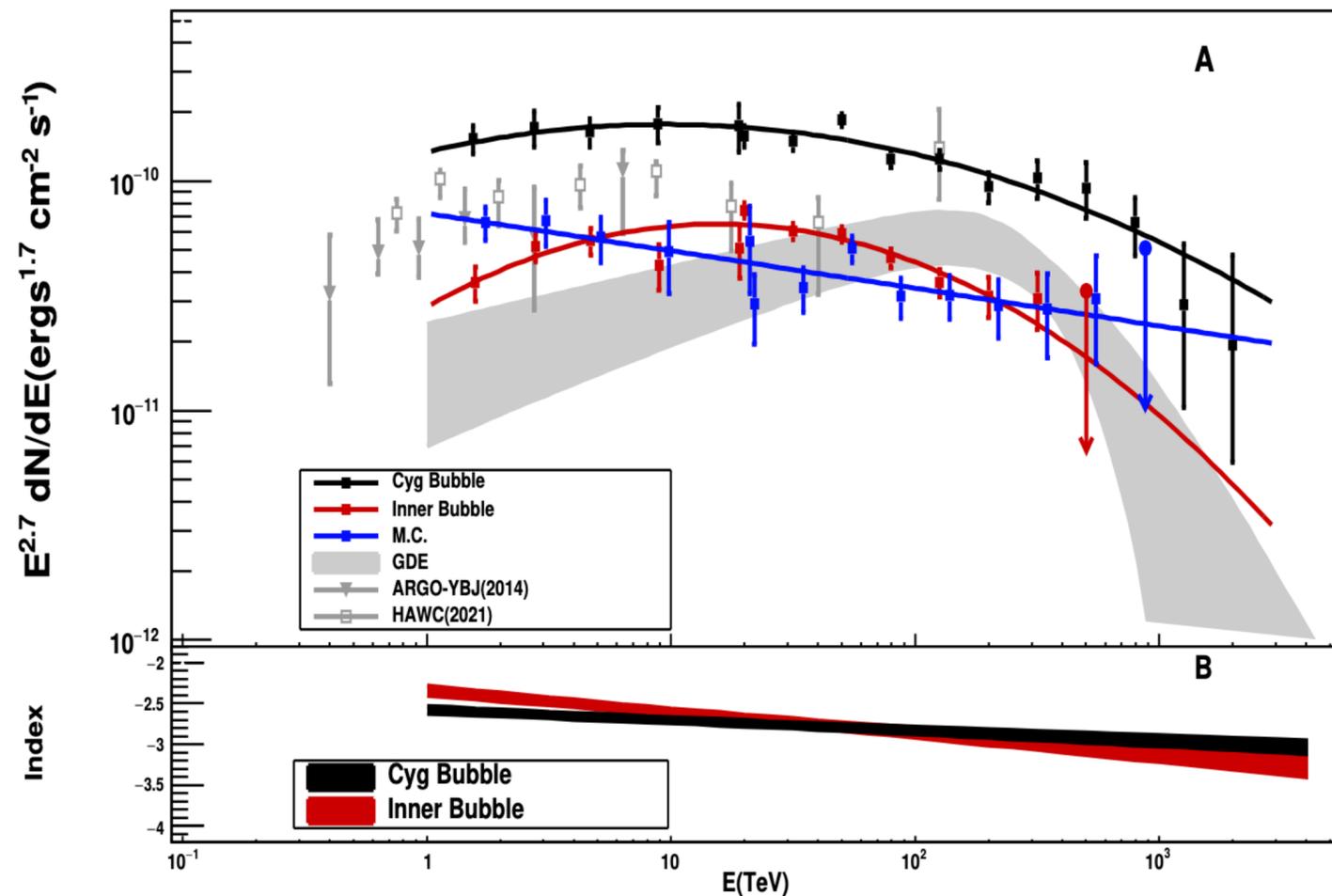
likelihood fitting derived 4 components:
1. inner bubble(Cocoon)
2. Cygnus bubble (~10 degrees, associated with HI gas)
3. Hotspots associated with molecular gas
4. Bright central source

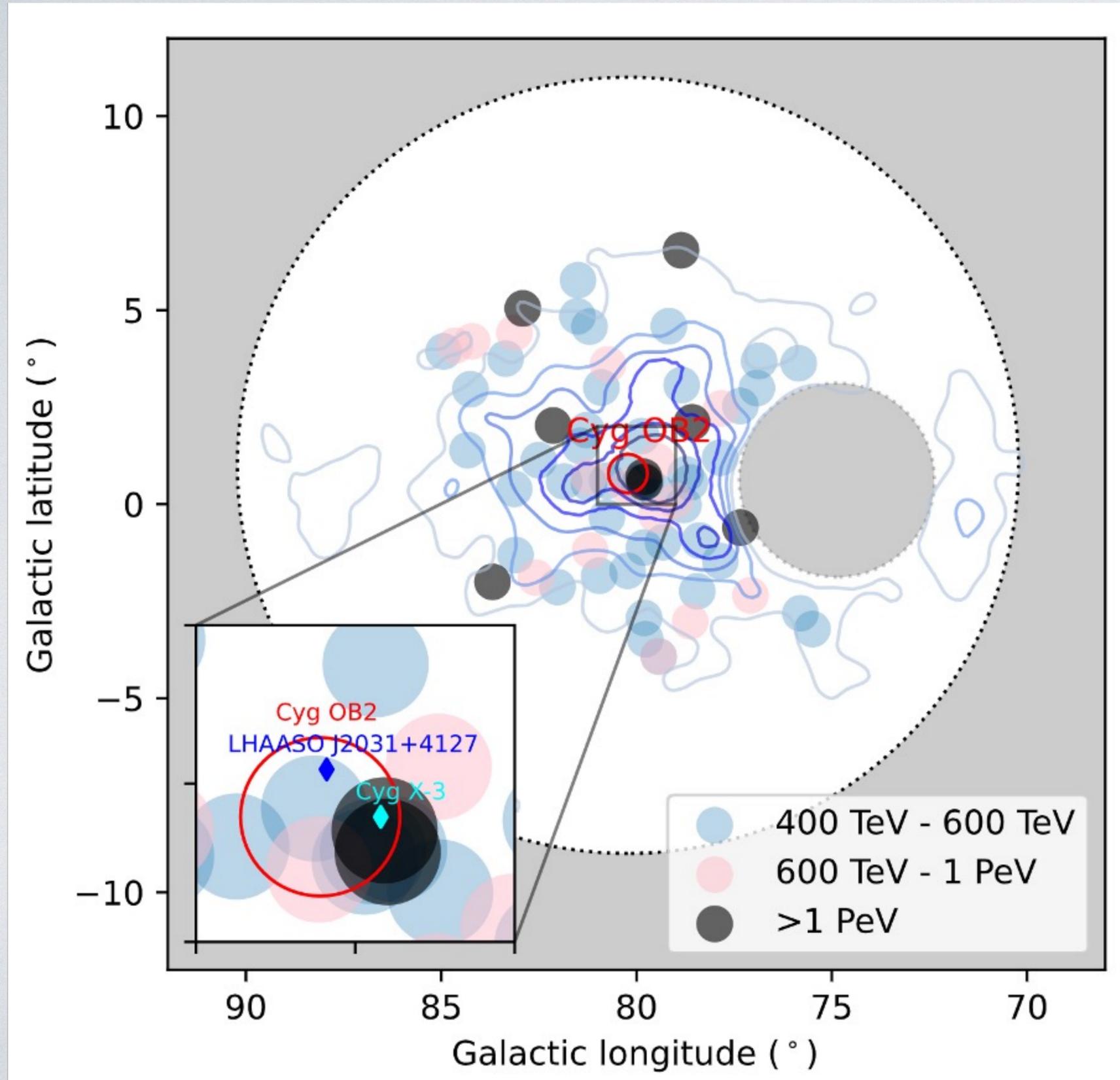**J2032+4127 (PWN/BINARY) are already subtracted from the analysis**

-10 to 20 km/s for CO
-20 to 30 km/s for HI are integrated
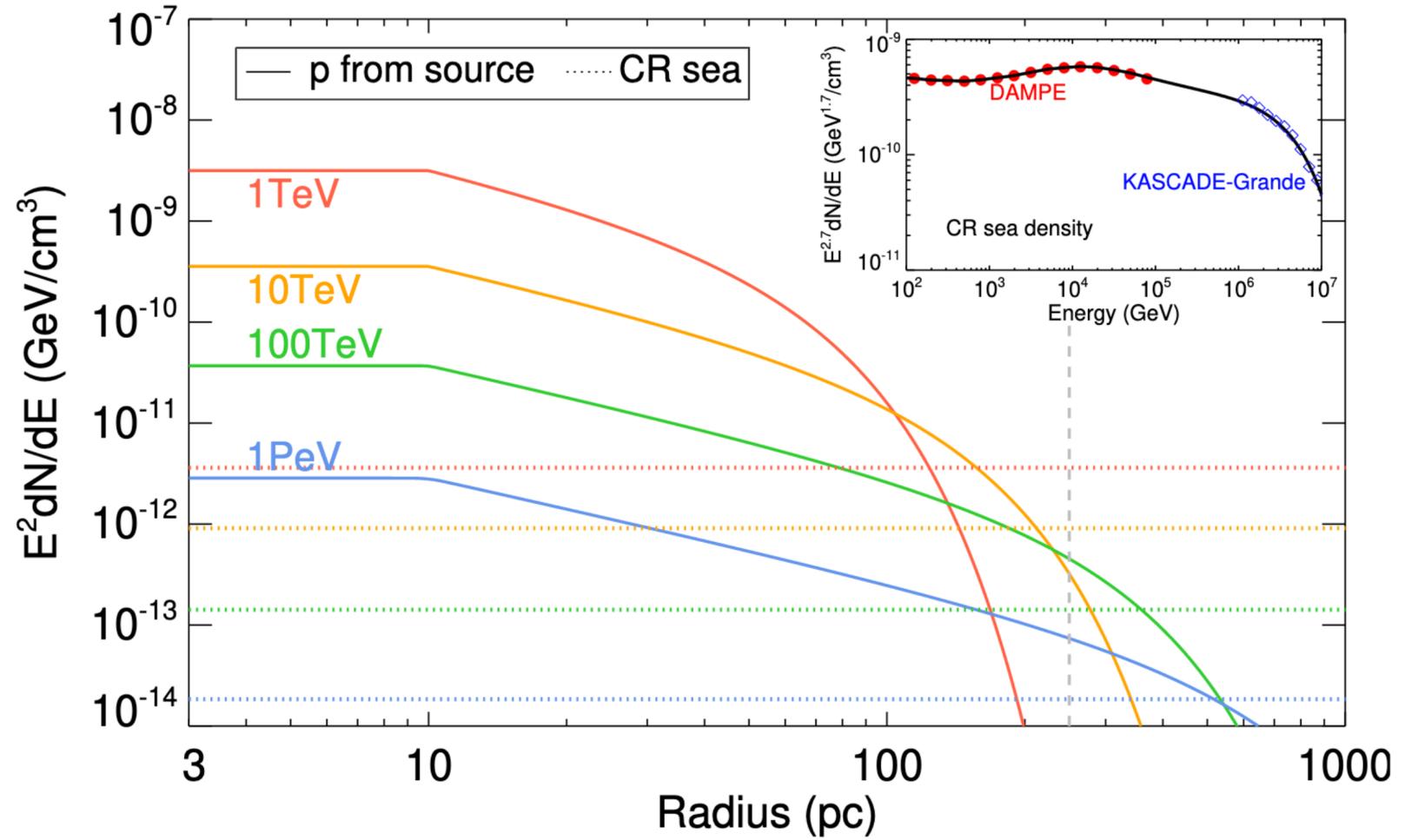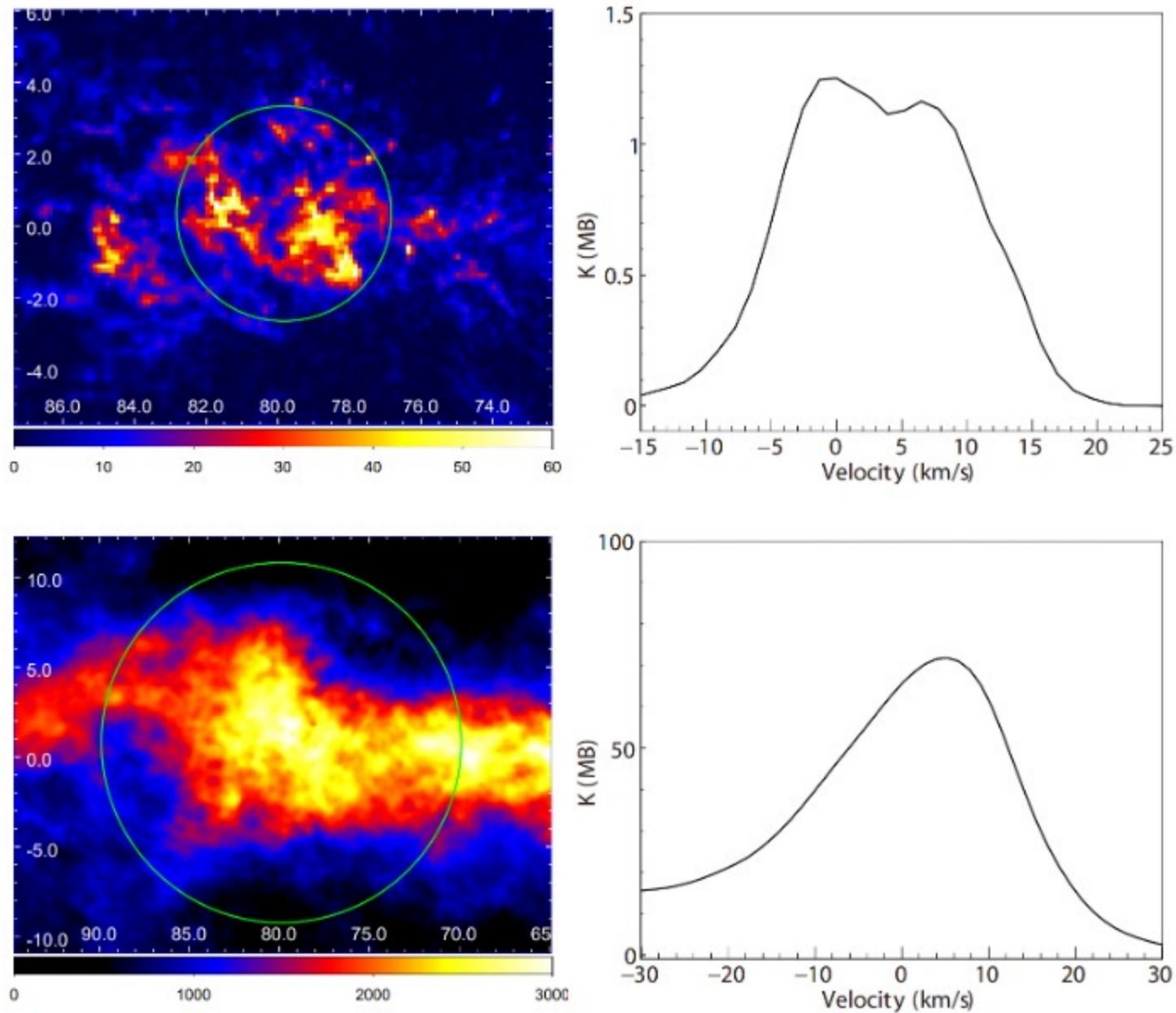
CR injected by the source dominate
the CR sea up to several hundred pc

HIGHEST ENETGY PHOTONS


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≈**0.5**
2/8 PeV event from central 0.5 deg region
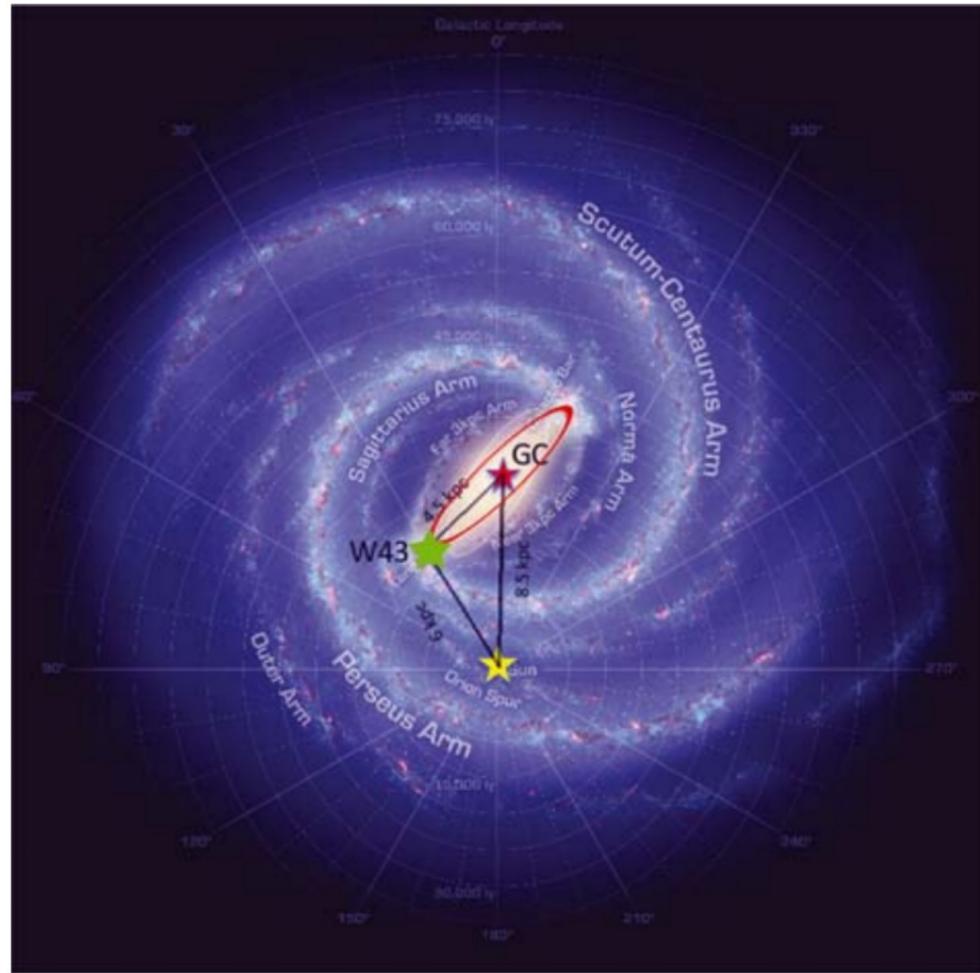
Overdensity at the centre – injection!

E (PeV)	δE (PeV)	N_e	N_μ	$\theta(°)$	$D_{edge}(m)$	$\psi(°)$
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

# Schematic fitting of observations
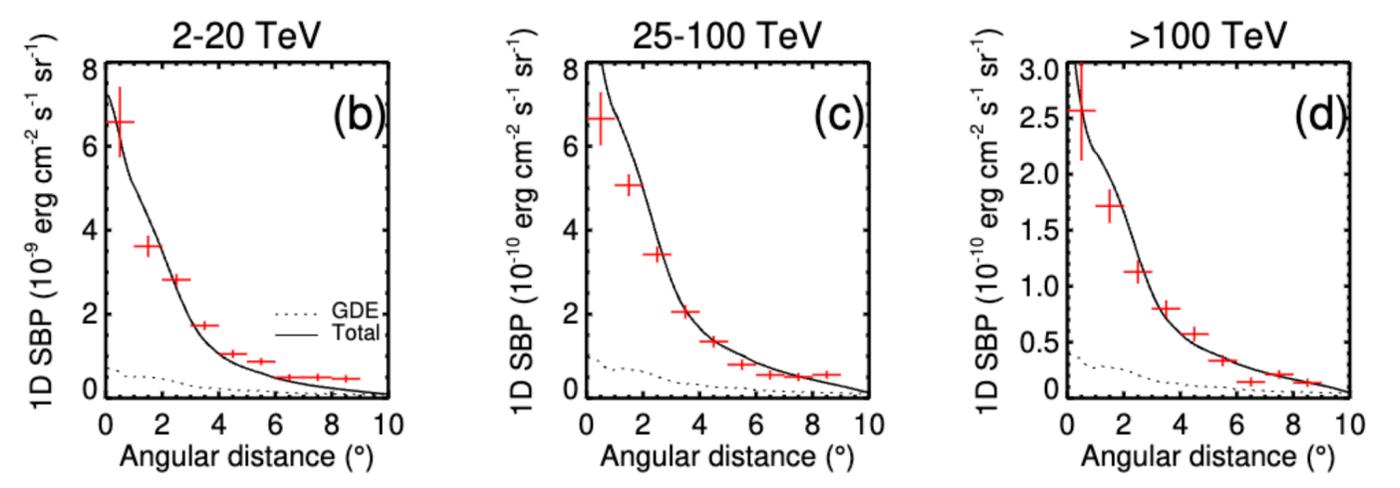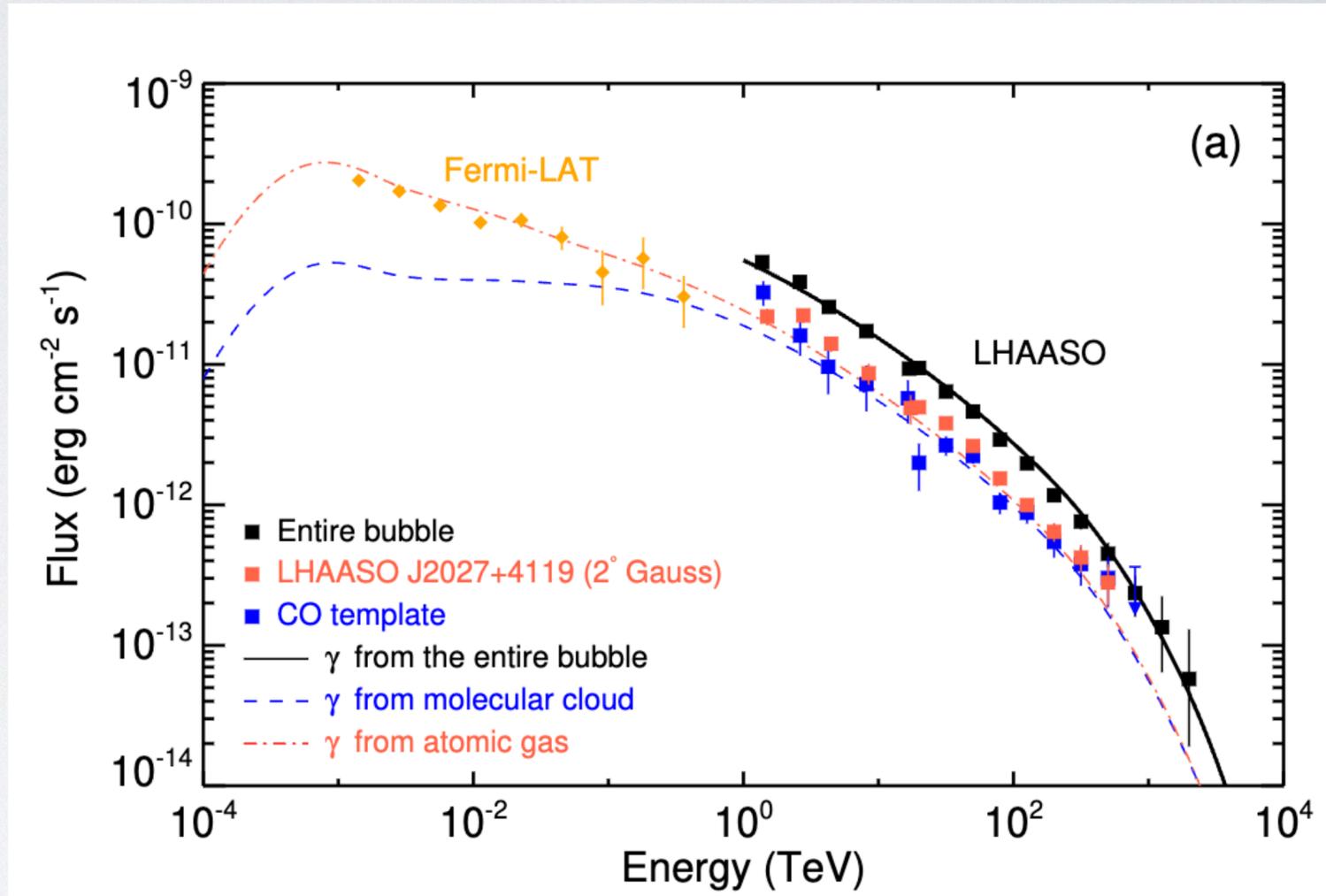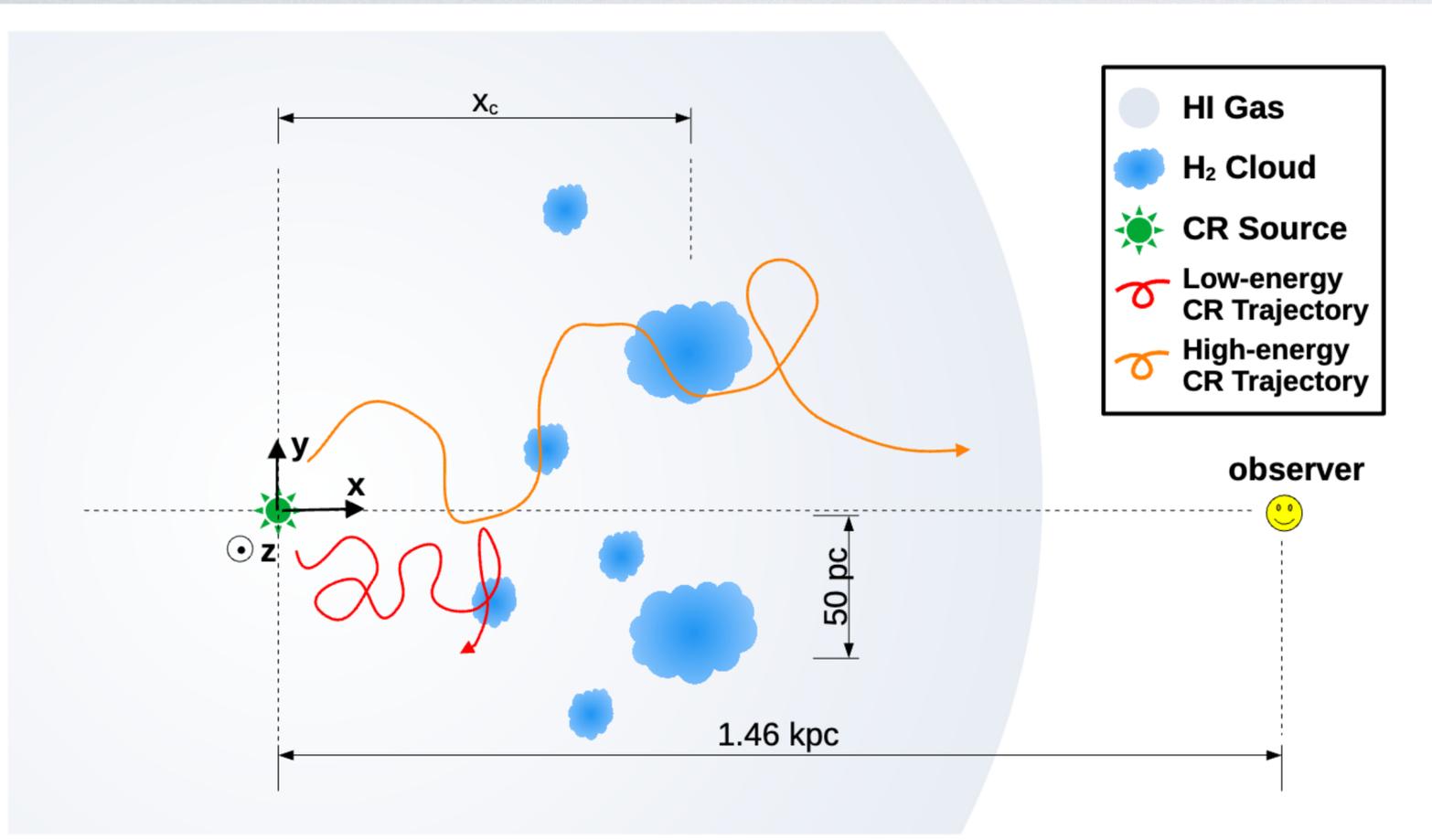
comments:
The inner bubble (cocoon/gaussian) component is **just functional representation** of the data
The similar spectrum reveal same origin of "inner bubble '' and Entire bubble

Fig. 9. Artist view of the Galaxy seen face-on with the "long bar" outlined by a red ellipse (Churchwell et al. 2009). W43 is located at the expected transition zone between the bar-dominated region ($R_{GC} < 5$ kpc) and the normal Galactic disk.

Yang & Wang 2020
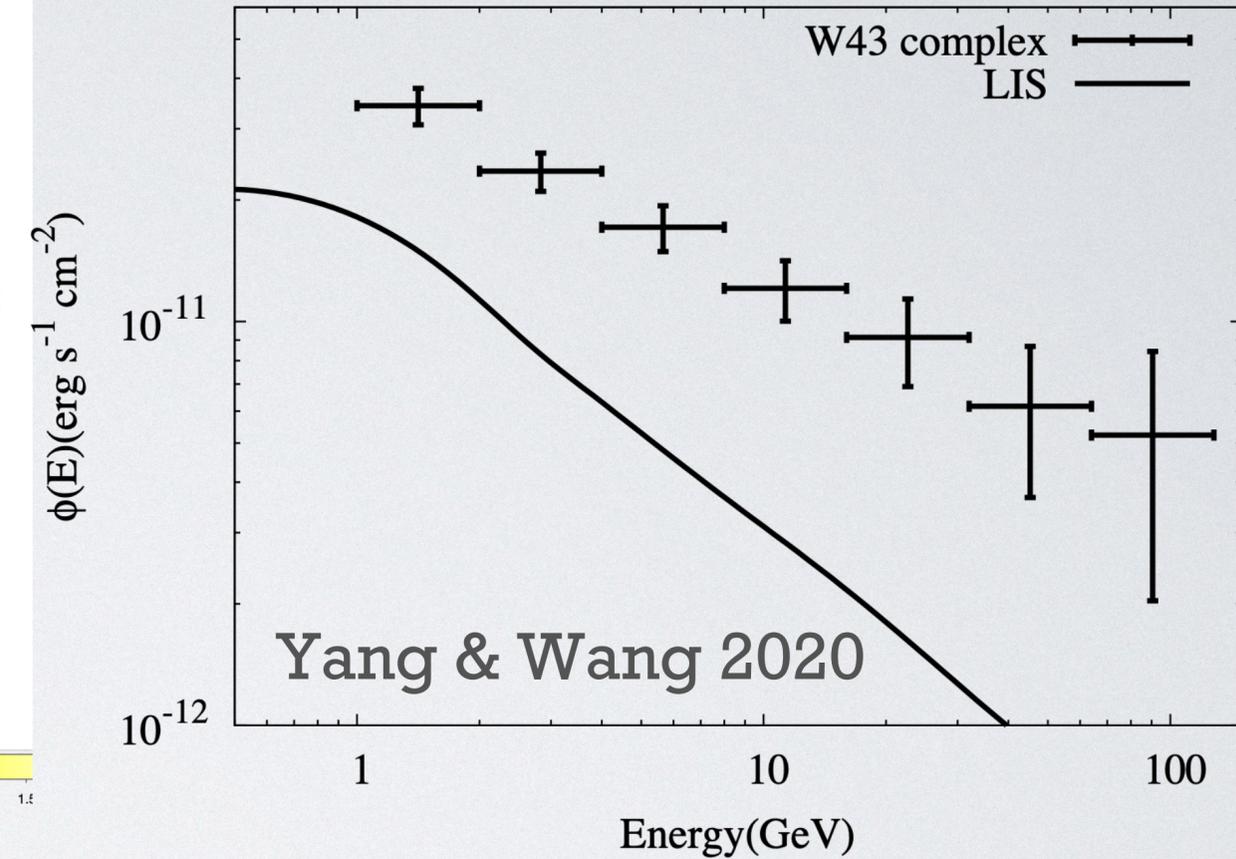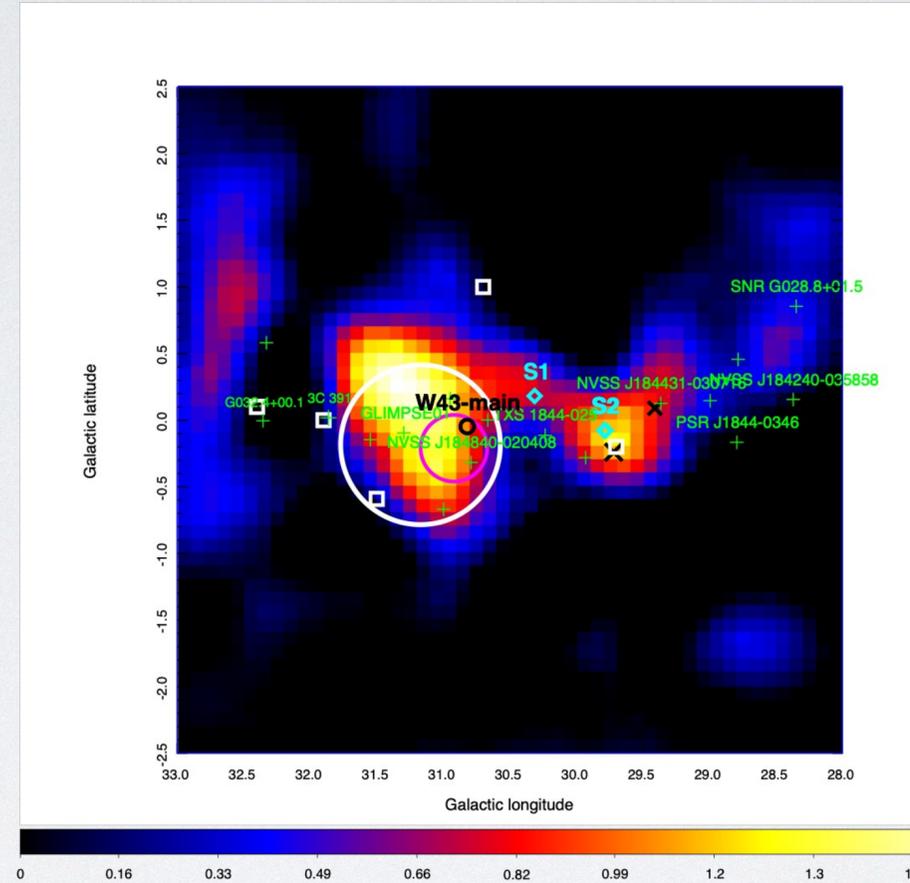
- Galactic mini star burst
- Contribute 10% of the Galactic star formation rate
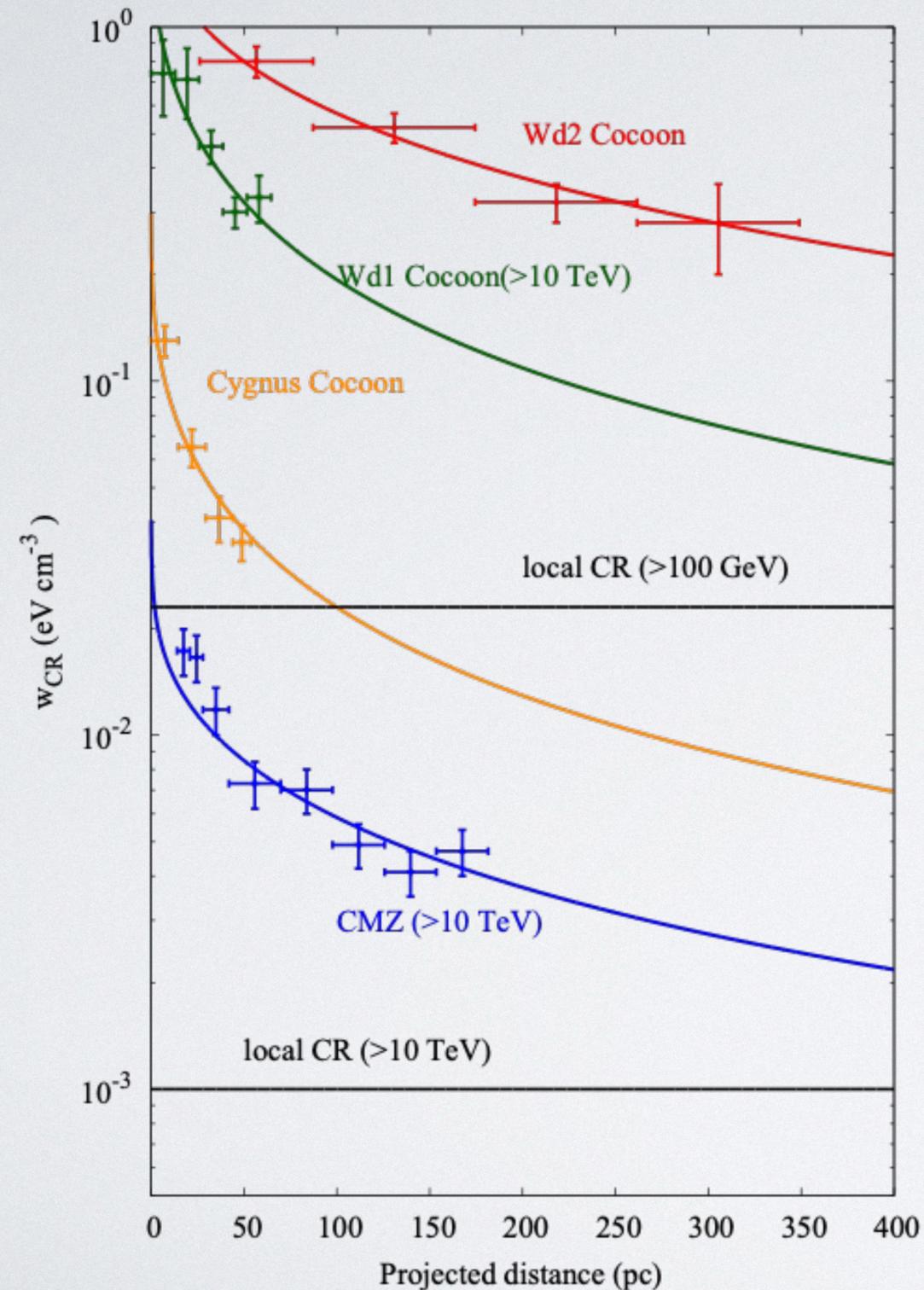- Huge HII region excited by central WR/OB cluster
- GeV detection

LHAASO VIEW ON W43

> 25TeV

> 100TeV

(a)
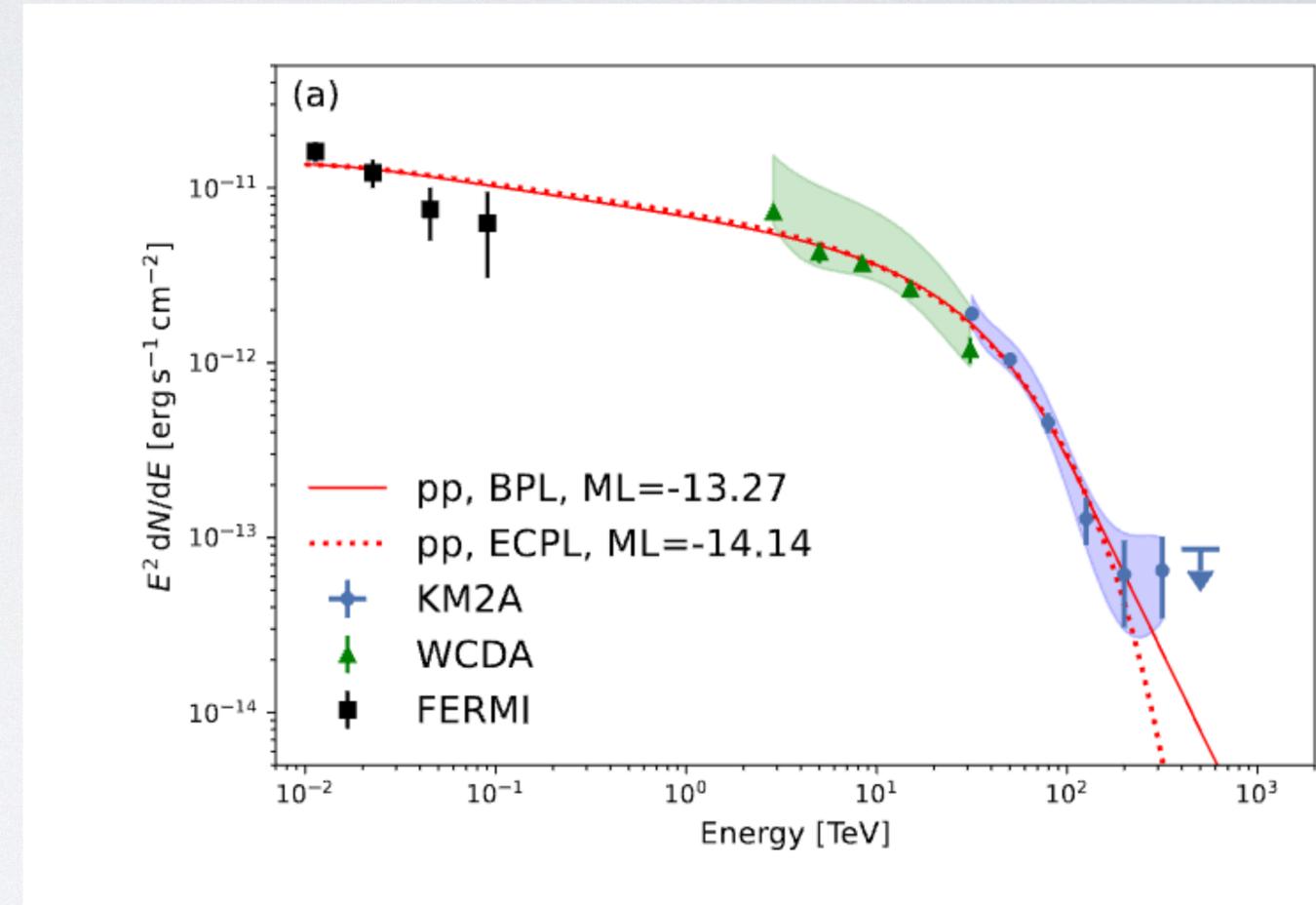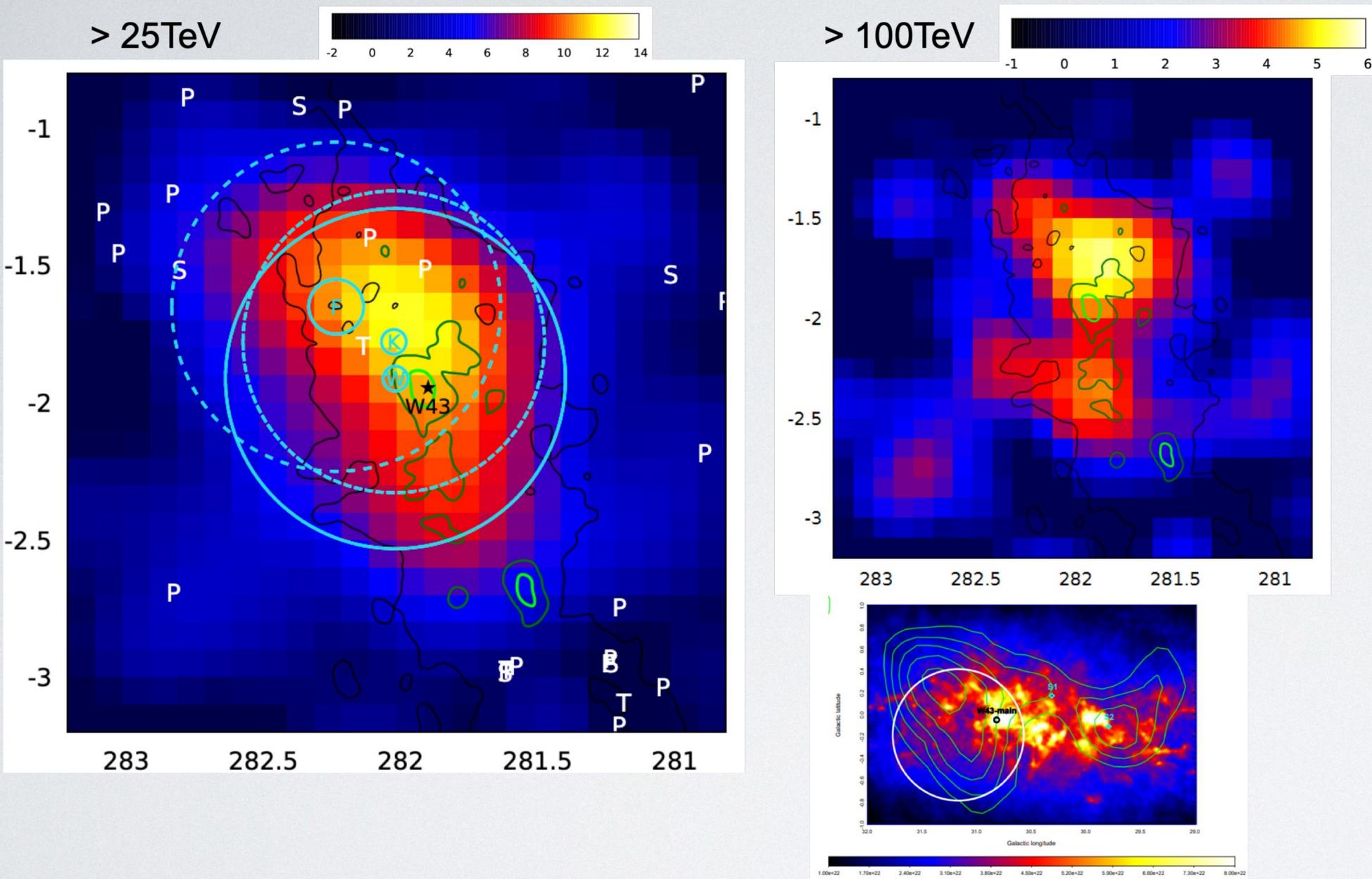
- •UHE gamma-ray emission reveal good correlation with dense gas
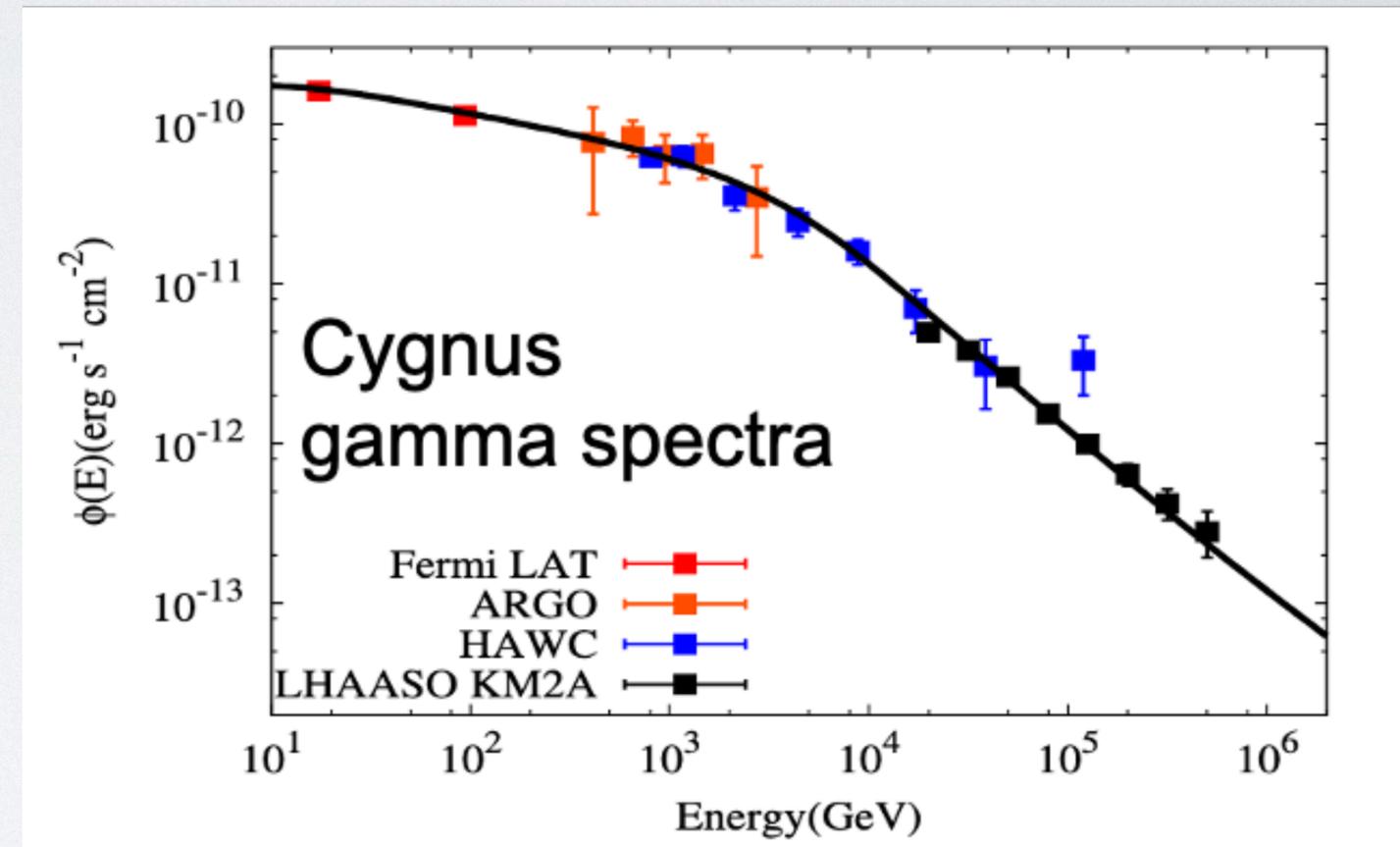- •Spectrum up to 400 TeV
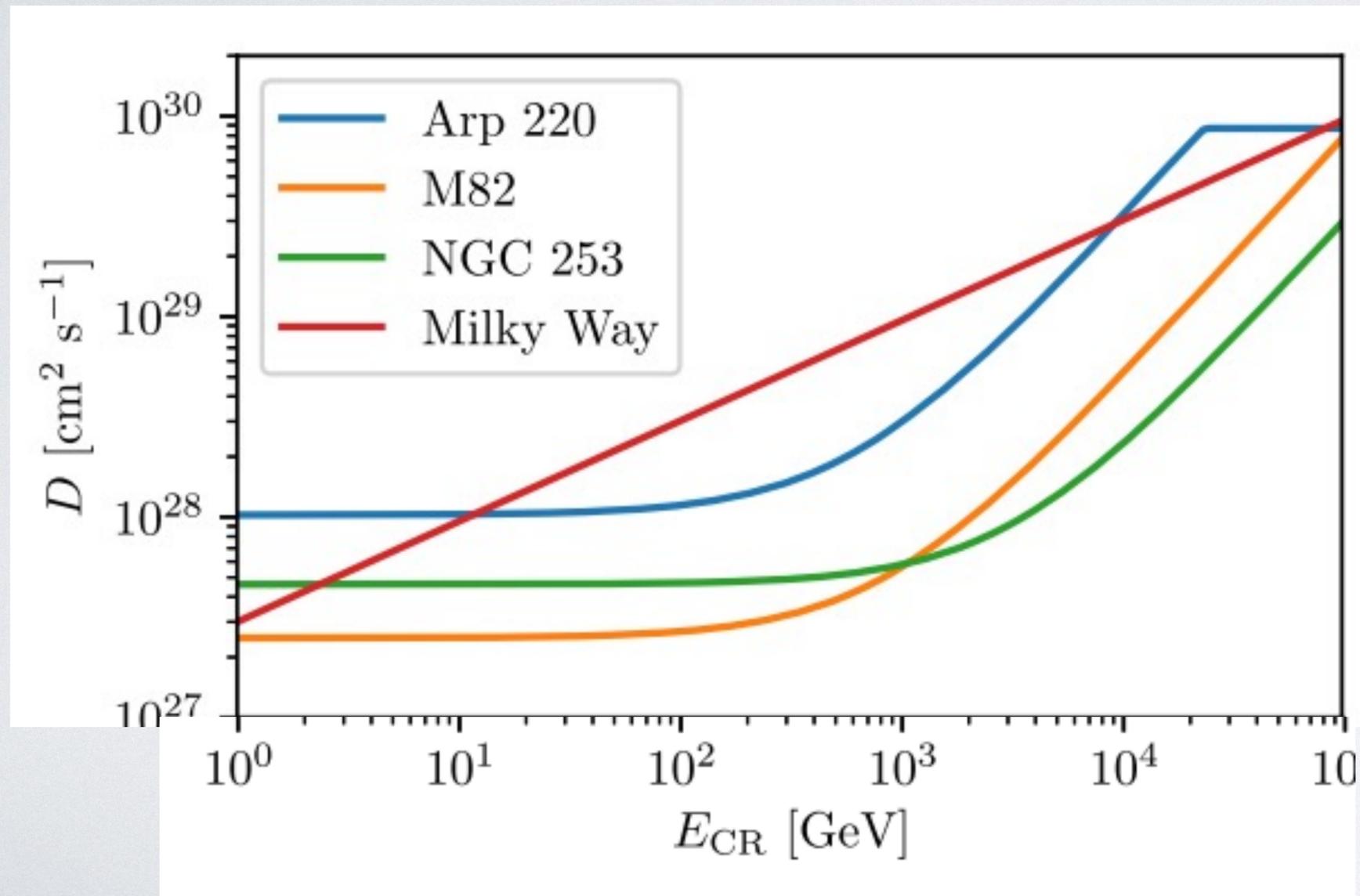
CONFINEMENT OF CRS

RADIAL DISTRIBUTION OF COSMIC RAYS

- CR distribution derived by gamma-ray profile and gas distributions

- All four sources (Wd1, Wd2, Cygnus cocoon, GC) show 1/r distribution of CRs

- In diffusion, 1/r profile implies a **continuous** injection, multiple SNRs or stellar winds
- **Slow diffusion** required by the total energy budget

Aharonian, Yang & de ona Wilhelmi Nature Astronomy(2019) 3,561

- Possible energy independent escape from Source regions (normal assumption if CR streaming dominate the magnetic turbulence, e.g. Krumholz 2019)
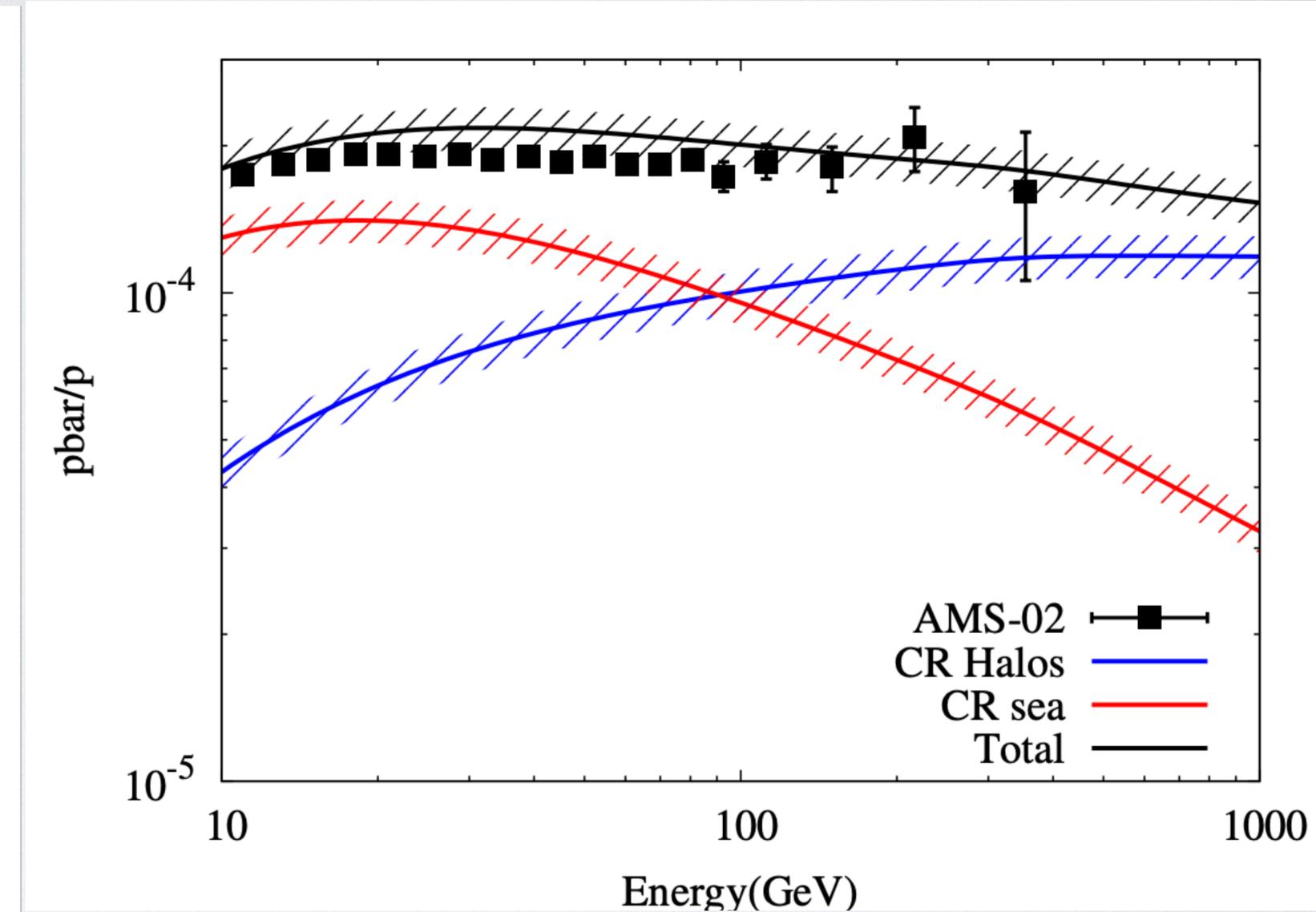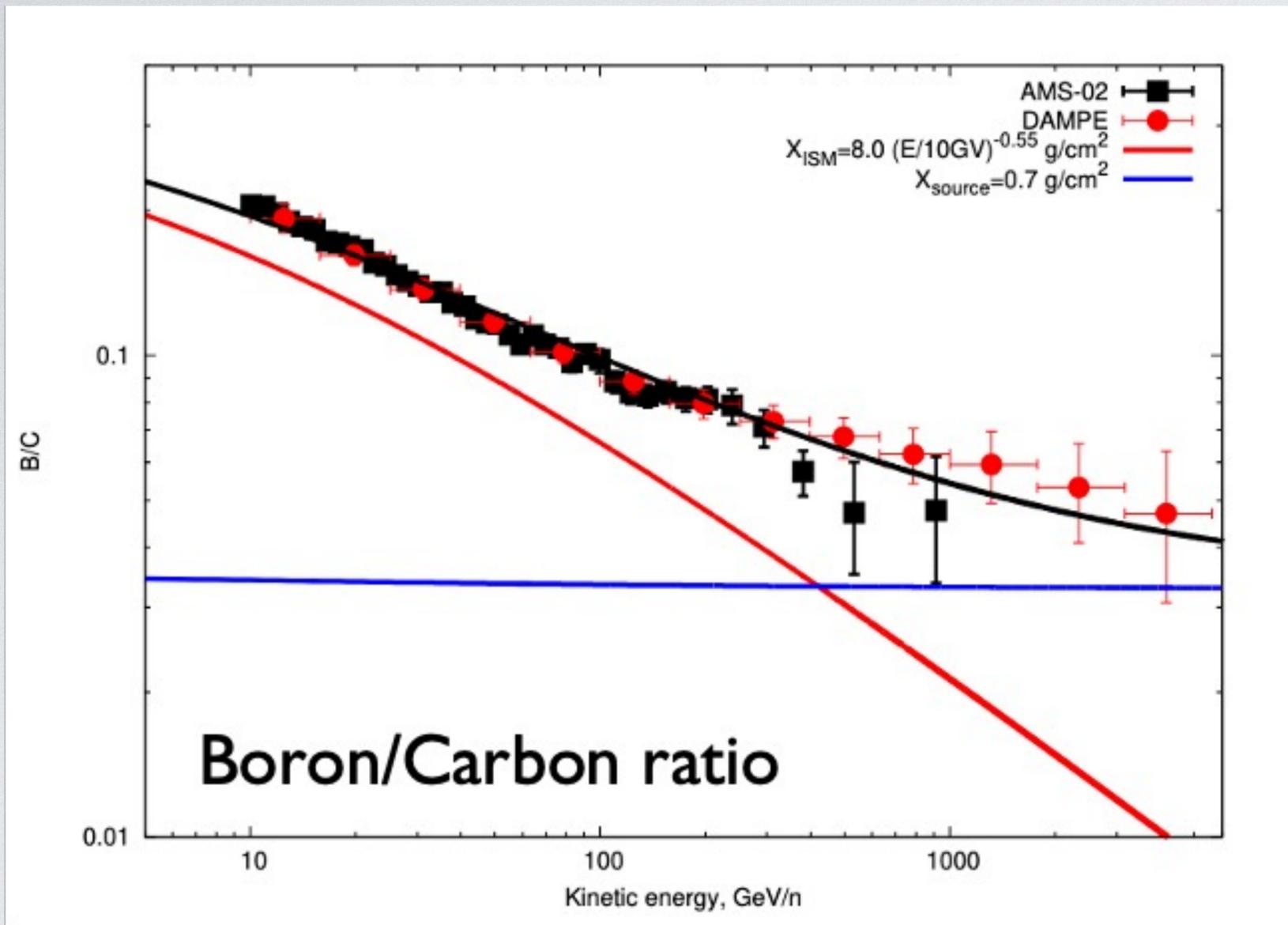

- Effective confinement (slow diffussion) of CR near accelerators
- energy independent below ~10 TeV, from Cygnus spectra

CONTRIBUTION TO DIFFUSE GAMMA
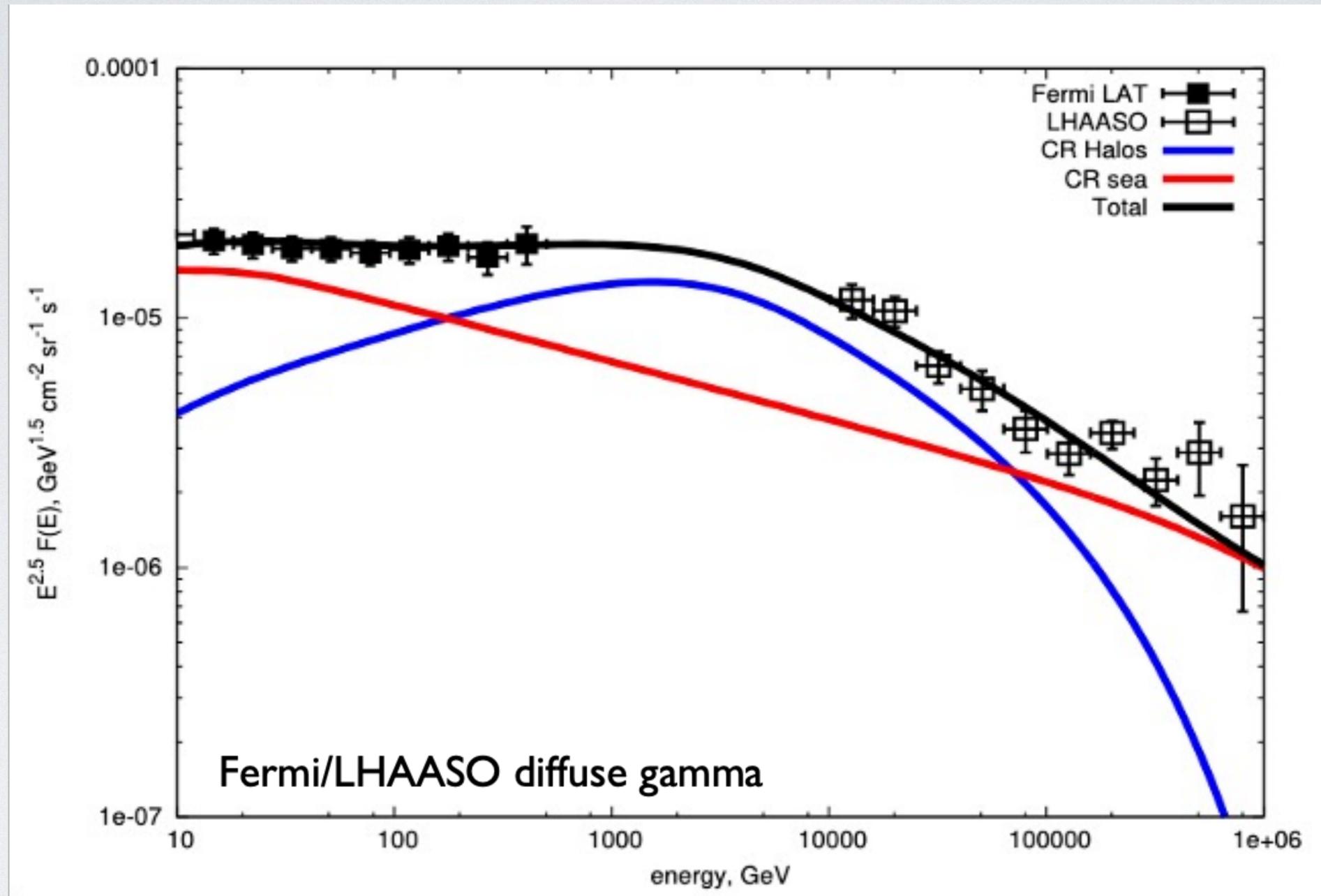
Yang and Aharonian, Phys. Rev. D 100, 063020(2019)
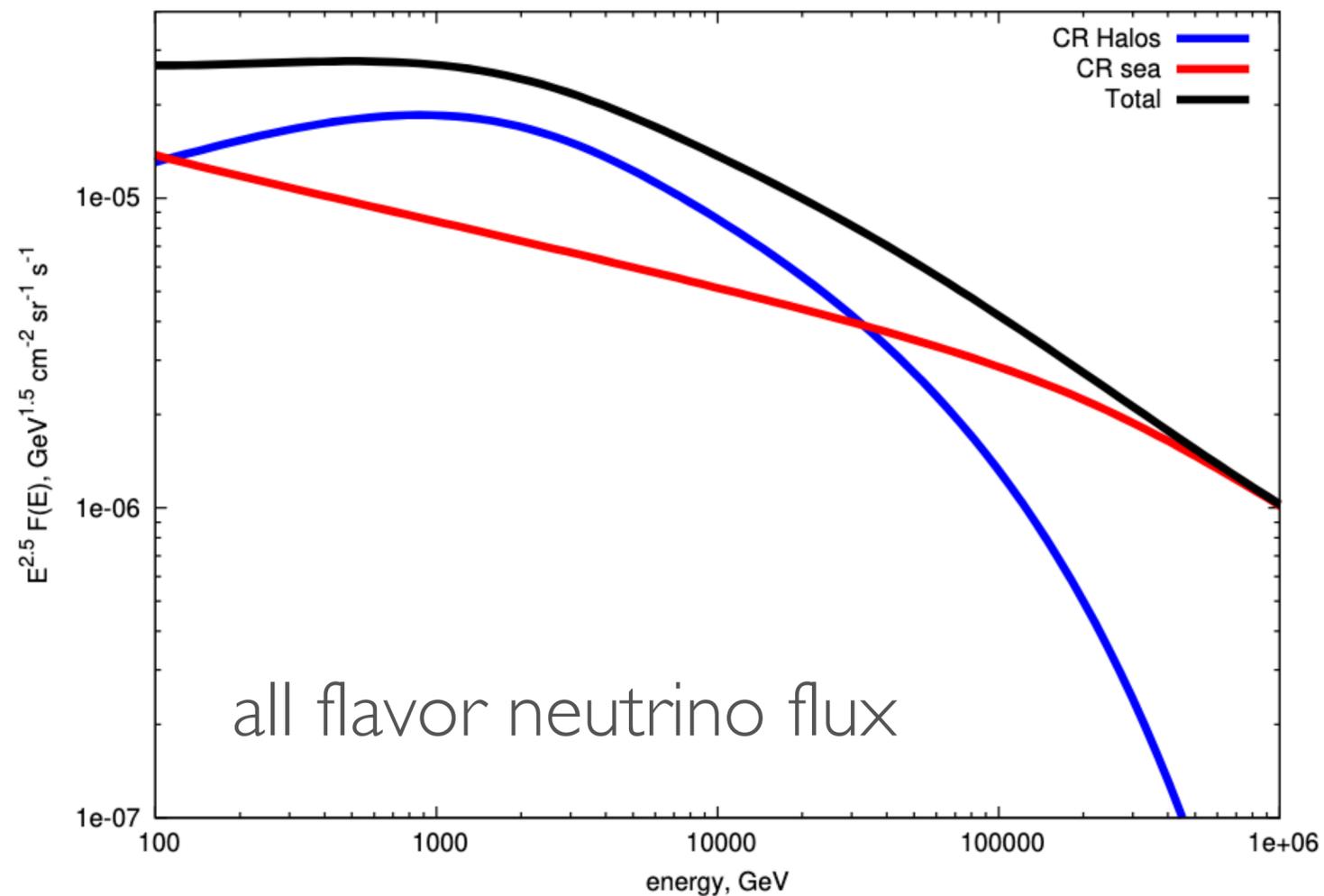Yang and Aharonian, Phys. Rev. D 111, 083040(2025)
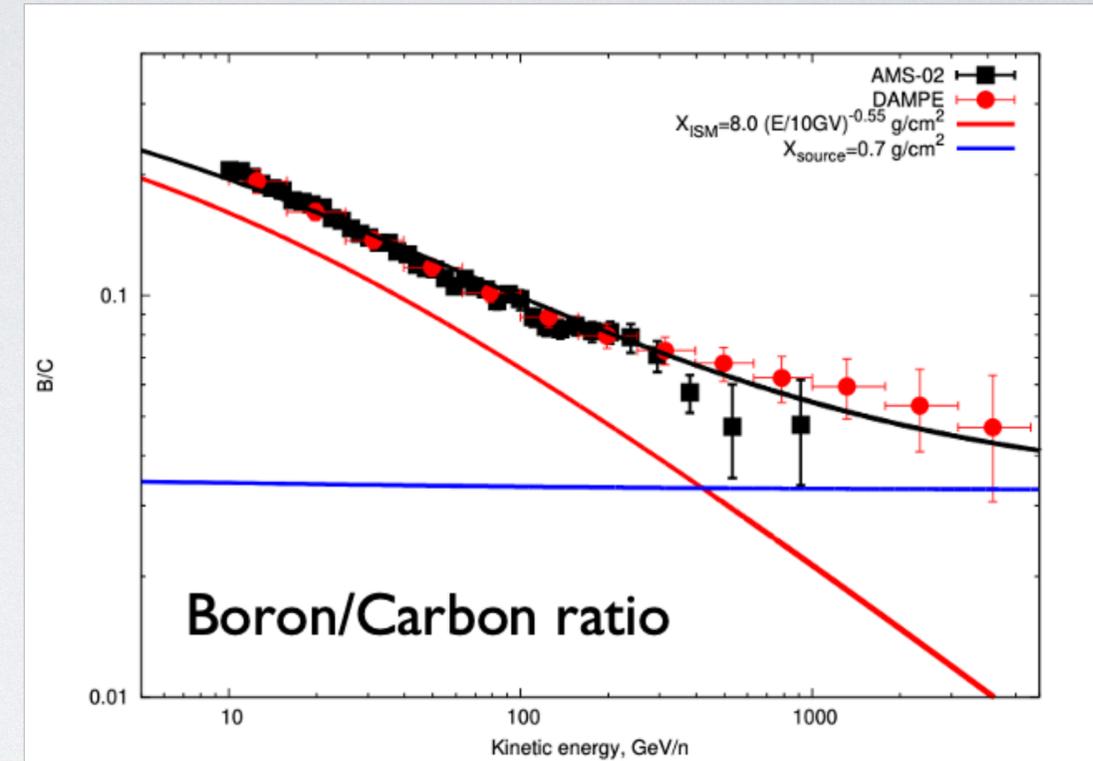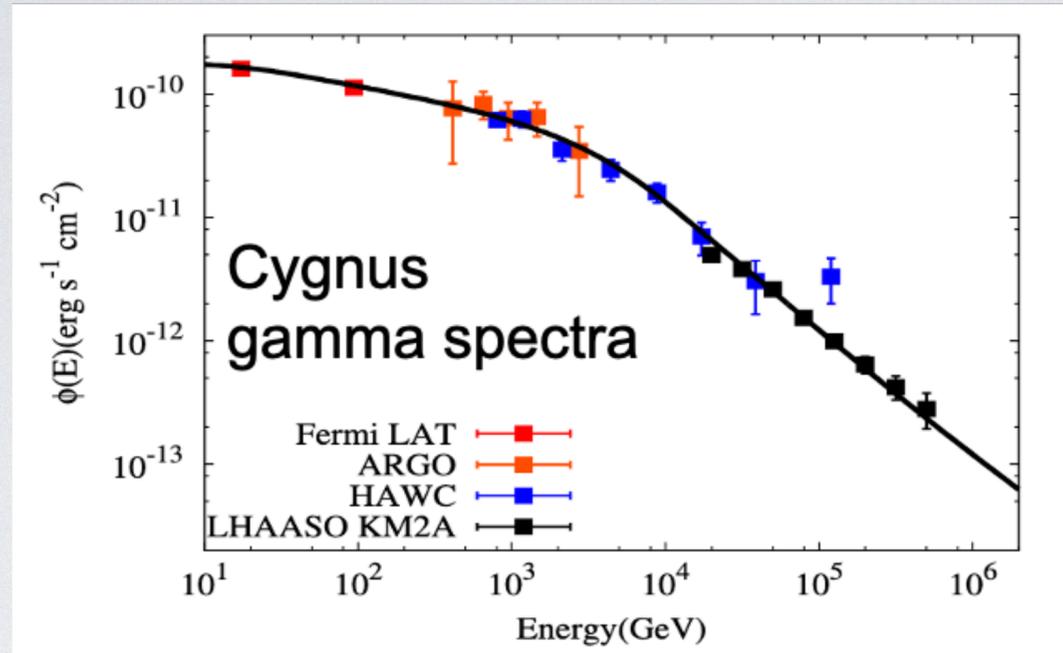
- Can also address the anomalies in CR direct measurement

Yang and Aharonian, Phys. Rev. D 100, 063020(2019)
Yang and Aharonian, Phys. Rev. D 111, 083040(2025)

all flavor neutrino flux

Can be tested by next generation neutrino telescopes such as HUNT

Yang and Aharonian, Phys. Rev. D 111, 083040

- Effective confinement (slow diffusion) of CR near "active" accelerators

- Energy independent below ~10 TeV, from Cygnus spectra

- Accumulation of extra component of "grammage"

- Can account for both B/C and diffuse gamma

Yang and Aharonian, Phys. Rev. D 111, 083040
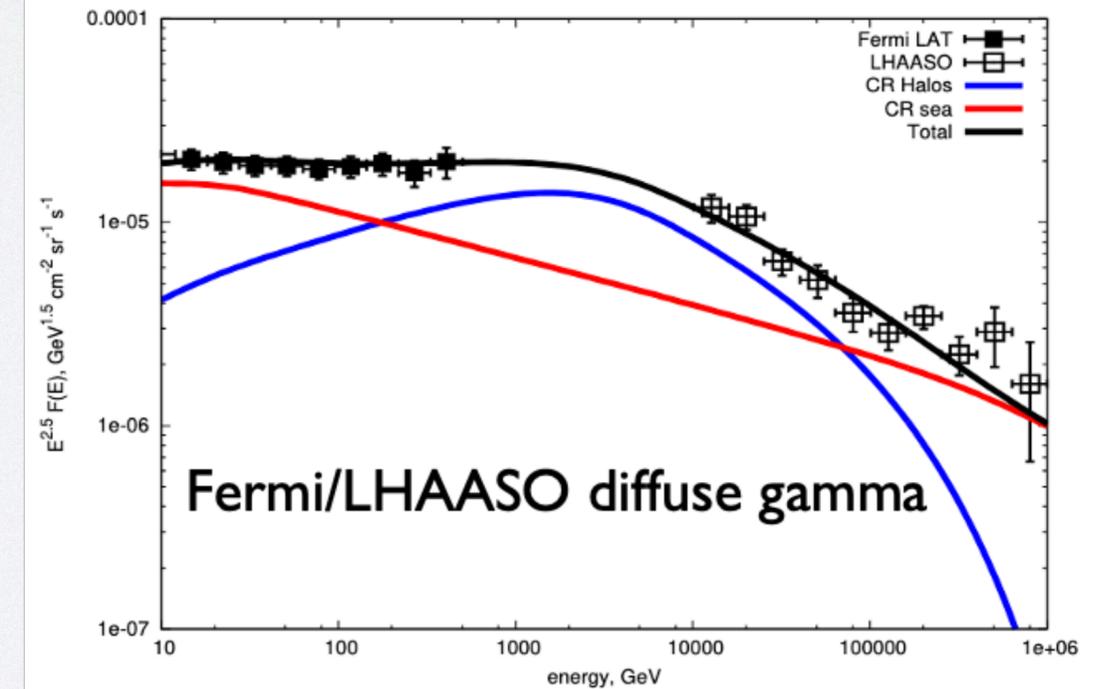
CONCLUSION AND PROSPECT

- Young star cluster can be CR sources, and even PeVatrons

- LHAASO has revealed a huge bubble beyond the former ''Cygnus cocoon'' structure. Cygnus region do harbor super-Pevatron

- Complex regions, synergy with IACTs can be extremely important, take advantage of both LHAASO (sensitivity and large FOV) and IACTs (angular resolution)

- Interesting regions to study CR propagation