LHAASO observations of SNRs G35.6-0.4 and CTB 87

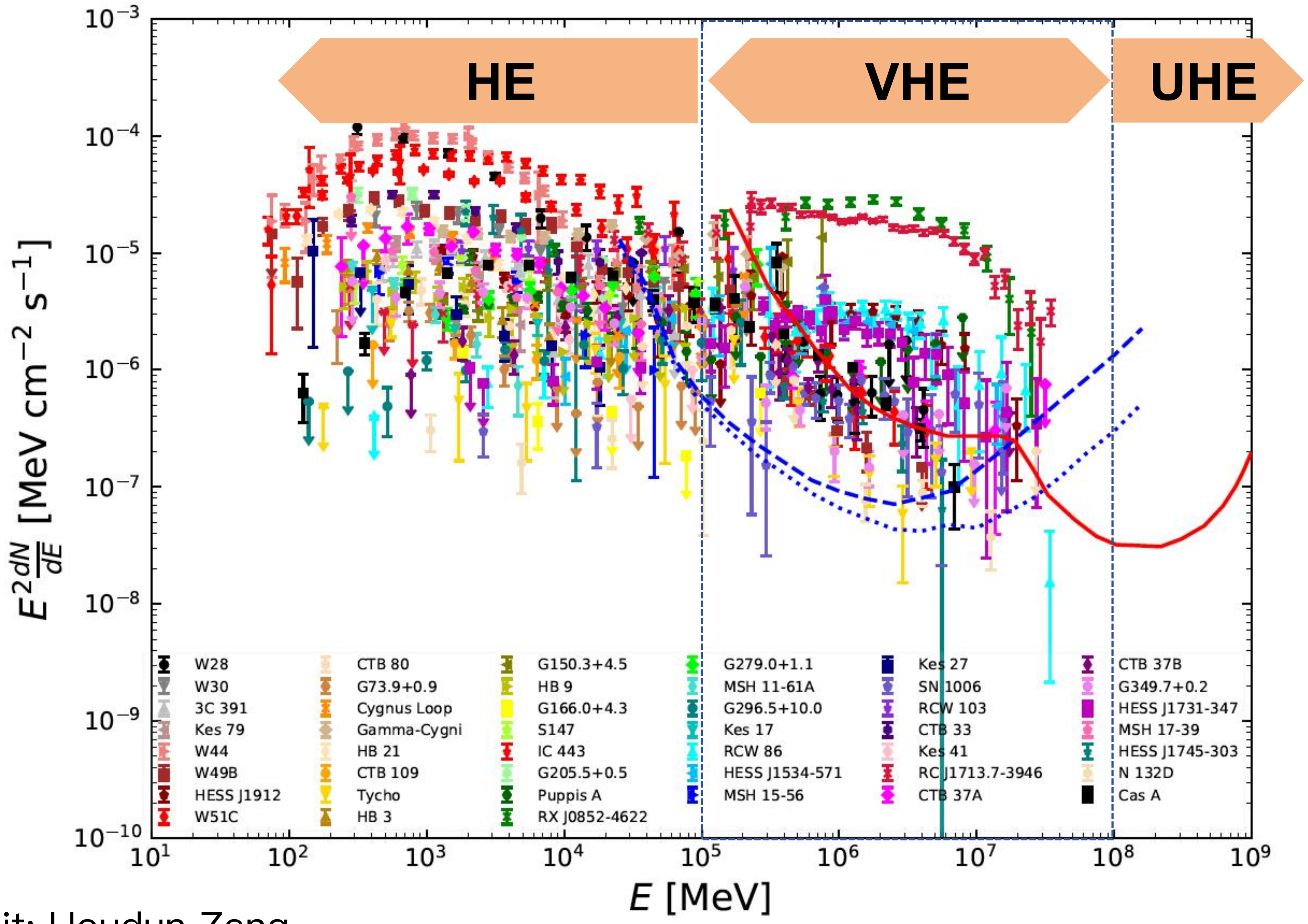
Xiao ZHANG (Nanjing Normal Uni.)

Work group:

Yang CHEN (NJU), Chao HOU (IHEP), Huicai LI (IHEP), Wenjuan ZHONG (DESY&NJU), and Xiao ZHANG (NNU) on behalf of LHAASO collaboration

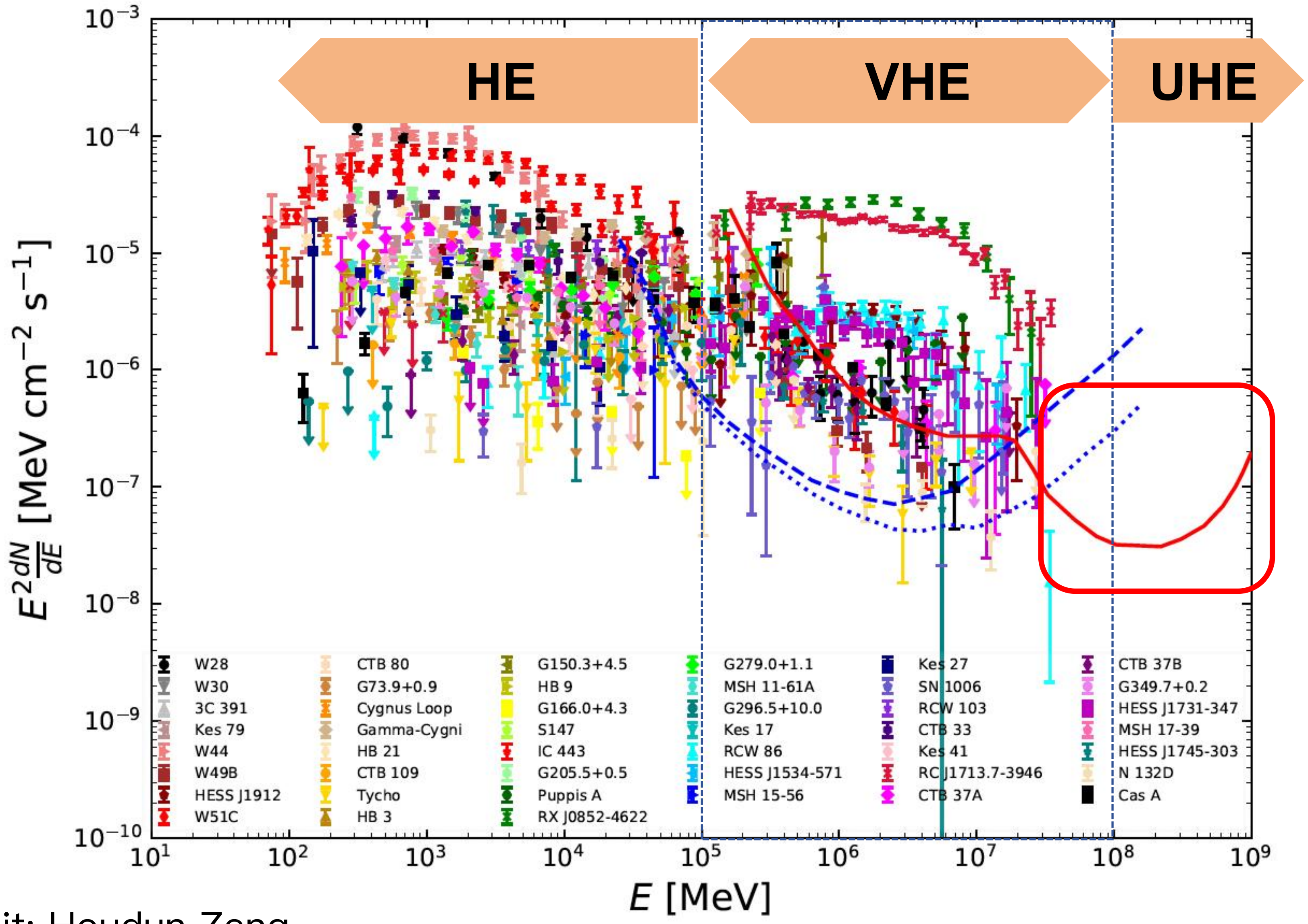
The Symposium of UHE Gamma Rays from SNRs and the Origin of Galactic CRs, Mar 2, 2026 @ Yuxi, China

Motivations



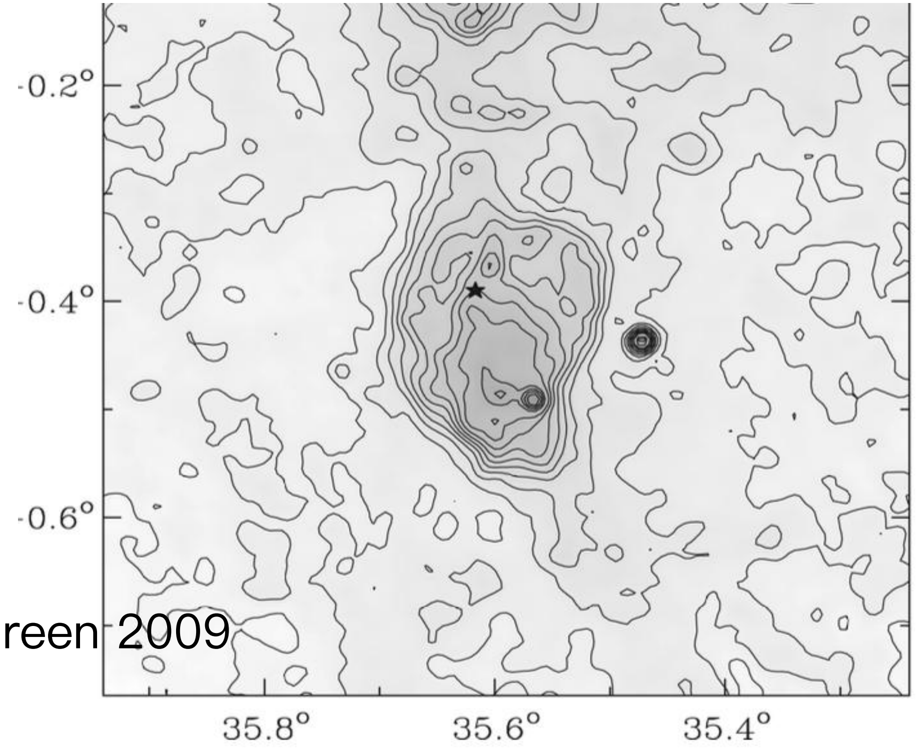
credit: Houdun Zeng

Motivations



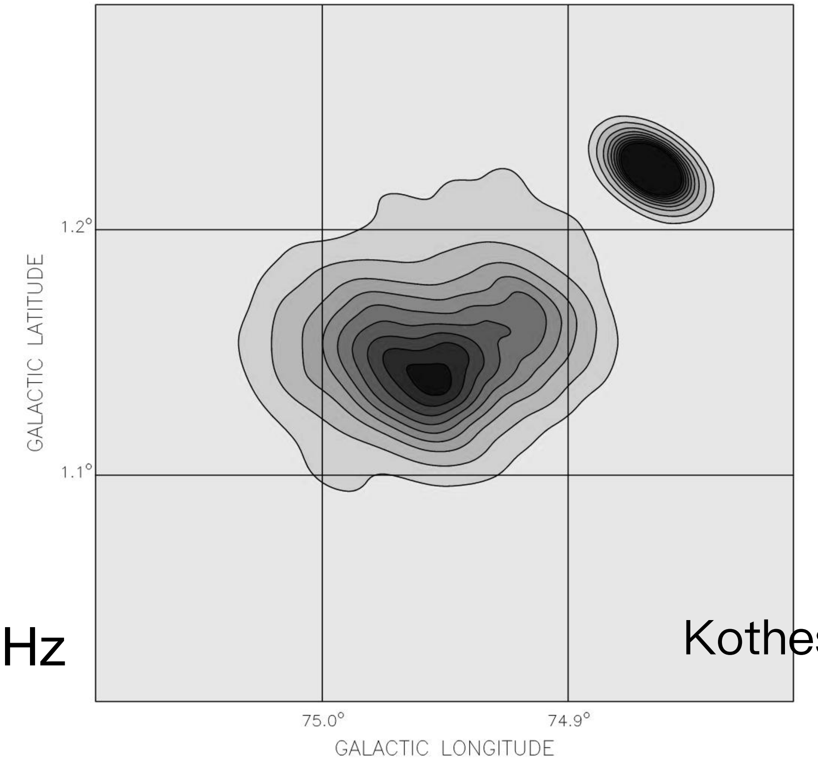
credit: Houdun Zeng

Targets: G35.6-0.4 and CTB 87



Green 2009

1.4 GHz



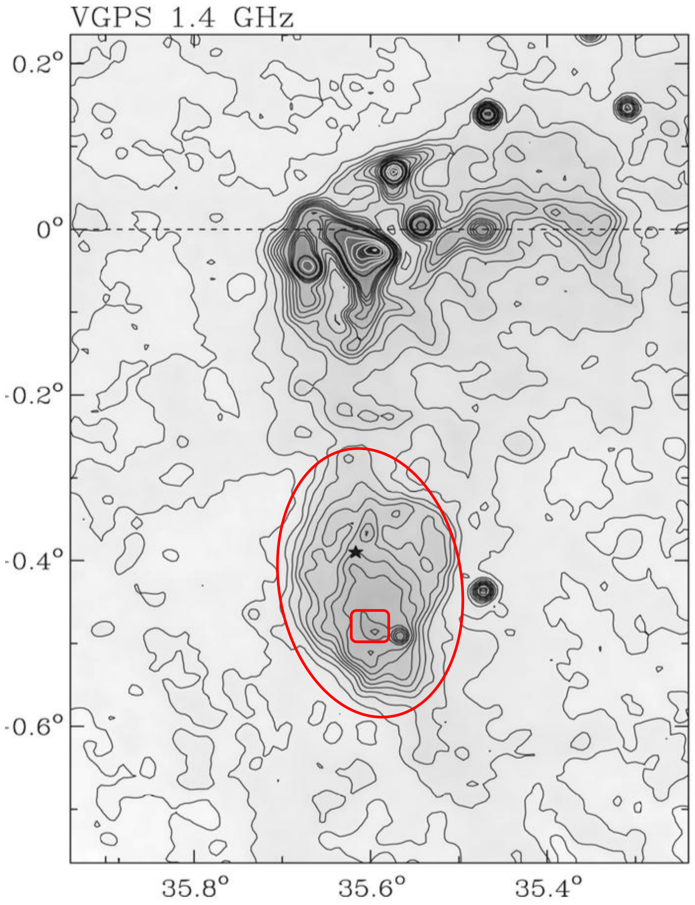
Kothes+2003

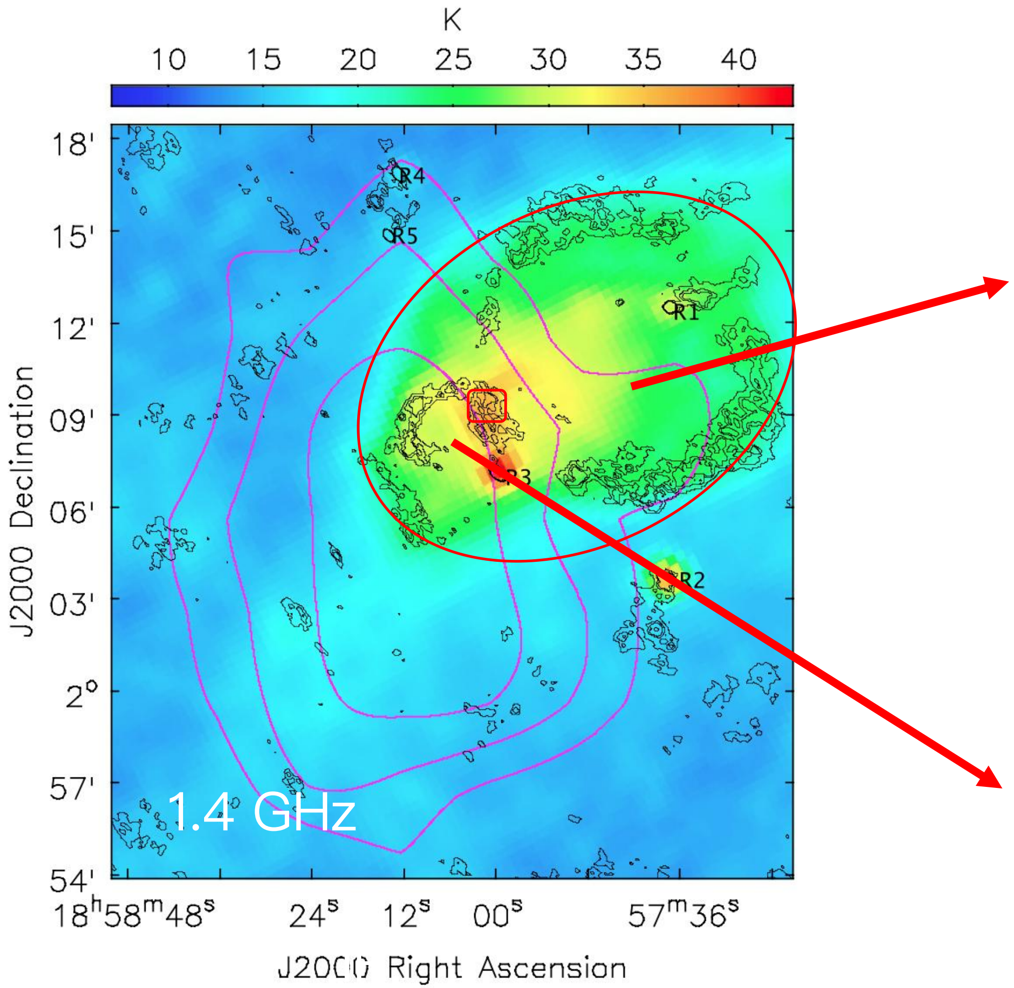
G35.6-0.4		CTB 87
shell	Type	plerion
~ 10 kyr	Age	~ 10 kyr
Yes	MC	Yes
Yes (HESS)	TeV	Yes (VERITAS)

Part I: SNR G35.6-0.4

Cao, et al., 2025, ApJ, 979, 90

Introduction: radio morphology





SNR (Green 2009)

- index ~ 0.46
- lack of IR

SNR+HII (Paredes+ 2014)

- black: GMRT 610 MHz
- magenta: HESS

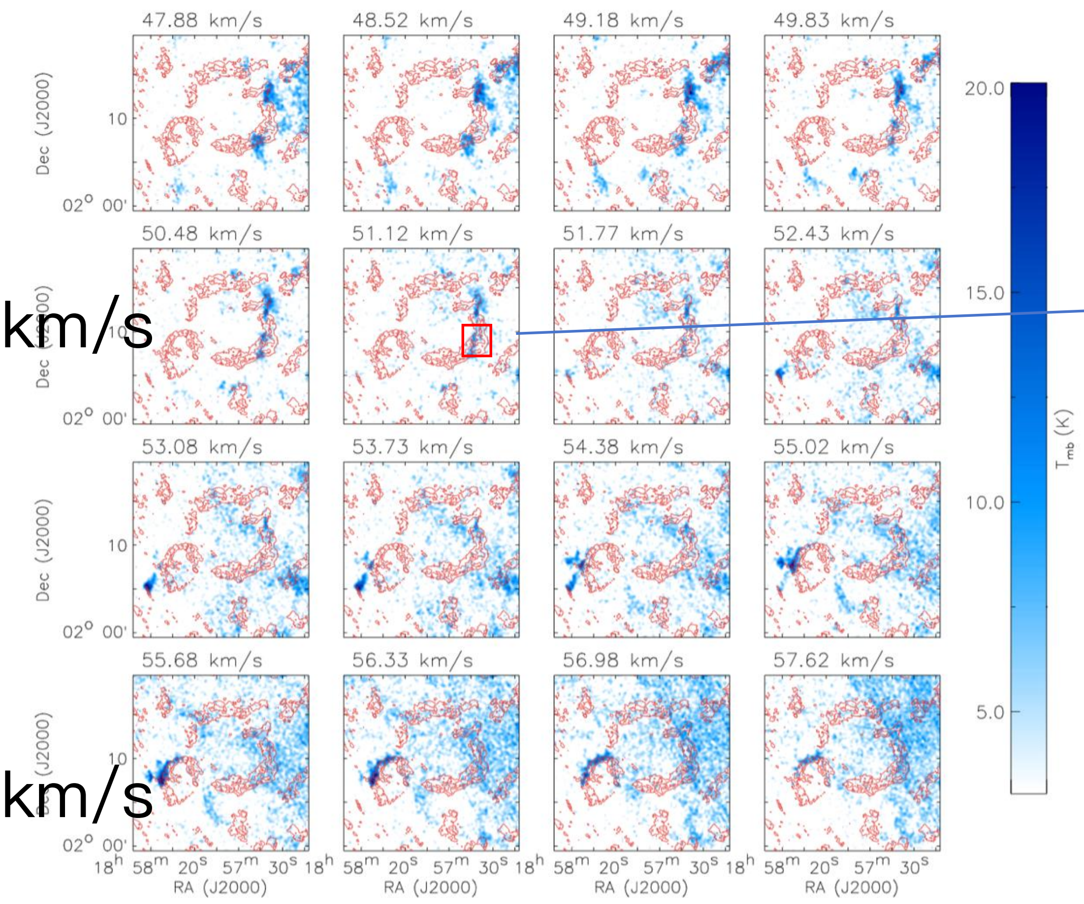
SNR
G35.6-0.4
d ~ 10.5 kpc

HI and CO
(zhang+2022)

HII region
G35.6-0.5
d ~ 3.4 kpc

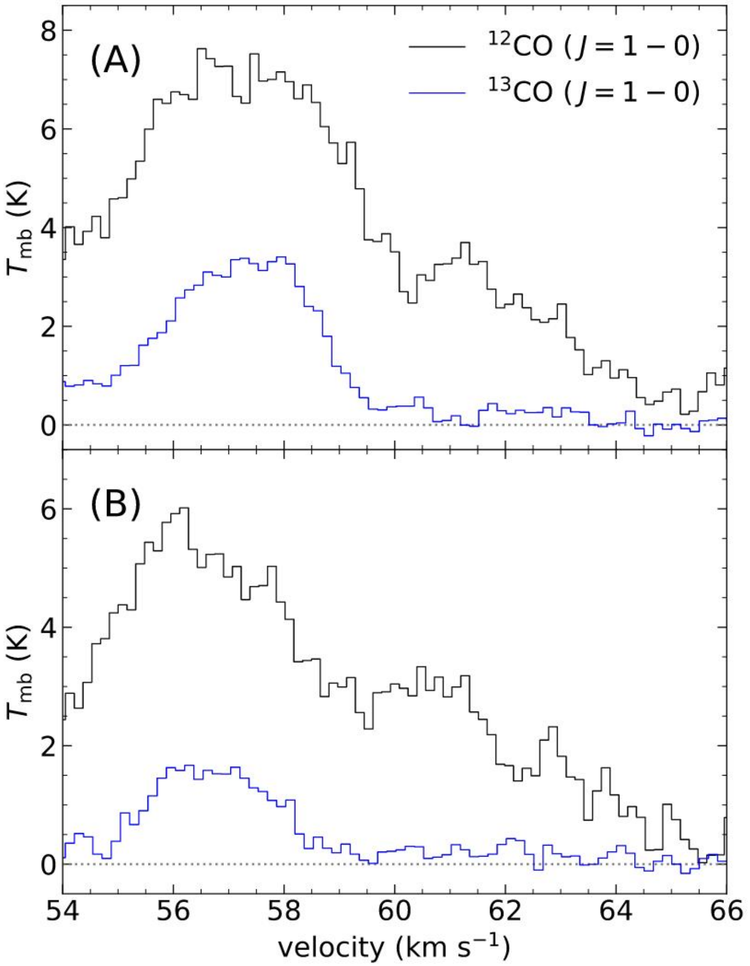
Introduction: Molecular Environments

Nobeyama 12CO channel maps (*T*)



~50 km/s

~56 km/s



Zhang+2022

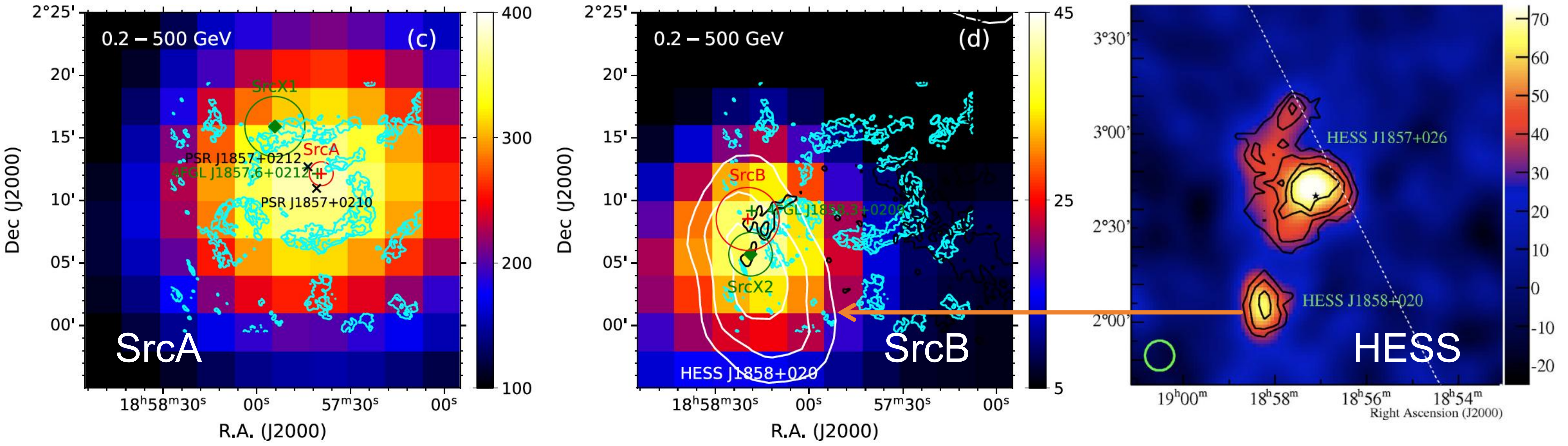
SNR: filament @ ~ 50 km/s;
HII region: arc @ ~ 56 km/s

1) asymmetric 12CO lines
2) high T ~ 20K

Introduction: GeV and TeV gamma-rays

Zhang+2022

Aharonian+2008



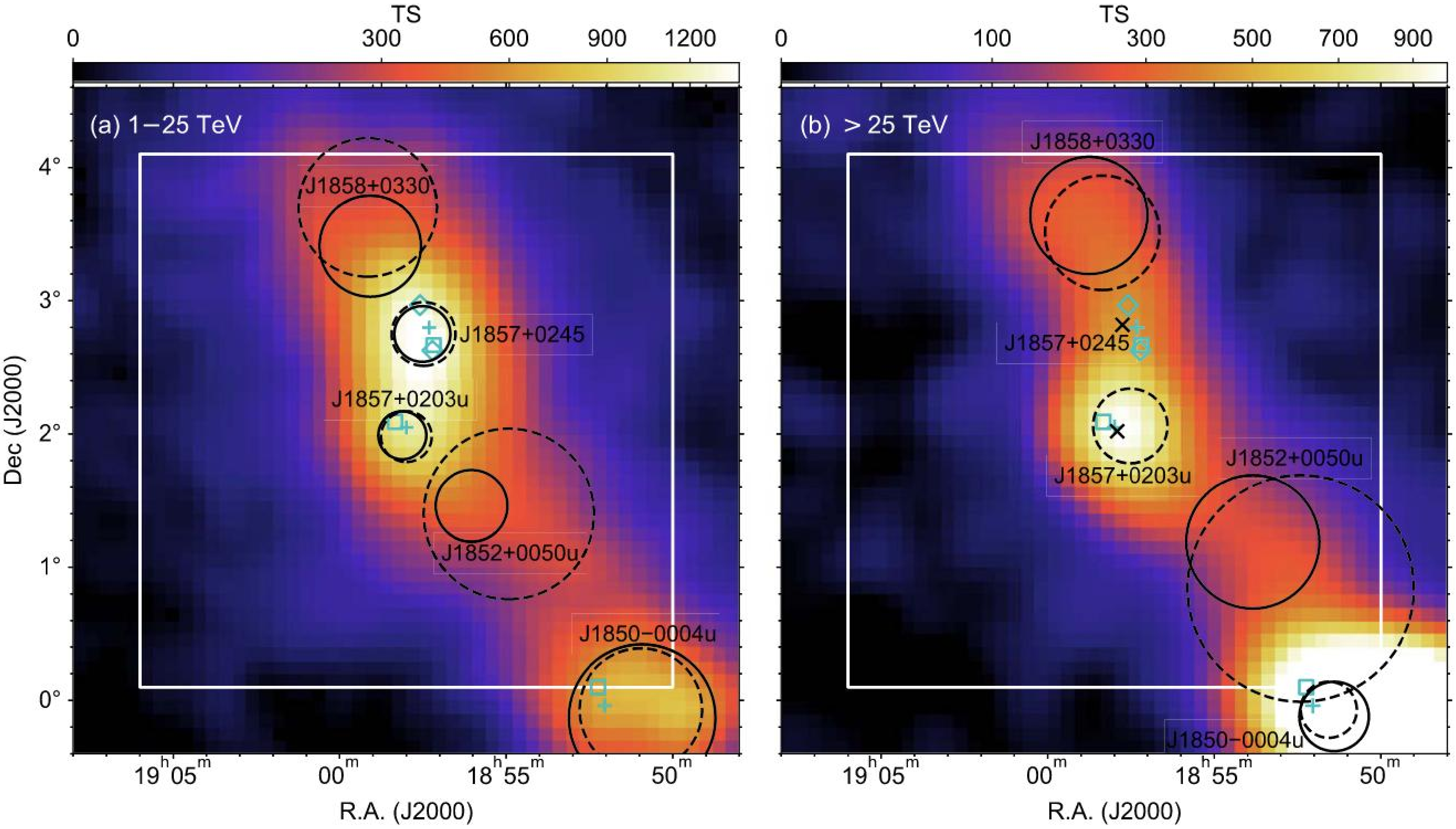
cyan contours: 610 MHz
black crosses: PSR

Black contours: 55-57 km/s CO
White contours: HESS J1858+020

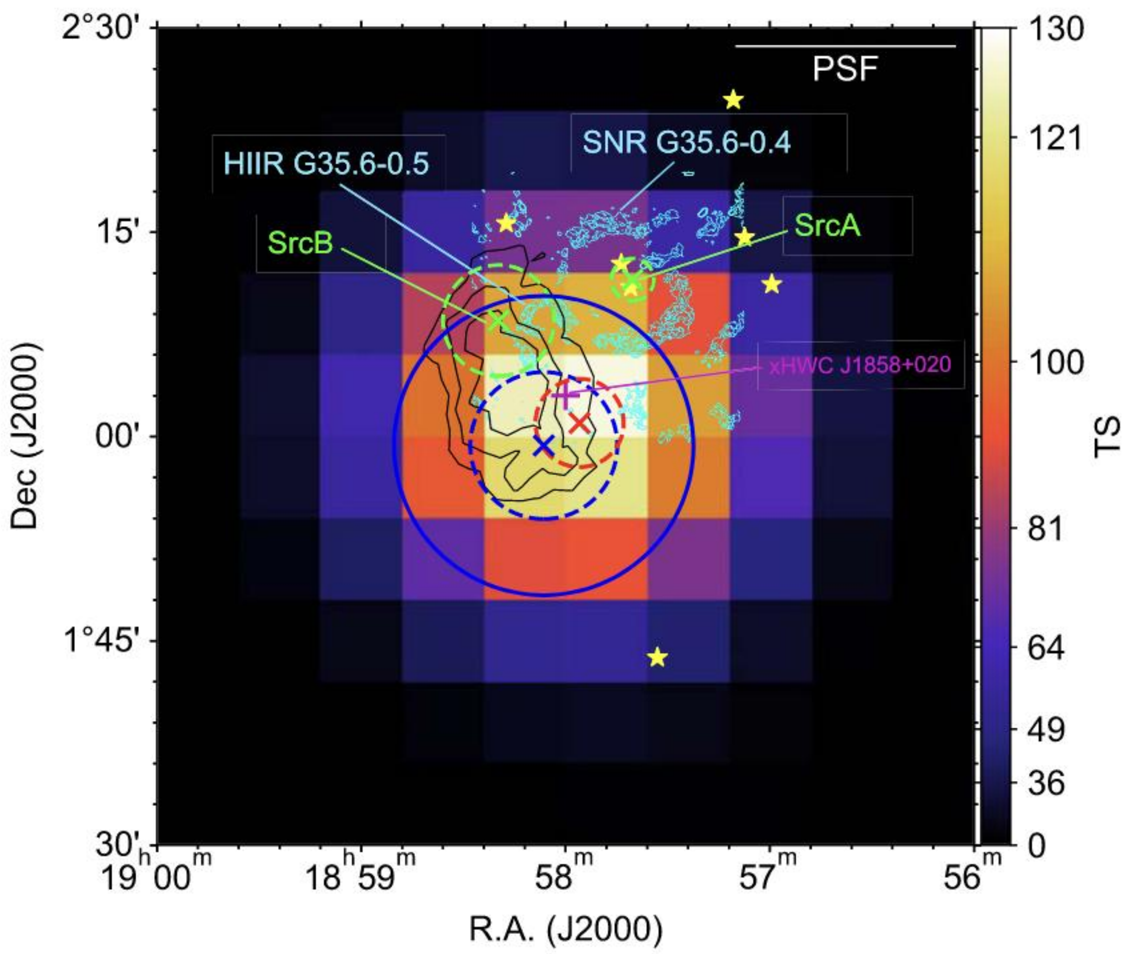
There are two point sources (Cui+2021, Zhang+2022): SrcA (SNR)and SrcB (HII)

LHAASO data analysis

performed by Wenjuan ZHONG



Results : Morphology and SED



> 100 TeV 1x1deg TS map

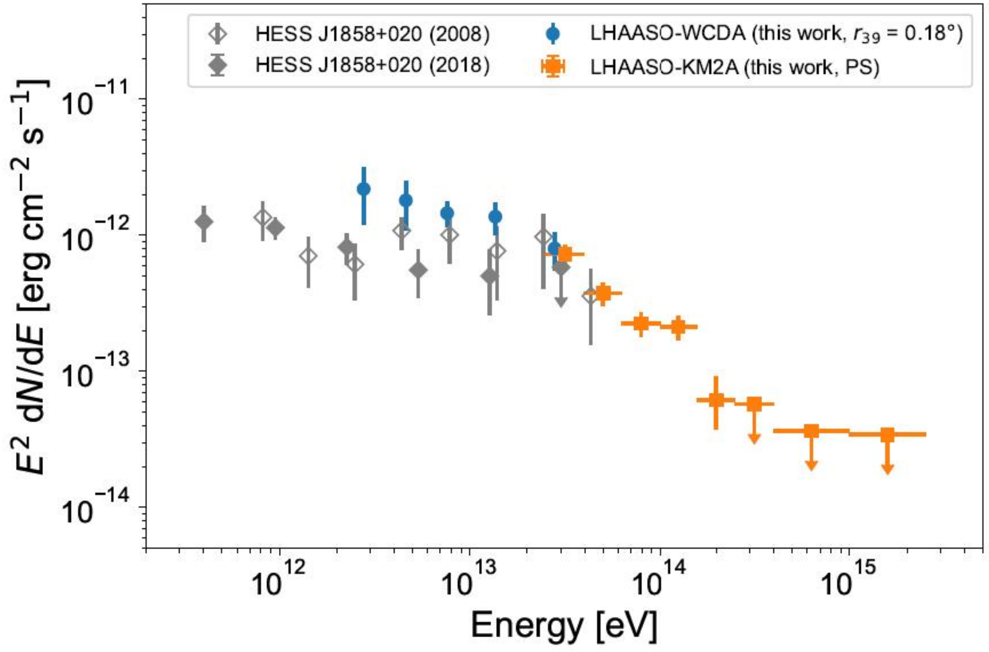
Green : Fermi (Zhang+2022), point, 2sigma error

Blue : WCDA (r39 = 0.18deg, TSext=25.2)

Red : KM2A, point, 2sigma error

Purple + : HAWC (PS search, Malone+2023)

yellow : pulsar



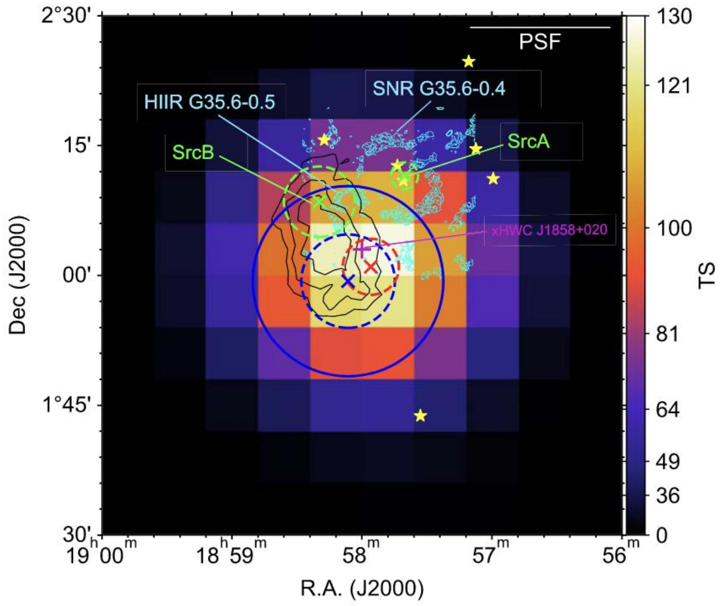
Scenario 1: the SNR model (delta-escape)

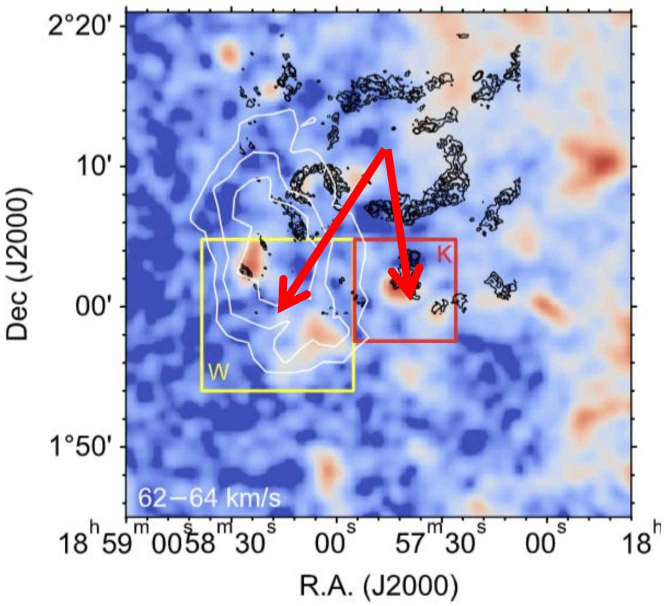
The SNR properties

d = 10.5 kpc, R = 15 pc, n_0 ~ 1cc, and E_{sn} ~ 10^{51} erg ⟹ t_{age} ~16 kyr.

The gamma-ray emission

- the trapped protons produce the GeV emission (SrcA)
- the escaped protons produce the > TeV emission





Cloud	Mass (Msun) 50-68 km/s	Distance to SNR centre
K (CO)	2.2 x 10^4	30 pc
W (CO)	4.0 x 10^4	45 pc
A (HI)	7.6 x 10^4	45 pc

Note: optimistic estimate

Scenario 1: the SNR model (delta escape)

■ The escaped protons

Gabici+2009

$$f_{esc}(E_p, R, t) = \frac{A_0 E_p^{-\alpha}}{\pi^{3/2} R_d^{3/2}} \exp\left(-\frac{R^2}{R_d^2}\right)$$

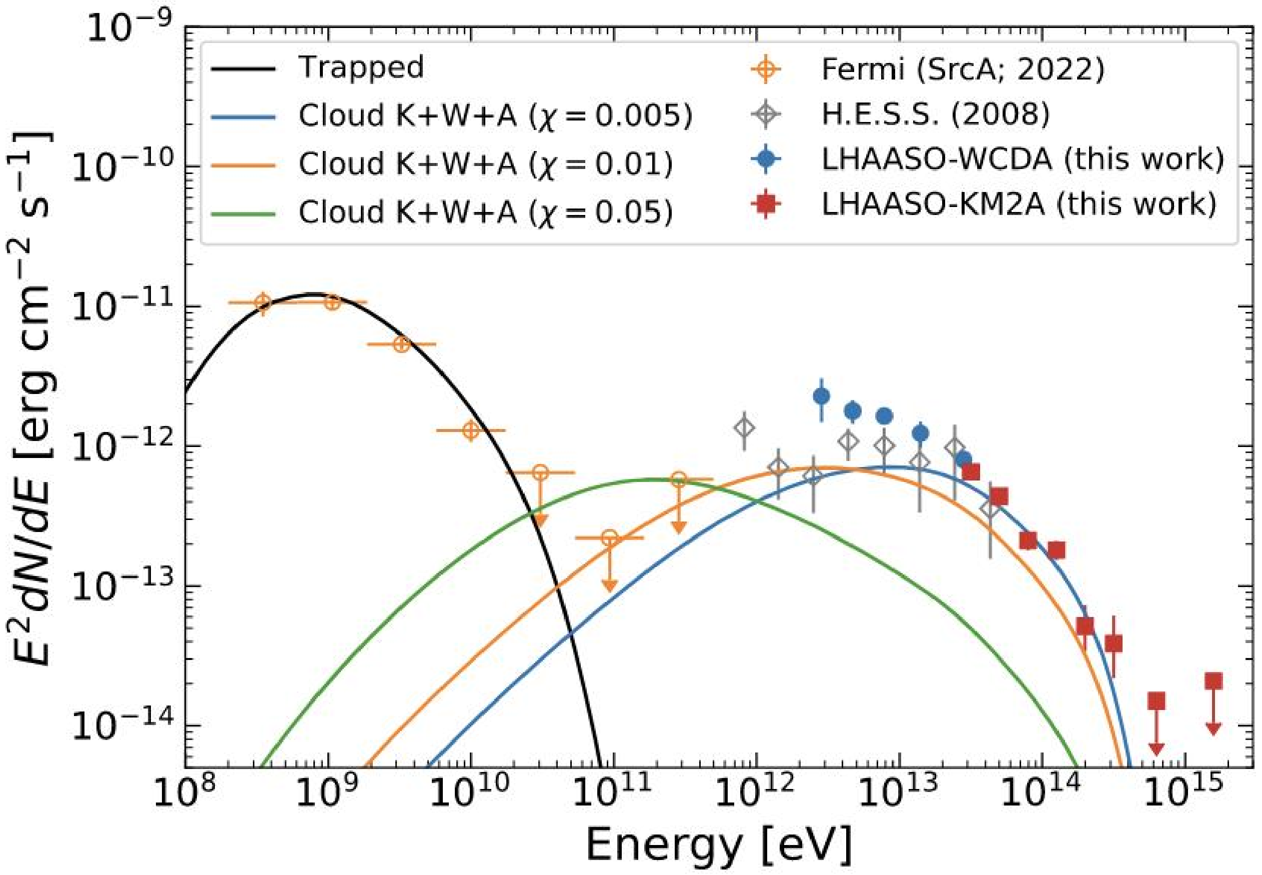
$\alpha = 2.0$
$\eta = 10\%$

$$R_d = \sqrt{4D(E_p)(t - t_{esc}(E_p))}$$

$$D(E_p) = \chi 10^{28} (E_p / 10\ \mathrm{GeV})^{\delta}$$

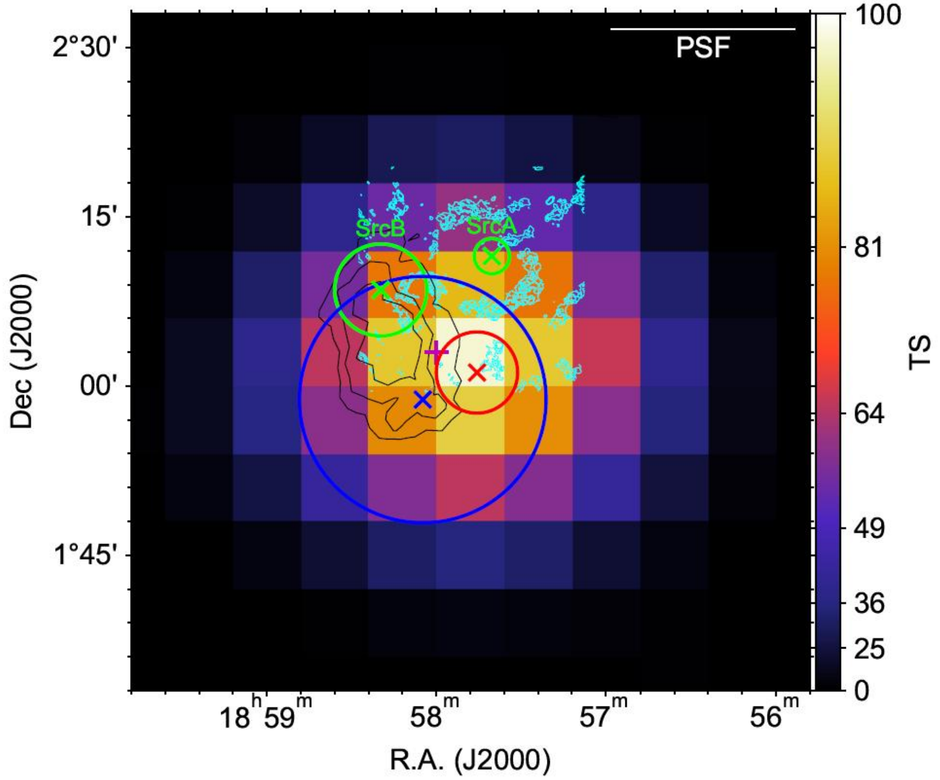
$$t_{esc}(E_p) = t_{sed}(E_p / E_{pmax})^{-1/s}$$

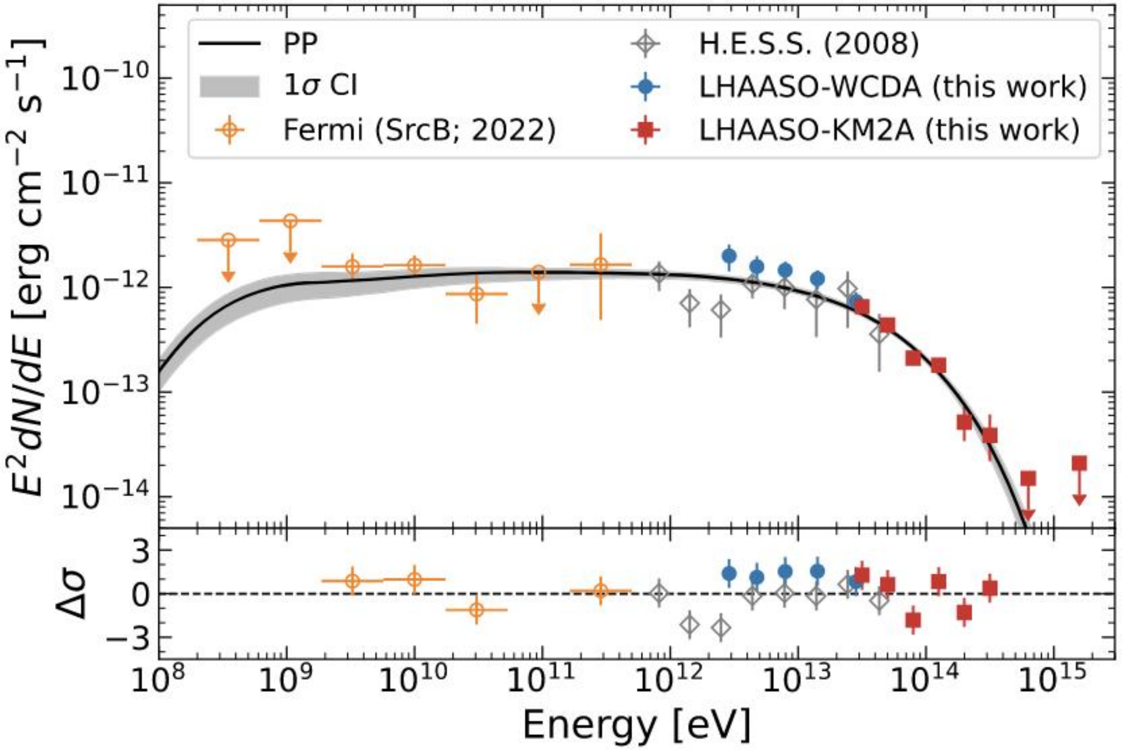
$$\frac{dN}{dE_\gamma} = \frac{M_c}{m_H} \frac{\epsilon_\gamma}{4\pi d^2}$$



Scenario 2: the HII region model

Fermi (SrcB), HESS, and LHAASO are related to the HII region





index ~ 2.00; E_{pcut} ~ 450 TeV

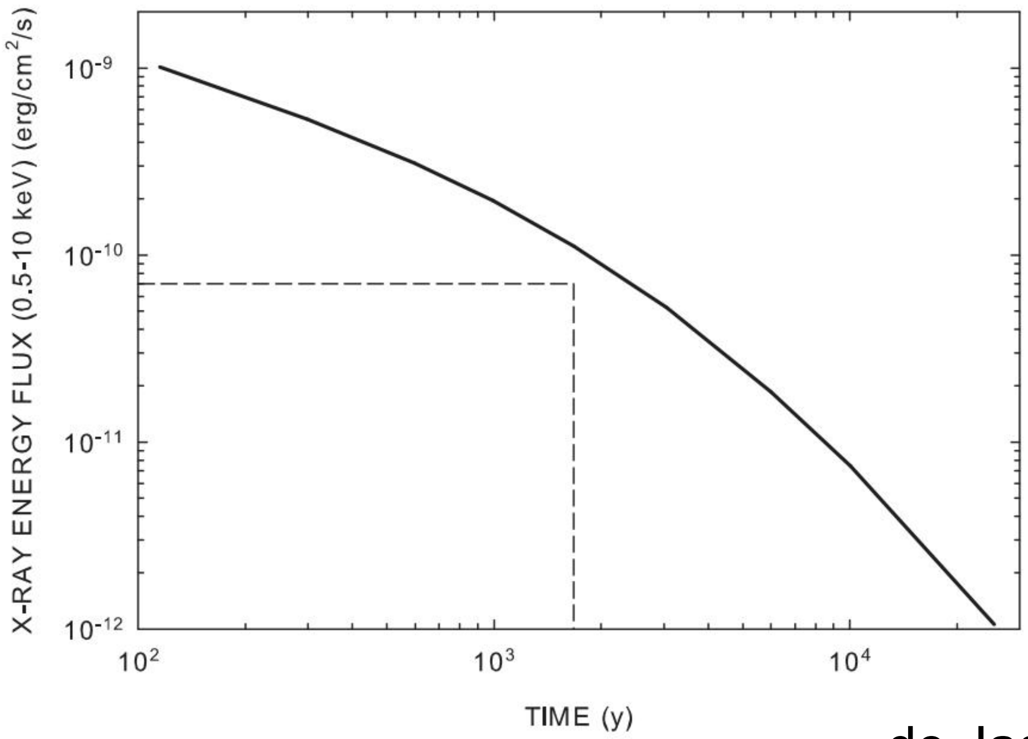
Wp ~ 10^{47} /(n/600cc) erg

$L_{\rm p} = W_{\rm p}/\min(\tau_{\rm pp}, t_{\rm dif}) \sim (5.0 - 50) \times 10^{35}$ erg/s

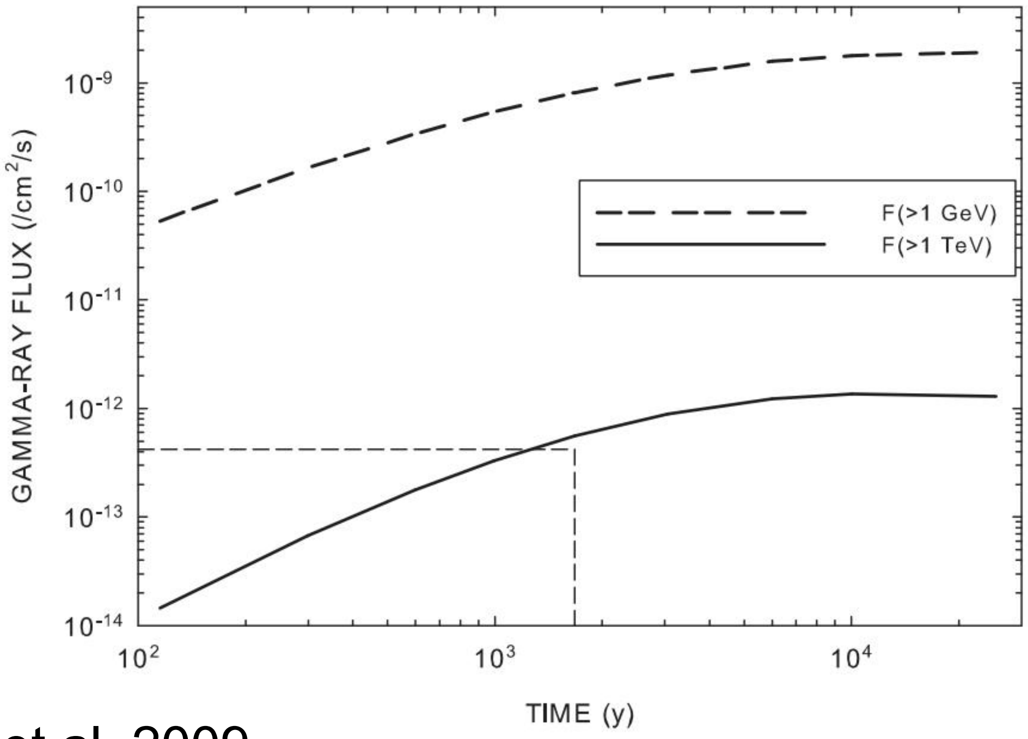
required massive stars is *N* ~ 100

Scenario 3: the ancient PWN model

X-ray Flux



gamma–ray Flux



de Jager et al. 2009

LHAASO source is an independent source powered by an unseen PSR, neither related to the SNR (SrcA) nor the HII region (SrcB)

Scenario 3: the ancient PWN model

- The *t*-integrated spectrum of leptons (Zhang+2020)

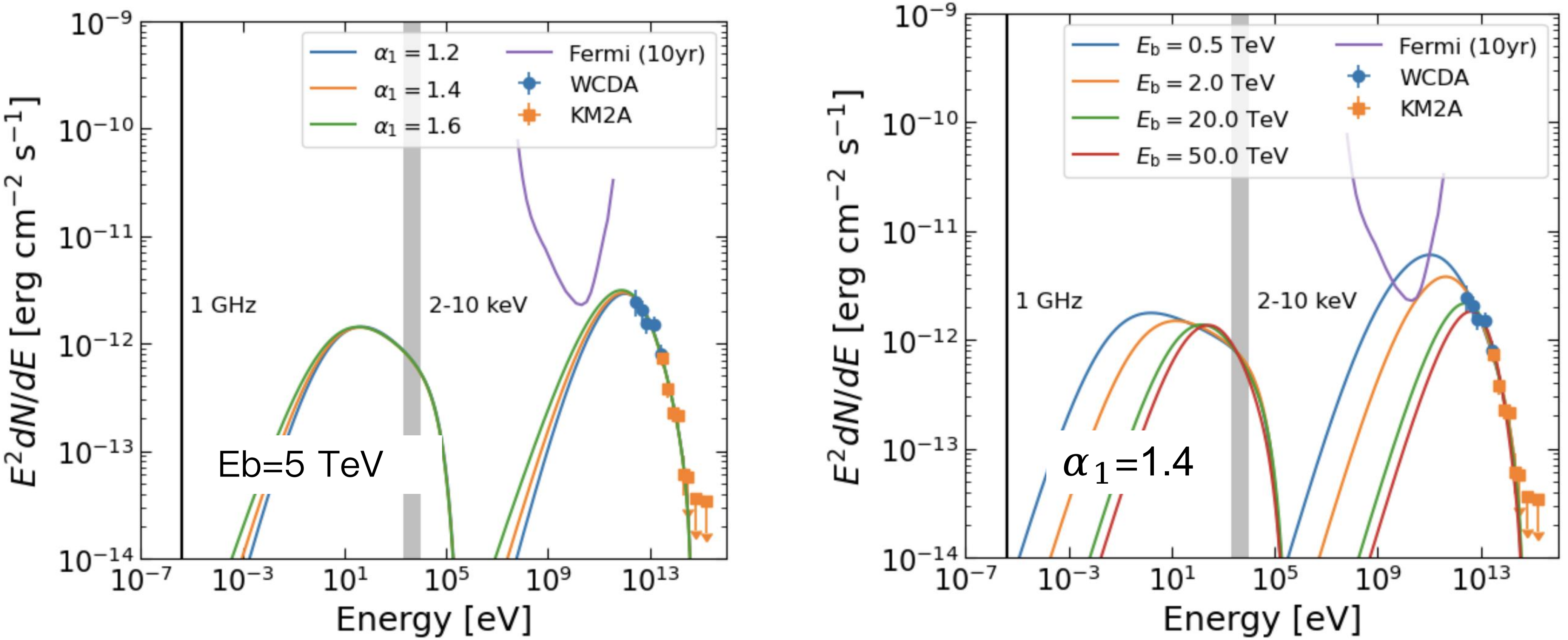
$$\frac{dN}{dE_{\rm e}} = A_{\rm e} E_{\rm e}^{-\alpha_1} \left[1 + \left(\frac{E_{\rm e}}{E_{\rm b}}\right)^s\right]^{\frac{\alpha_1-\alpha_2}{s}} \exp\left[-\left(\frac{E_{\rm e}}{E_{\rm ecut}}\right)^\beta\right]$$

Parameters: $\beta = 3,\ s = 1,\ \alpha_1, \alpha_2,\ E_{\rm b},\ E_{\rm c},\ W_{\rm e}$

- Seed photons and Distance is assumed

$U_{\rm IR}$ ~ 0.6 eV/cm3 and d ~ 3.4 kpc

Scenario 3: the ancient PWN model



We>10^{47} erg → [Age > ~10 kyr] (< 100 kyr)

$L_{sd} > 3 \times 10^{35} \left(\frac{t_{psr}}{10\ \mathrm{kyr}}\right)^{-1} \left(\frac{d}{3.4\ \mathrm{kpc}}\right)^{-2}$ erg/s

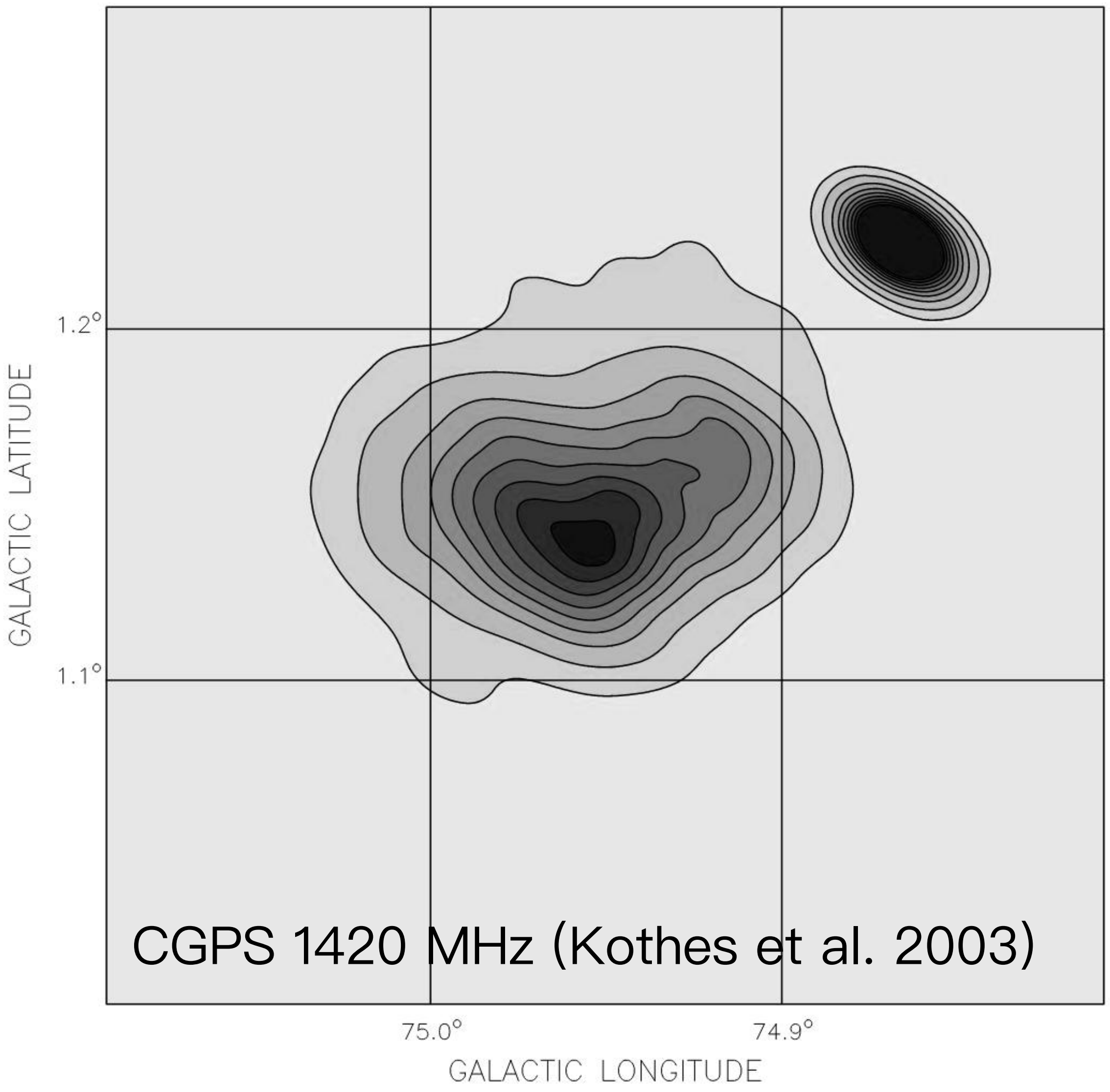
→ ATNF PSR Cat ~100 (~3%)

Summary (I)

- G35.6-0.4
  - A gamma-ray source, closing to SNR G35.6-0.4, is detected by WCDA (extended, r39~0.18deg) and KM2A (PS).
  - It seems unlikely that the gamma-rays are from the clouds illuminated by the protons escaped from SNR G35.6-0.4.
  - The HII region or ancient PWN model are possible.

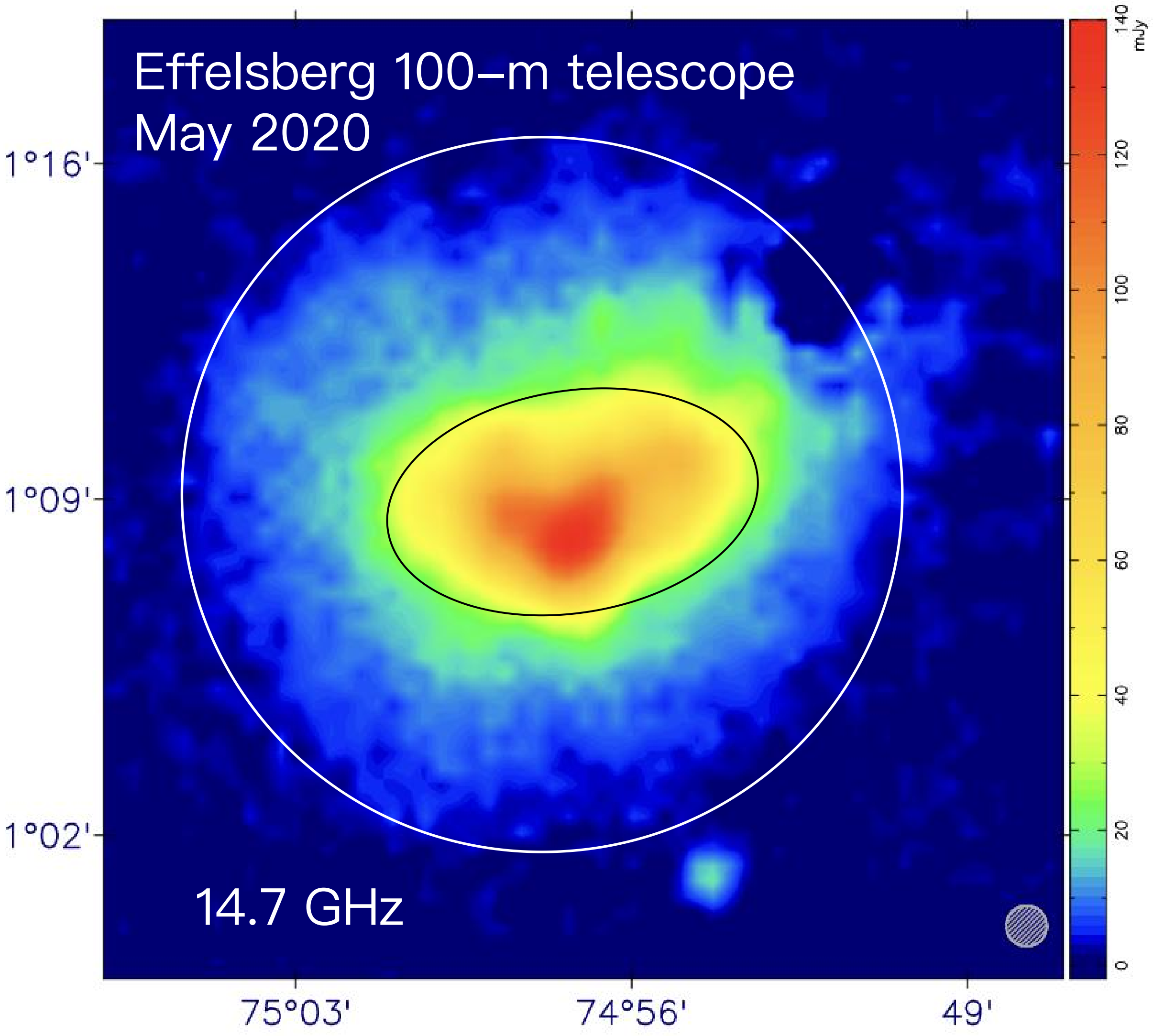
Part II: SNR CTB 87

Introduction: radio observations



- ✓ filled–center SNR (Dickel & DeNoyer 1975)
- ✓ radio index ~ 0.3
- ✓ size: 8’ x 6’
- ✓ *d* = 6.1±0.9 kpc (Kothes et al. 2003)
- ✓ age ~ 18000yr (Kothes et al. 2020)

Introduction: radio observations

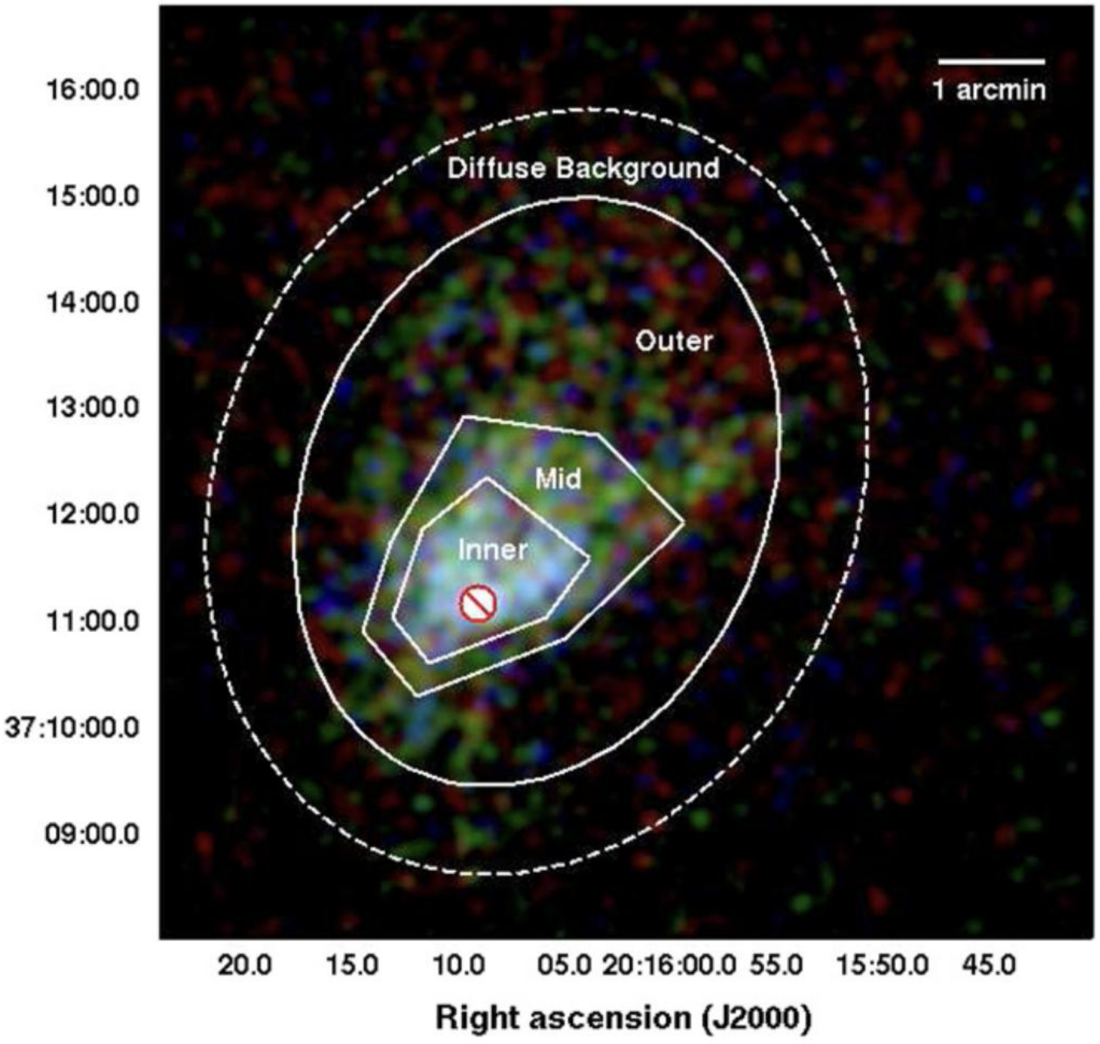


Reich et al. 2022

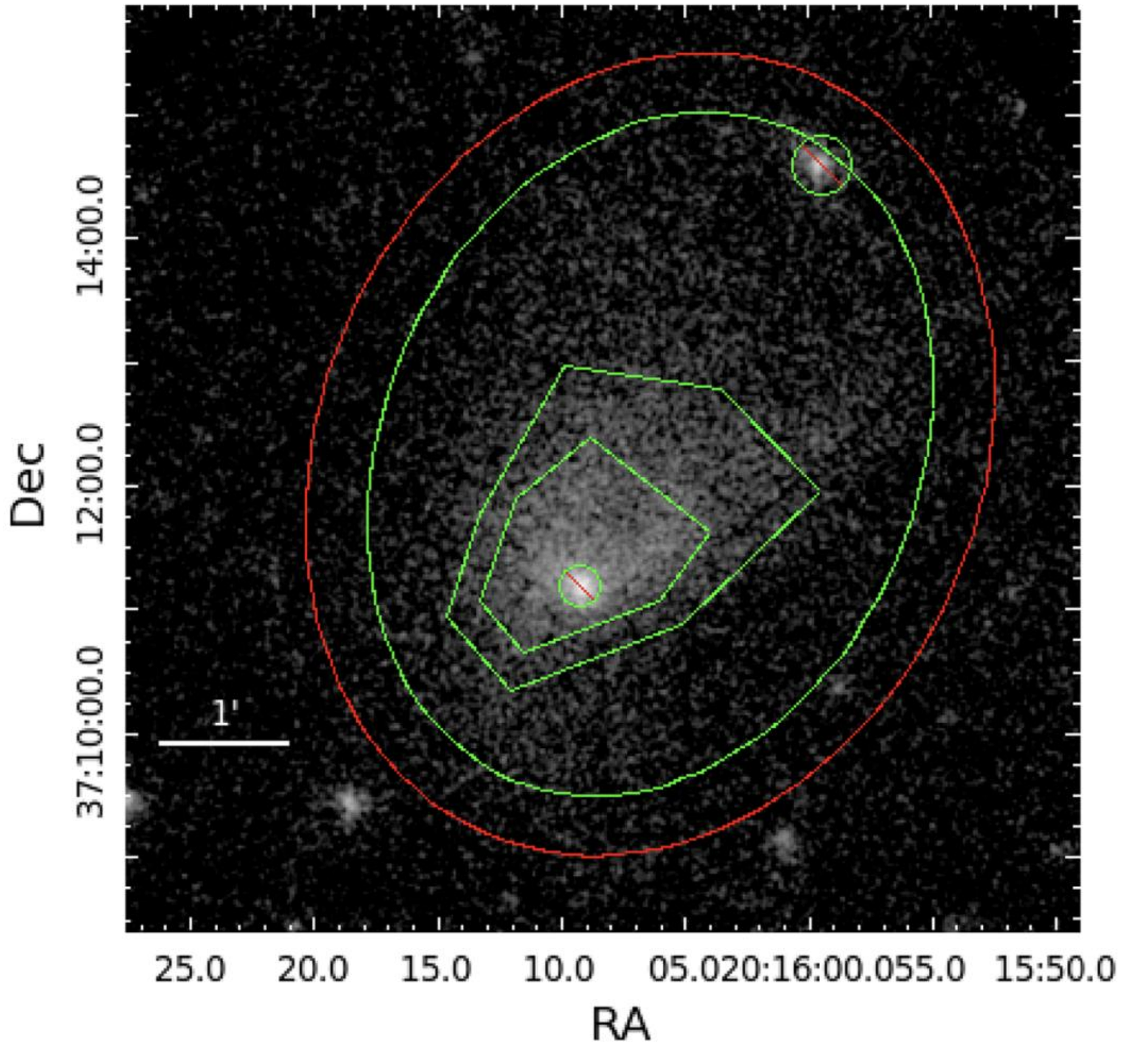
Two components:

- ➢ Compact
  - Index: $\alpha = 0.43 \pm 0.04$
  - Size: 7.8'x4.8' (14x8.5 pc)
  - Flux: 1.6±0.2 Jy @14.7 GHz
- ➢ Diffuse
  - Index: $\alpha = 0.24 \pm 0.09$
  - Size: 17' (30 pc)
  - Flux: 2.6±0.2 Jy @14.7 GHz
- ➢ Total
  - $\alpha = 0.31 \pm 0.02$

Introduction: X-ray observations

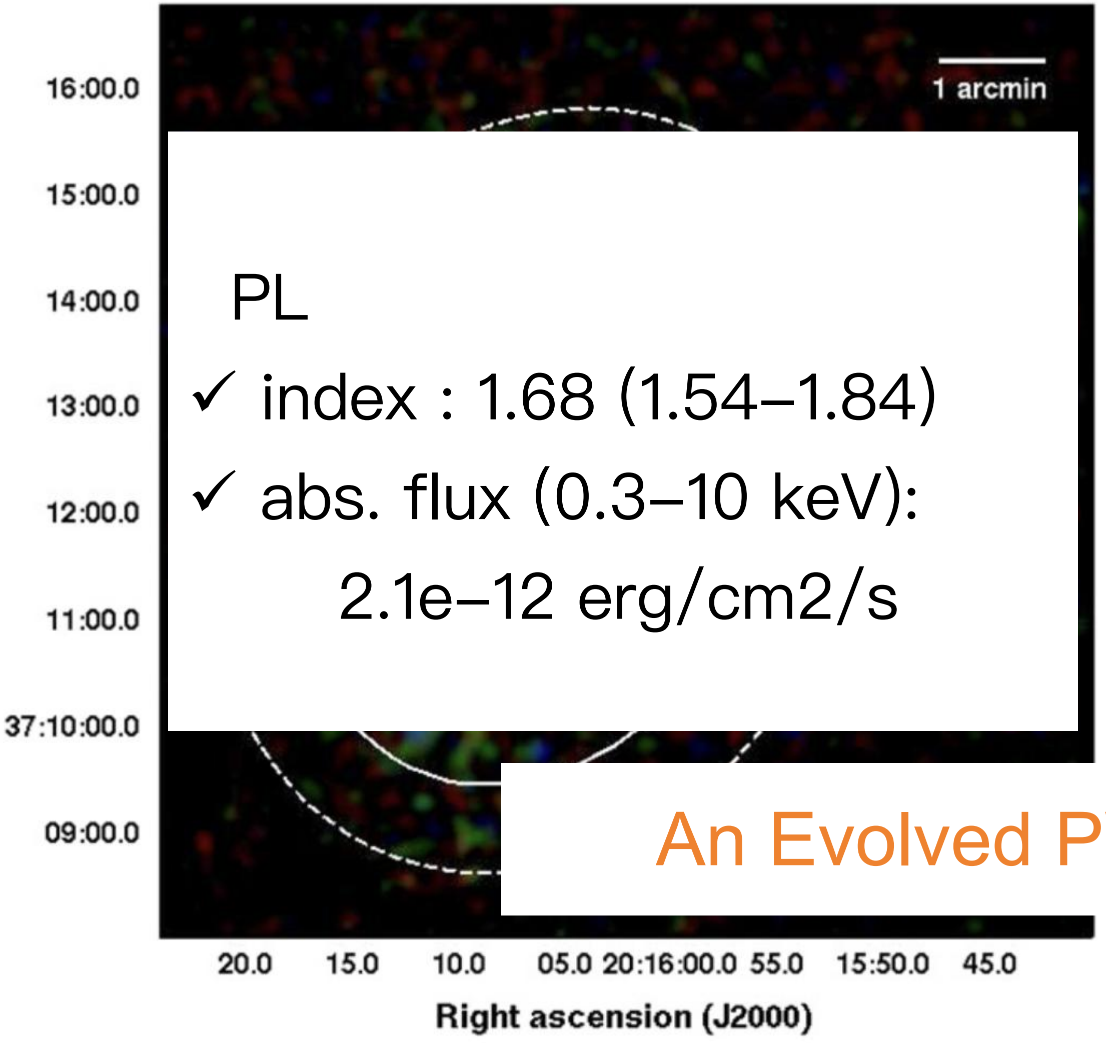


Chandra (Matheson et al. 2013)



XMM (Guest et al. 2020)

Introduction: X-ray observations

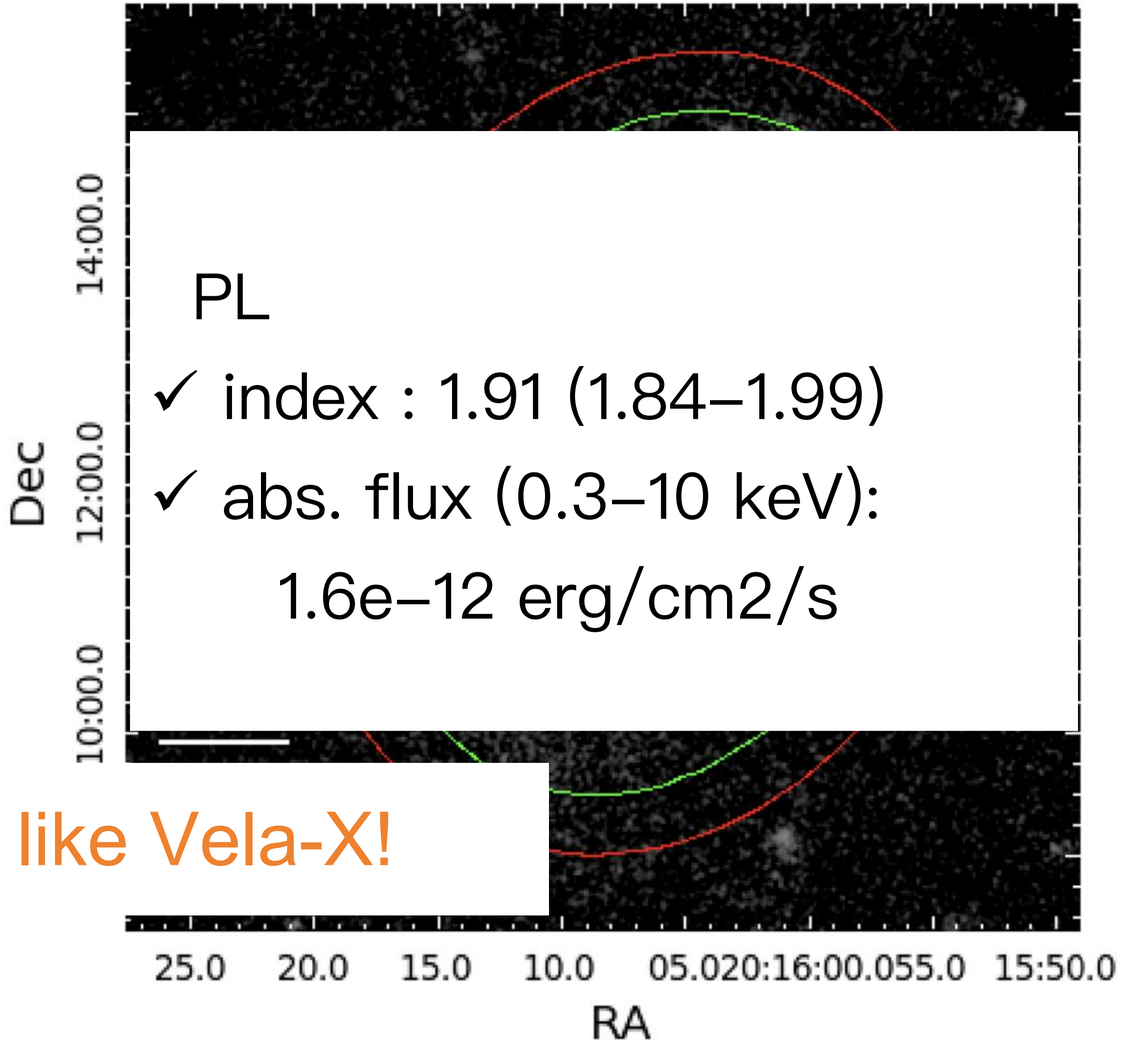


PL

✓ index : 1.68 (1.54–1.84)

✓ abs. flux (0.3–10 keV): 2.1e–12 erg/cm2/s

Chandra (Matheson et al. 2013)



PL

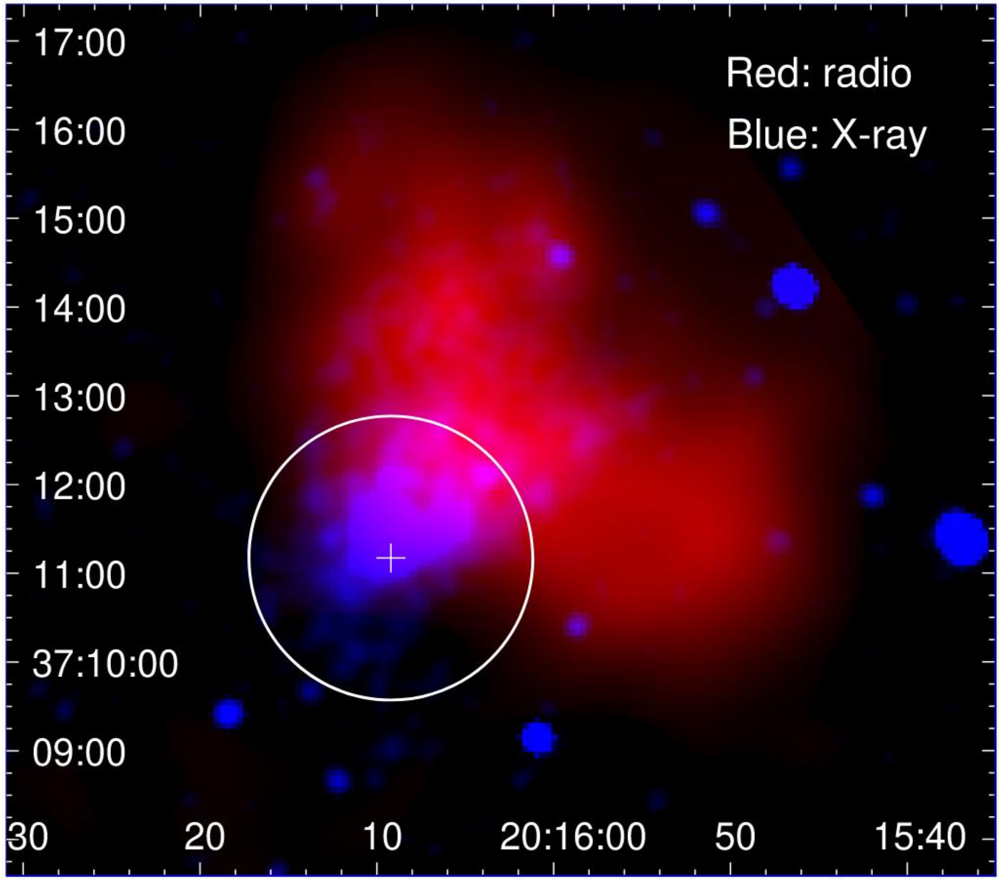
✓ index : 1.91 (1.84–1.99)

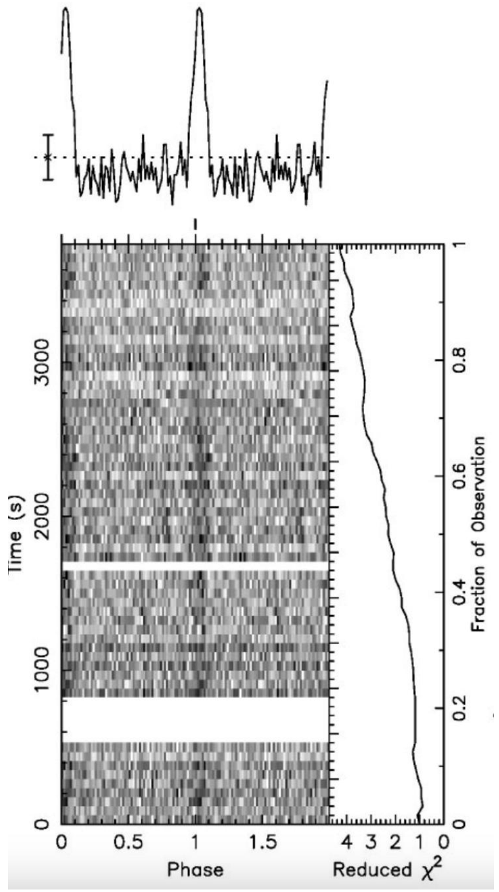
✓ abs. flux (0.3–10 keV): 1.6e–12 erg/cm2/s

XMM (Guest et al. 2020)

An Evolved PWN like Vela-X!

Introduction: Discovery of PSR J2016-3711





$$P = 50.81 \text{ ms}$$

$$\dot{P} = 7.27 \times 10^{-14} \text{ s s}^{-1}$$

$$B = 1.9 \times 10^{12} \text{ G}$$

$$\text{DM} = 428.0 \text{ pc cm}^{-1}$$

$$\tau_c = 11.1 \text{ kyr}$$

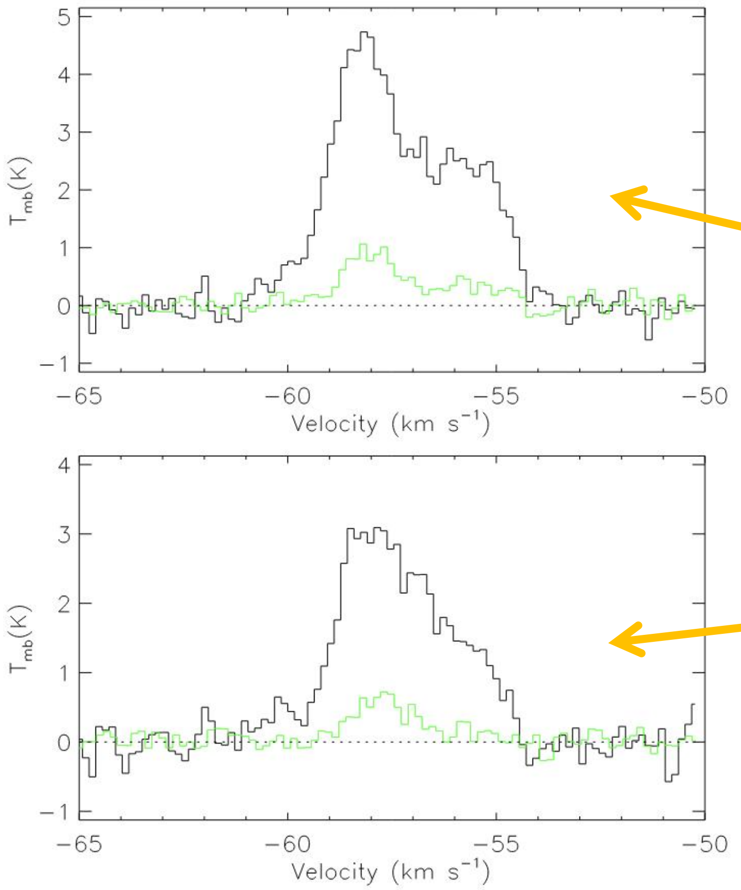
$$L_{\text{SD}} = 2.2 \times 10^{37} \text{ erg s}^{-1}$$

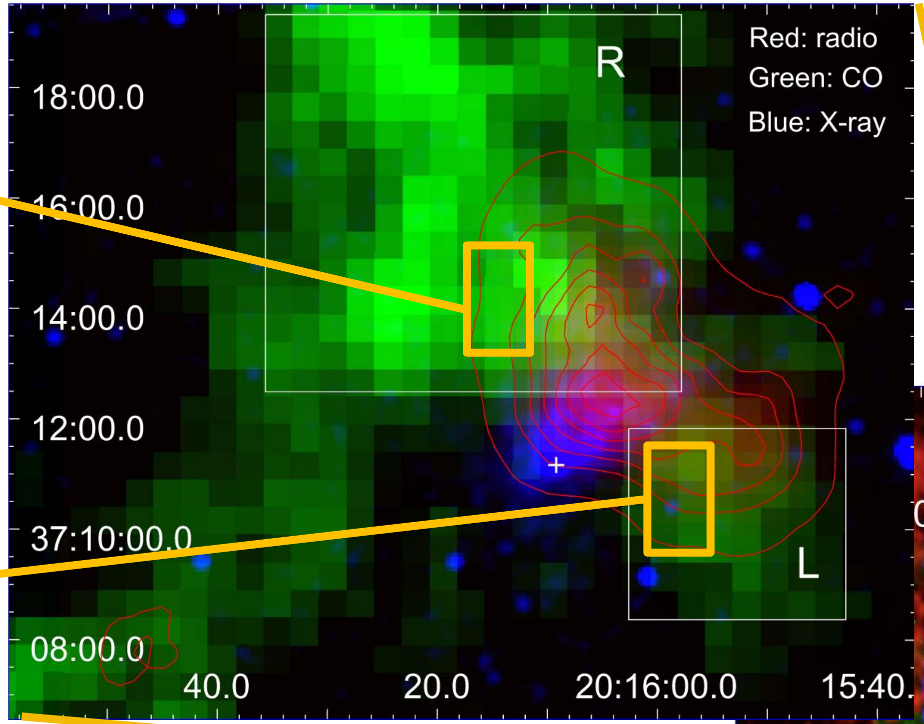
$$d_{\text{DM}} = 13.3 \text{ kpc}$$

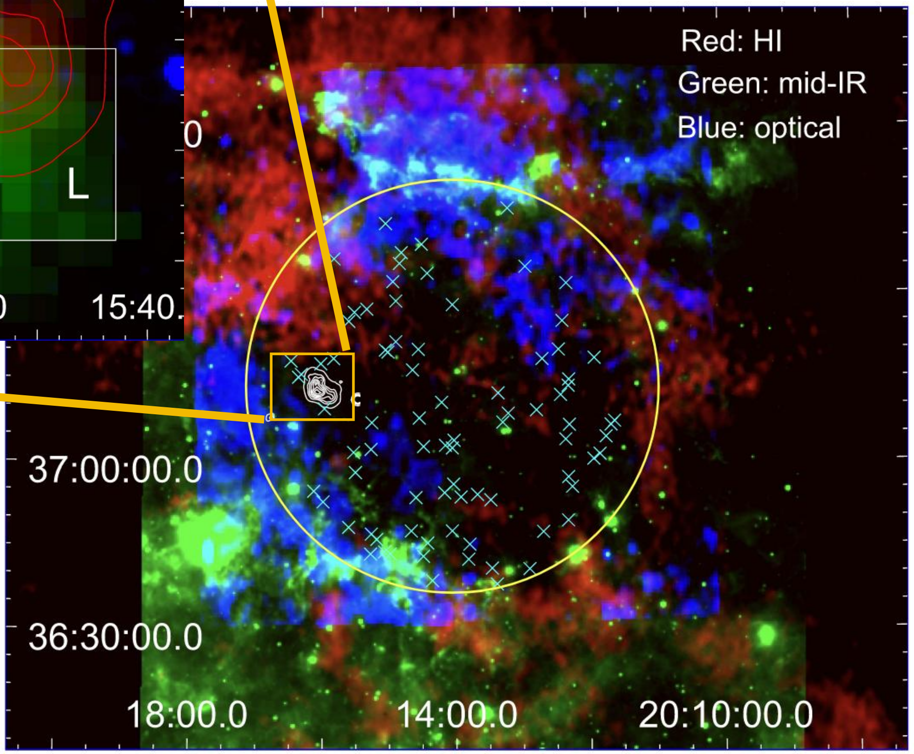
Circle: the beam size of Five-hundred-meter Aperture Spherical radio Telescope (FAST)

Liu Q. C, et al., 2024

Introduction: CO observations and environments





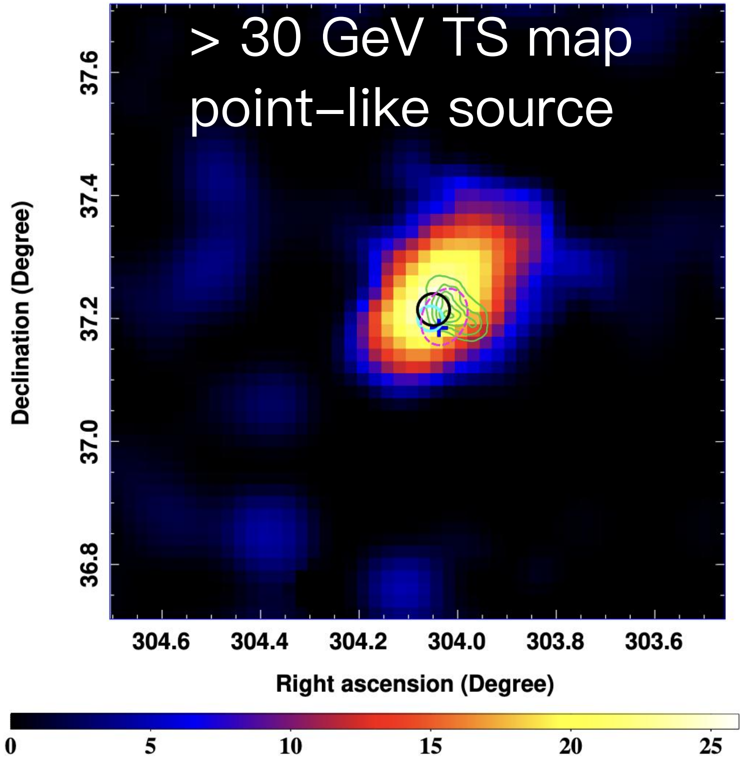


−60 to −54 km/s
(d ~ 6.1 kpc)

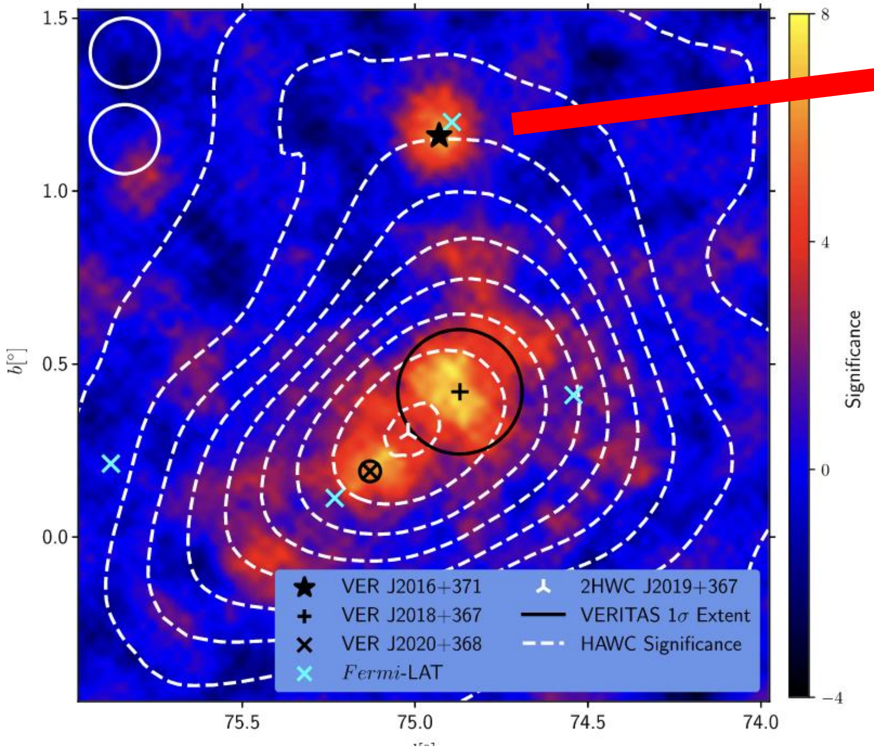
Liu Q. C, et al., 2018

the radio relic (compact) is part of SNR

Introduction: GeV and TeV

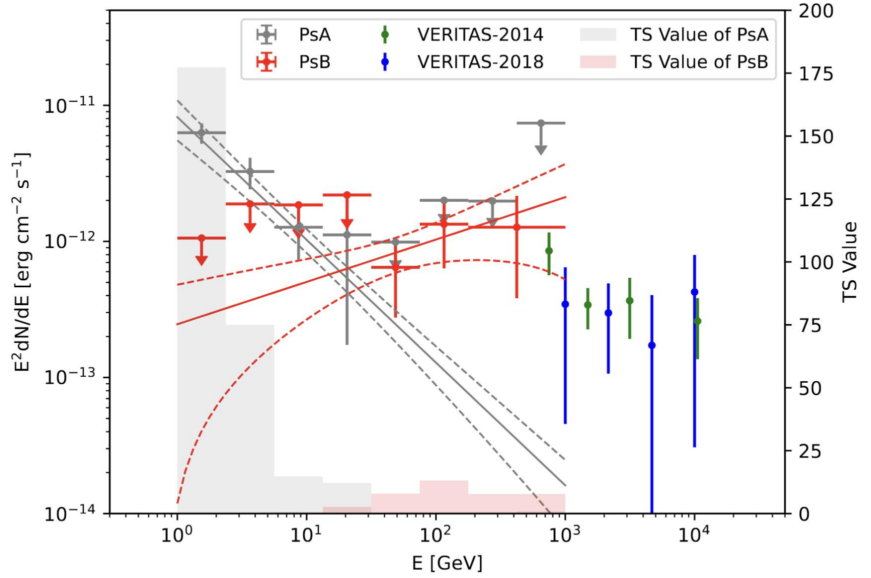


Xin et al. 2025
gong et al. 2025



VERITAS significance map
Abeysekara et al. 2018

CTB 87

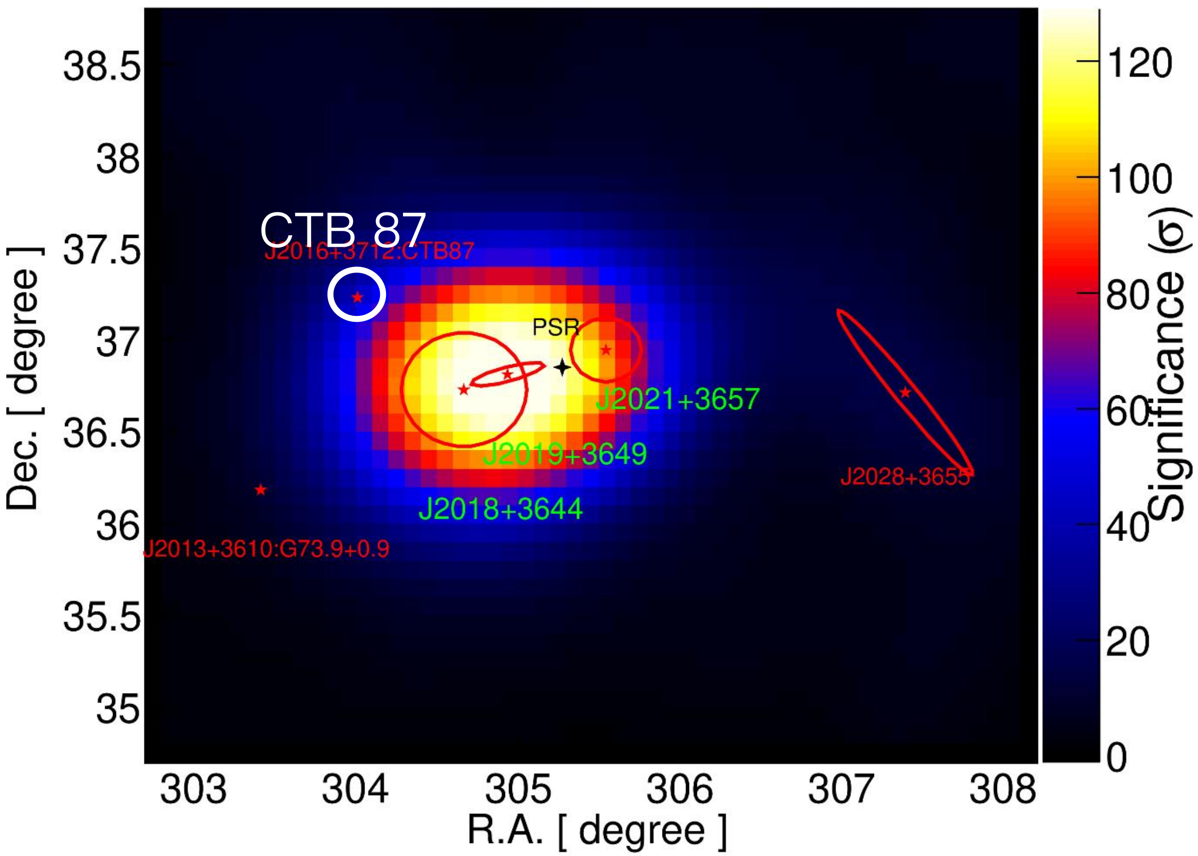


LHAASO data analysis

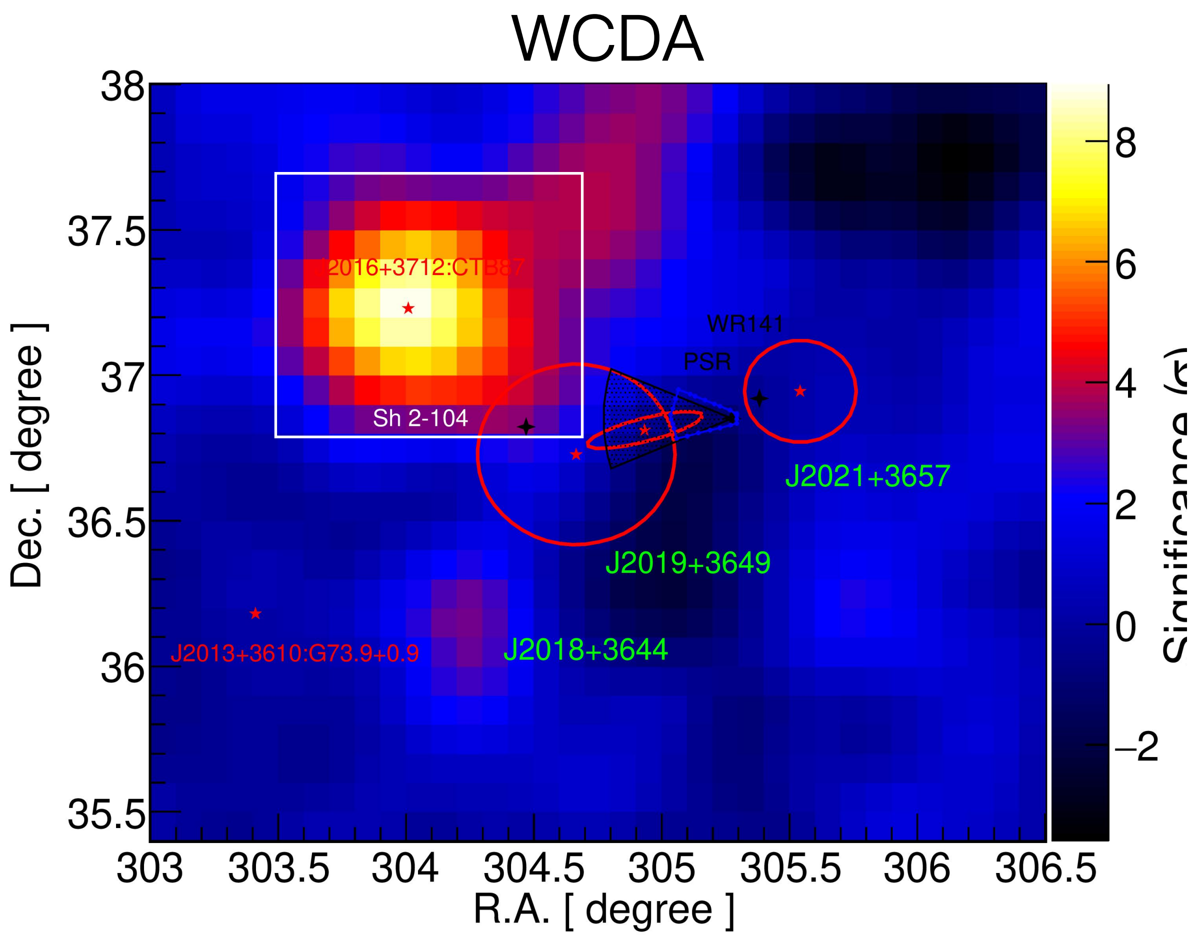
performed by Li, Huicai

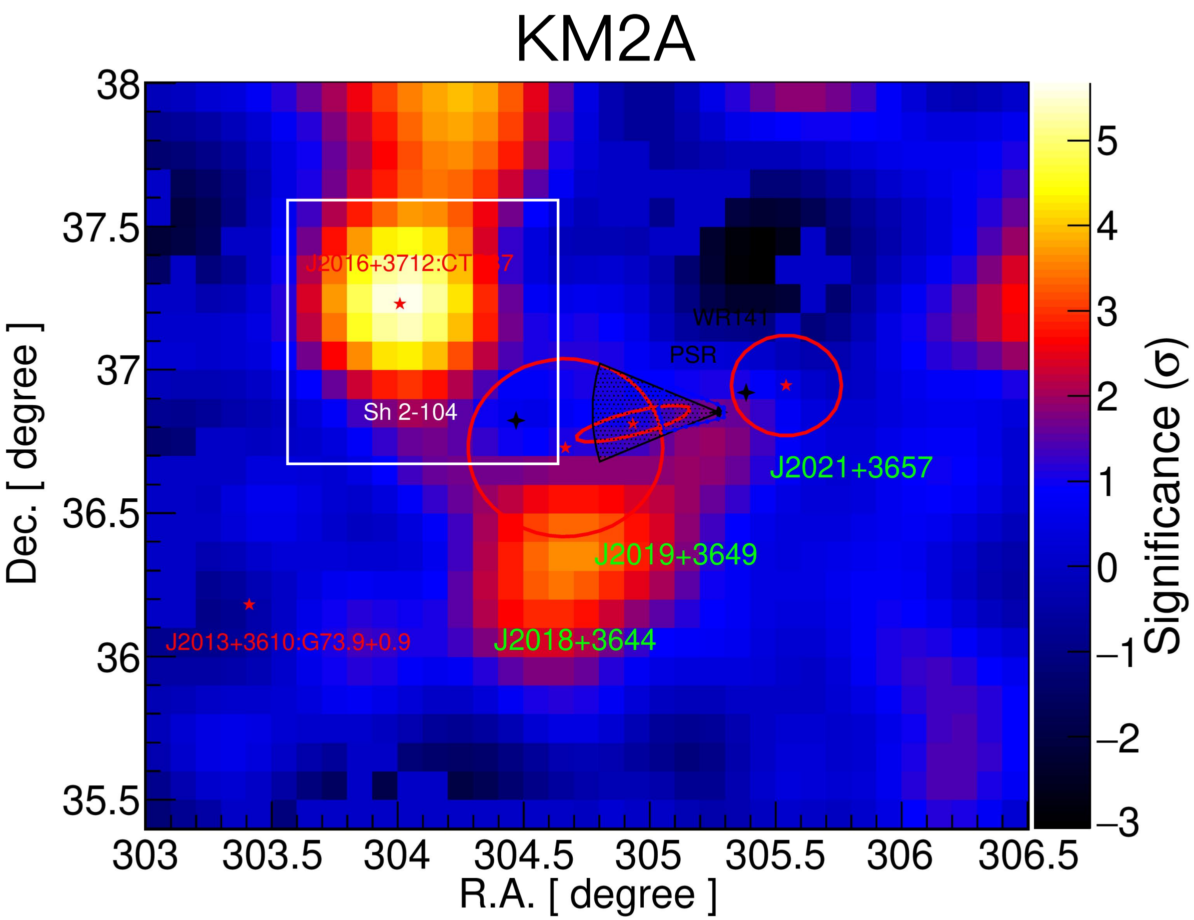
- **Data:**
  - WCDA Full-Array: 2021-03-08 to 2024-7-31, 1136 days
  - KM2A Full-Array: 2021-07-20 to 2024-07-31, 1065 days
  - KM2A 1/2Array: 2019-12-27 to 2020-11-30, 290 days
  - KM2A 3/4Array: 2020-12-01 to 2021-07-19, 215 days
- **Analysis:**
  - Selection: Same as Crab analysis (CPC paper)
  - Background estimation: direct integration method
  - Method: 3D Likelihood analysis
  - DGE: Planck Dust model

LHAASO J2018+3651 region



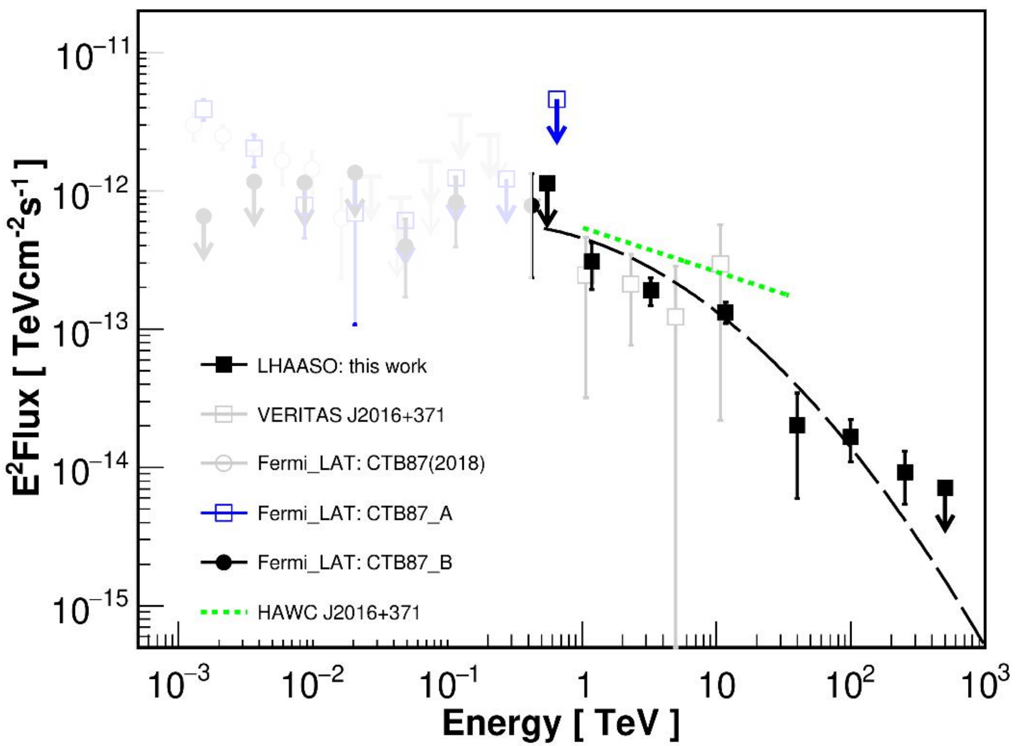
LHAASO significance map

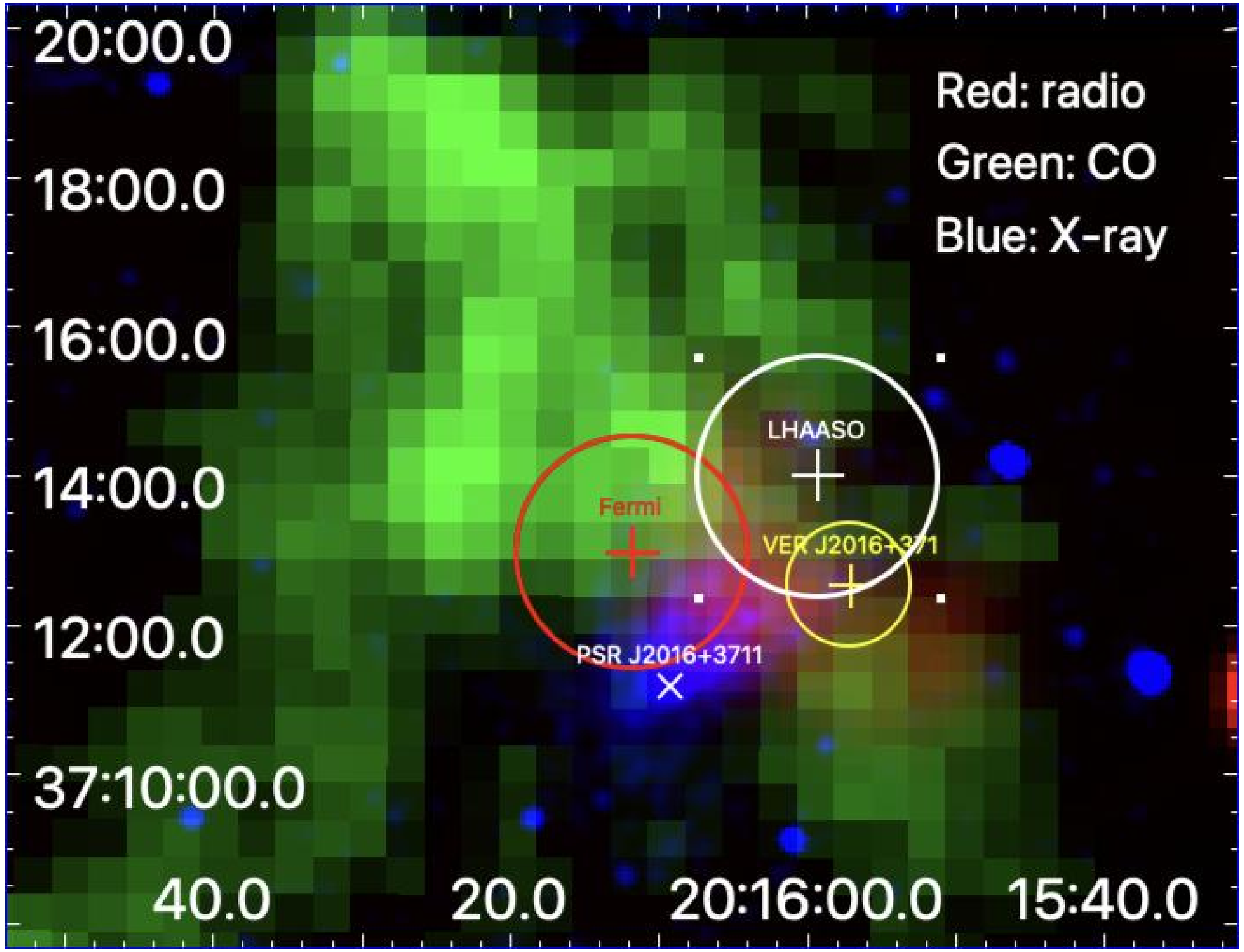




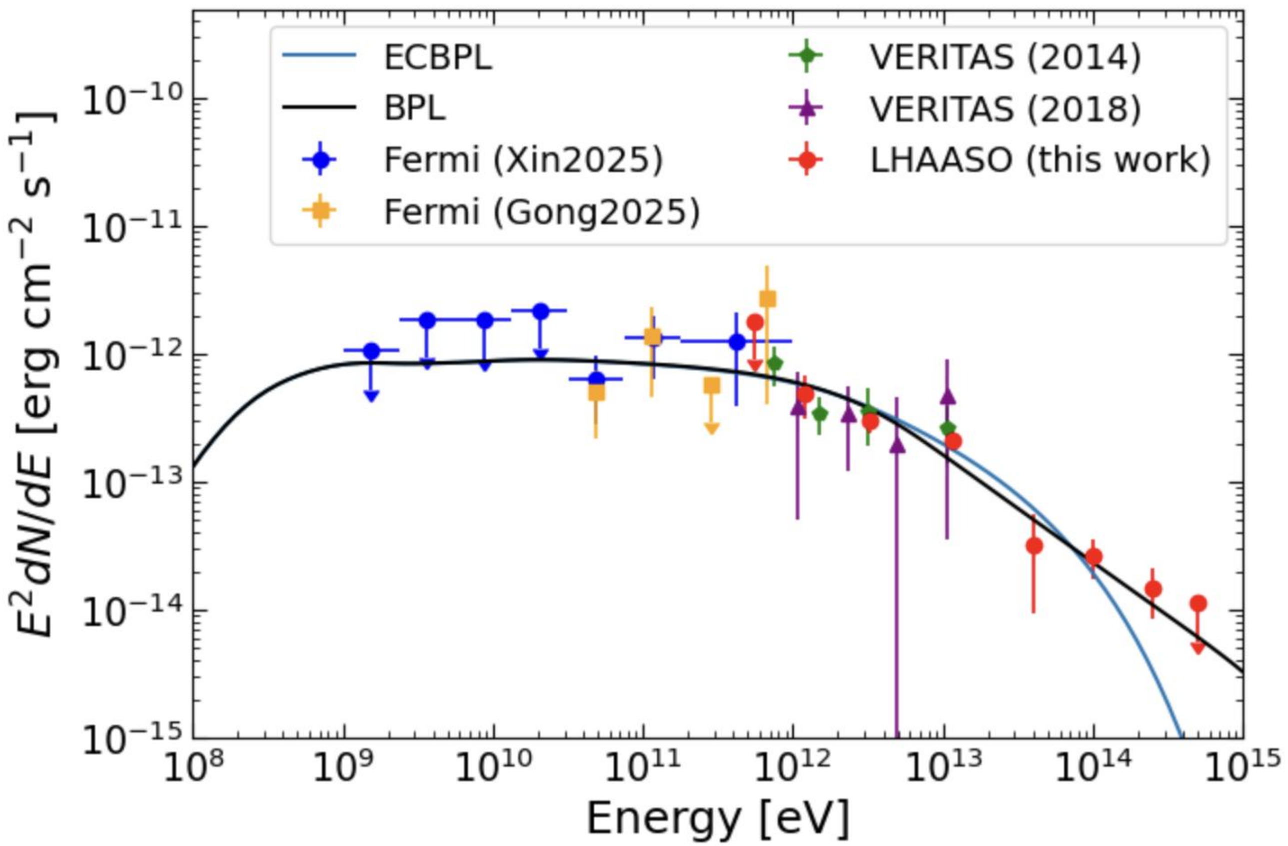
point-like source, TS ~ 101

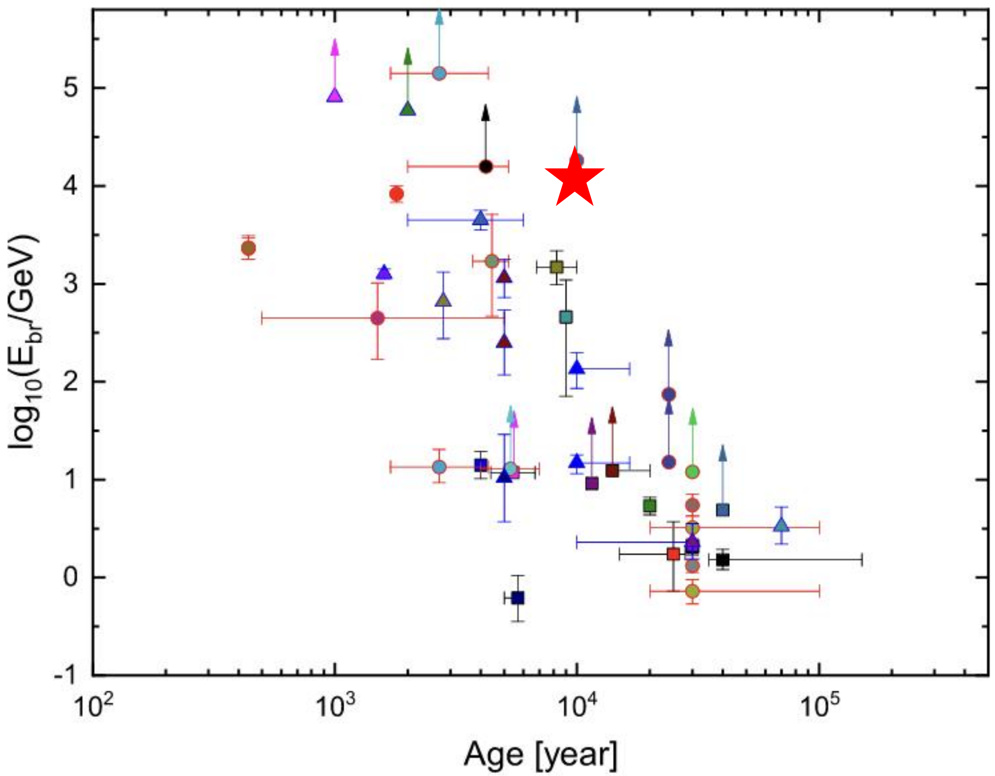
Reuslts and Multiwavelength scan





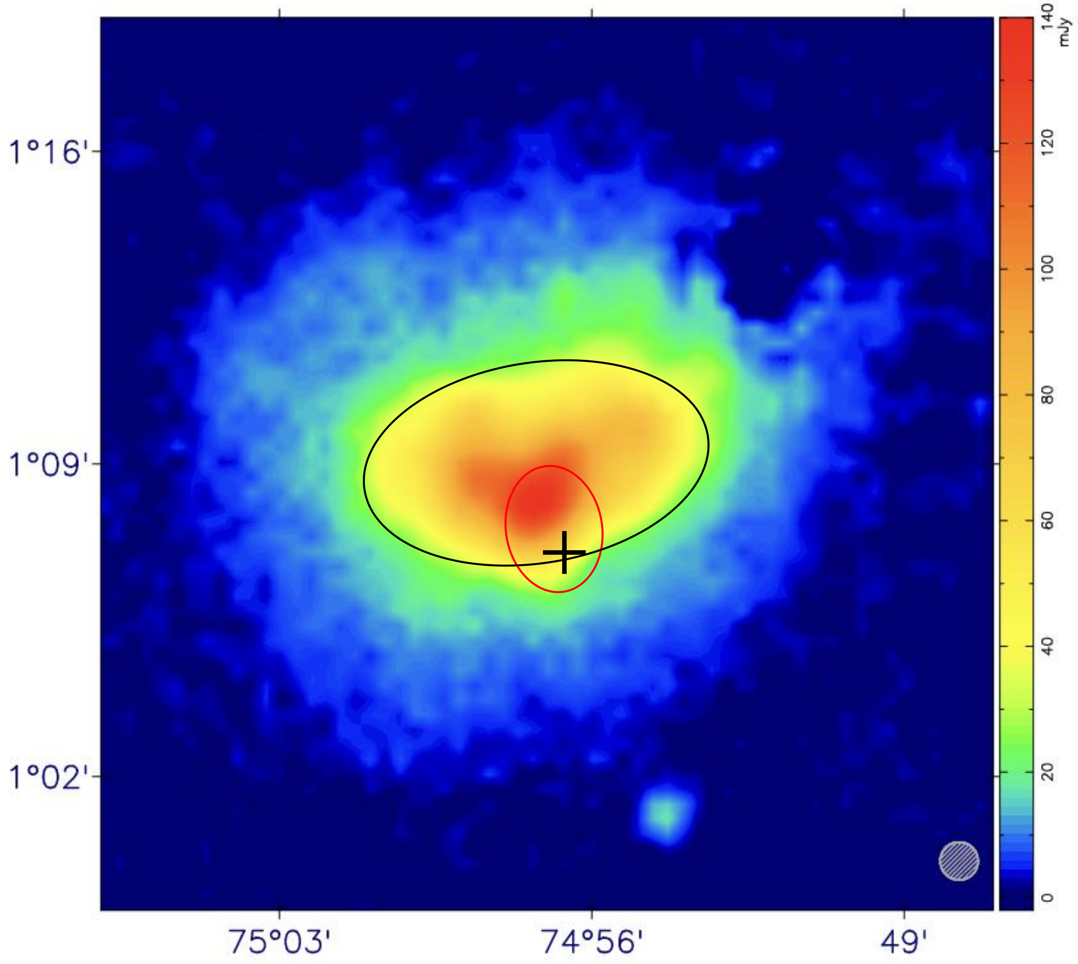
Origin of the gamma-ray: SNR Scenario





BPL: nH ~ 80 cc,
alpha1~2.1, alpha2~2.9, Ebre ~ 15 TeV, Wp ~ 2.1e48 erg

Origin of the gamma-ray: PWN Scenario



The electrons are divided into two 'generations':

(1) evolved electrons

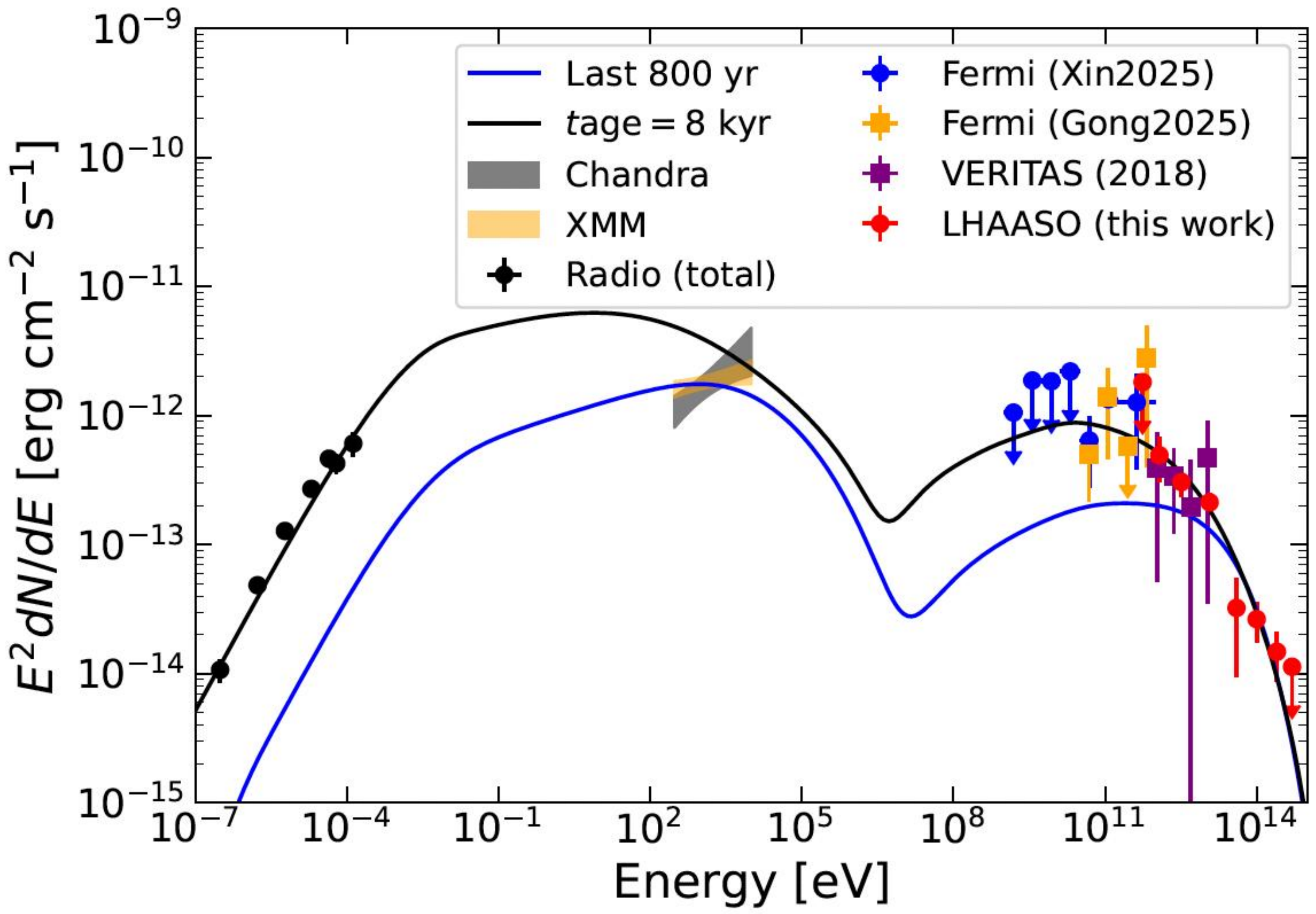
(2) young (fresh injection) electrons produce the X-ray emission.

Model

$$\frac{\partial N(\gamma,t)}{\partial t} = -\frac{\partial}{\partial \gamma}[\dot{\gamma}(\gamma,t)N(\gamma,t)] - \frac{N(\gamma,t)}{\tau(\gamma,t)} + Q(\gamma,t),$$

$$Q(\gamma,t) = Q_0(t)\begin{cases} \left(\frac{\gamma}{\gamma_b}\right)^{-\alpha_1} & \text{for} \quad \gamma \le \gamma_b, \\ \left(\frac{\gamma}{\gamma_b}\right)^{-\alpha_2} & \text{for} \quad \gamma > \gamma_b, \end{cases}$$

Origin of the gamma-ray: PWN Scenario



params	value
alpha_1	1.55
alpha_2	2.75
gamma_b	2e5
eta_B	0.07
B	10.0

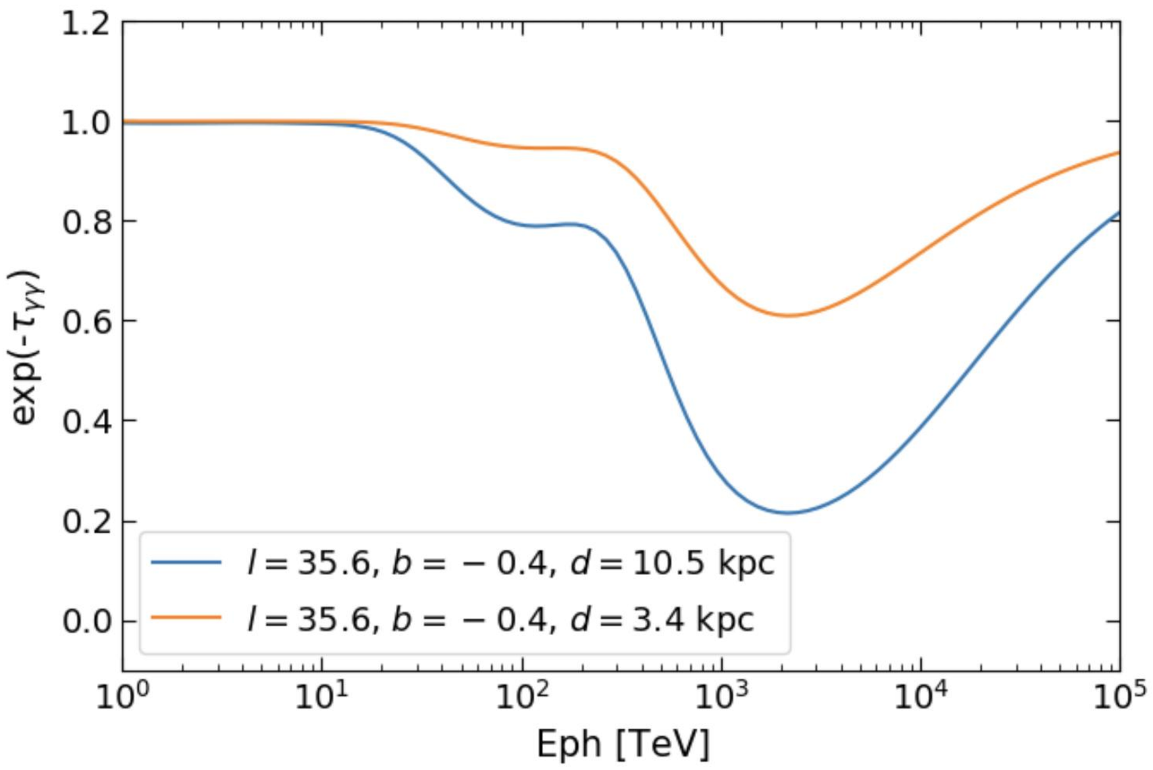
Summary

- G35.6-0.4
  - A gamma-ray source, closing to SNR G35.6-0.4, is detected by WCDA (extended, r39~0.18deg) and KM2A (PS).
  - It seems unlikely that the gamma-rays are from the clouds illuminated by the protons escaped from SNR G35.6-0.4.
  - The HII region or ancient PWN model are possible.
- CTB87
  - Based on WCDA and KM2A data, CTB 87 was detected as a point-like source with ~10sigma.
  - PWN scenario can explain the broadband SED, althoug the SNR model can not be ruled out.

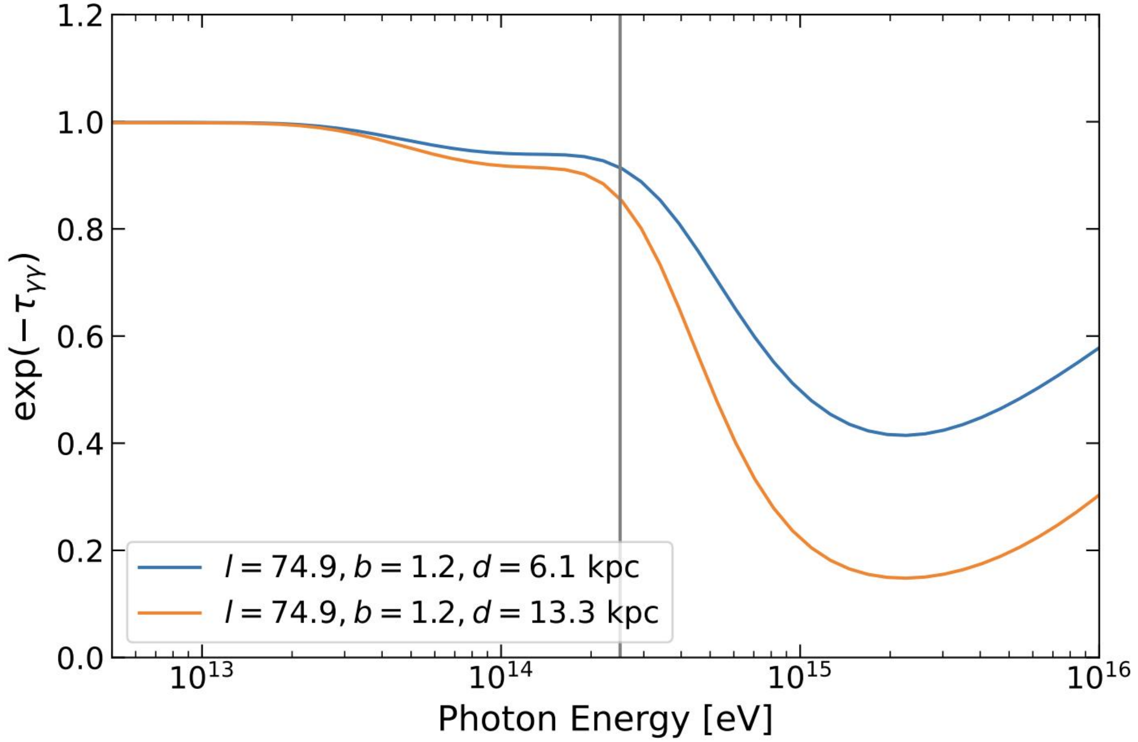
For both cases, >100 TeV gamma-rays are detected, but it is difficult to attribute them to SNRs.

Thanks

Discusssion: Gamma–Gamma absorption



G35.6–0.4



CTB 87

LHAASO data analysis

- WCDA (1-30 TeV)

Data: Full array 508 d (2021/03/05-2022/09/30);

ROI: 4 deg x 4 deg

Source name	Free parameters
1LHAASO J1858+0330	norm
1LHAASO J1857+0203u	norm, index, ext, RA, Dec
1LHAASO J1857+0245	norm, index, ext
1LHAASO J1852+0050u	norm, index, ext
1LHAASO J1850−0004u	norm
GDE is free, impact on flux ~ 7%	

1LHAASO J1857+0203u:

- R.A. = $284.51^{\circ} \pm 0.07^{\circ}_{stat} \pm 0.04^{\circ}_{sys}$
- Dec = $1.98^{\circ} \pm 0.09^{\circ}_{stat} \pm 0.04^{\circ}_{sys}$
- r39 = $0.18^{\circ} \pm 0.03^{\circ}_{stat} \pm 0.05^{\circ}_{sys}$ (TS_{ext} = 25.2)
- $\Gamma = 2.47 \pm 0.10_{stat}$

almost consistent with the results in the catalog paper

LHAASO data analysis

- KM2A (> 25 TeV)

Data: 1/2array (296 d) + 3/4array (217 d) + full array (420 d)

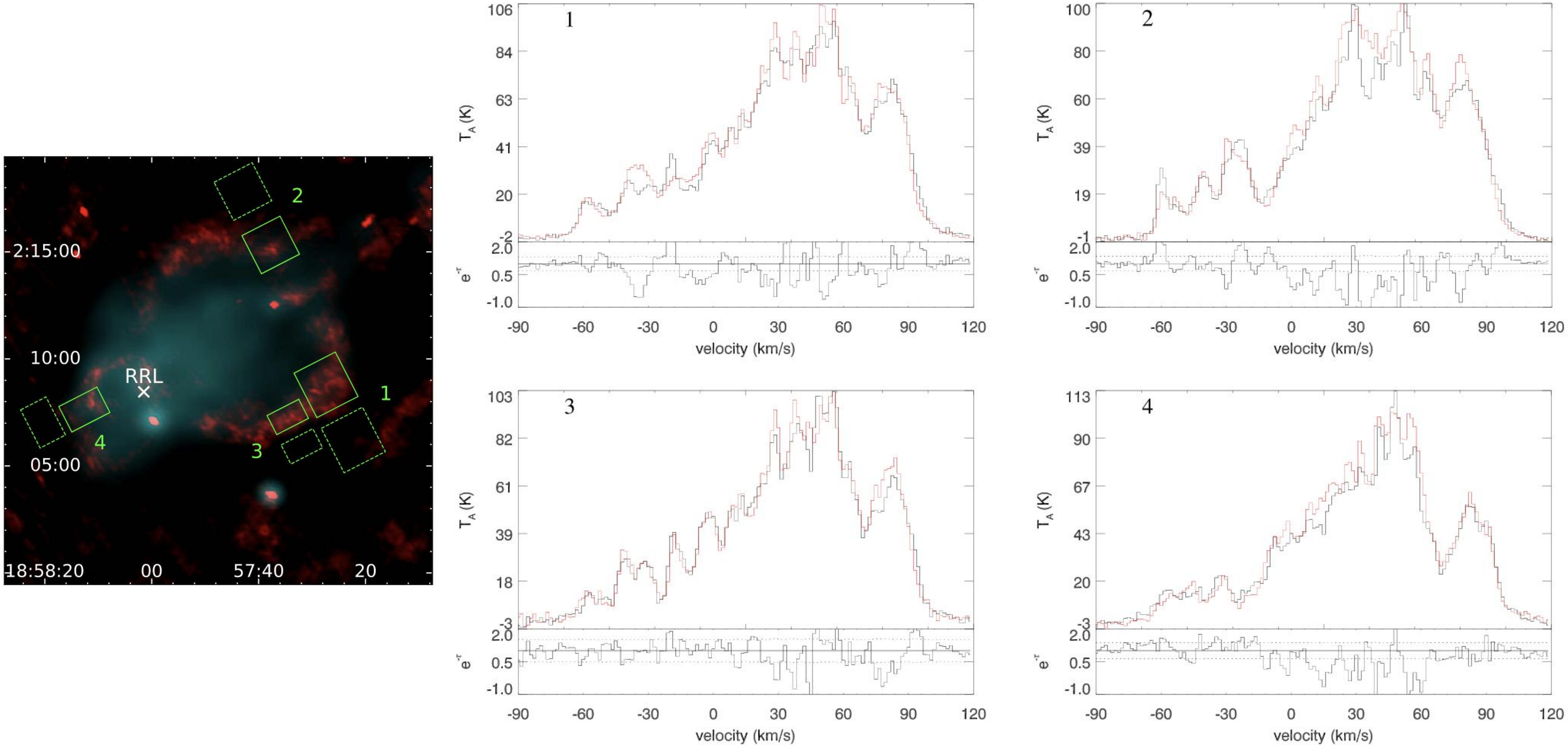
ROI: 4 deg x 4 deg

	GDE fixed	GDE free
Point	P1	P2
Gaussian	G1	G2
G0：catalog and refit		

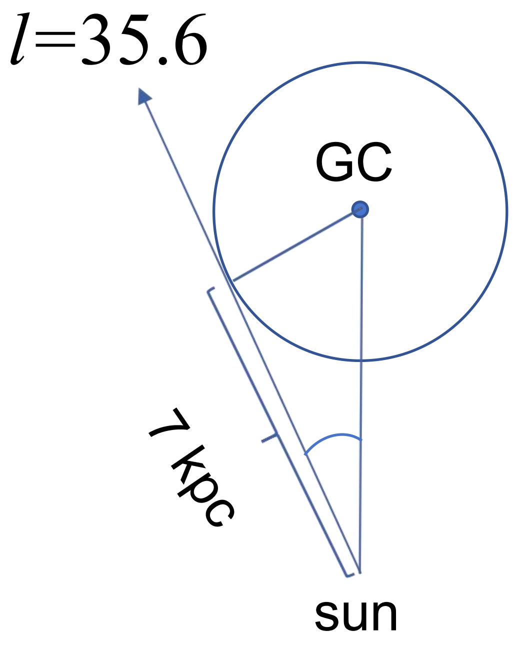
1LHAASO Sources	Component	R.A. (°)	Dec (°)	Extension [a] (°)
1LHAASO J1858+0330	WCDA	284.79	3.70	0.52
	KM2A	284.64	3.73	0.33
1LHAASO J1857+0245	WCDA	284.37	2.75	0.23
new src (TS~60)	KM2A	284.41	2.80	0.21
1LHAASO J1857+0203u	WCDA	284.51	1.98	0.18
	KM2A	284.44	2.02	–
1LHAASO J1852+0050u	WCDA	283.73	1.40	0.54
	KM2A	283.47	1.26	0.47
1LHAASO J1850−0004u	WCDA	282.74	−0.07	0.46
	KM2A	282.83	−0.04	0.21

Models	R.A. (°)	Dec (°)	Extension [a] (°)	Δk [b]	ΔAIC [b]
G0	284.38	2.07	0.29	0	0
P1	284.45	2.02	–	4	−26.4
G1	284.42	2.04	0.21	5	−28.8
P2	284.44	2.02	–	6	−35.4
G2	284.42	2.03	0.15	7	−37.0

$TS_{ext} < 4$


2:15:00
10:00
05:00
18:58:20
00
57:40
20
RRL
1
2
3
4
T_A (K)
e^-τ
velocity (km/s)

Scenario 3: the ancient PWN model



■ Seed photons and Distance

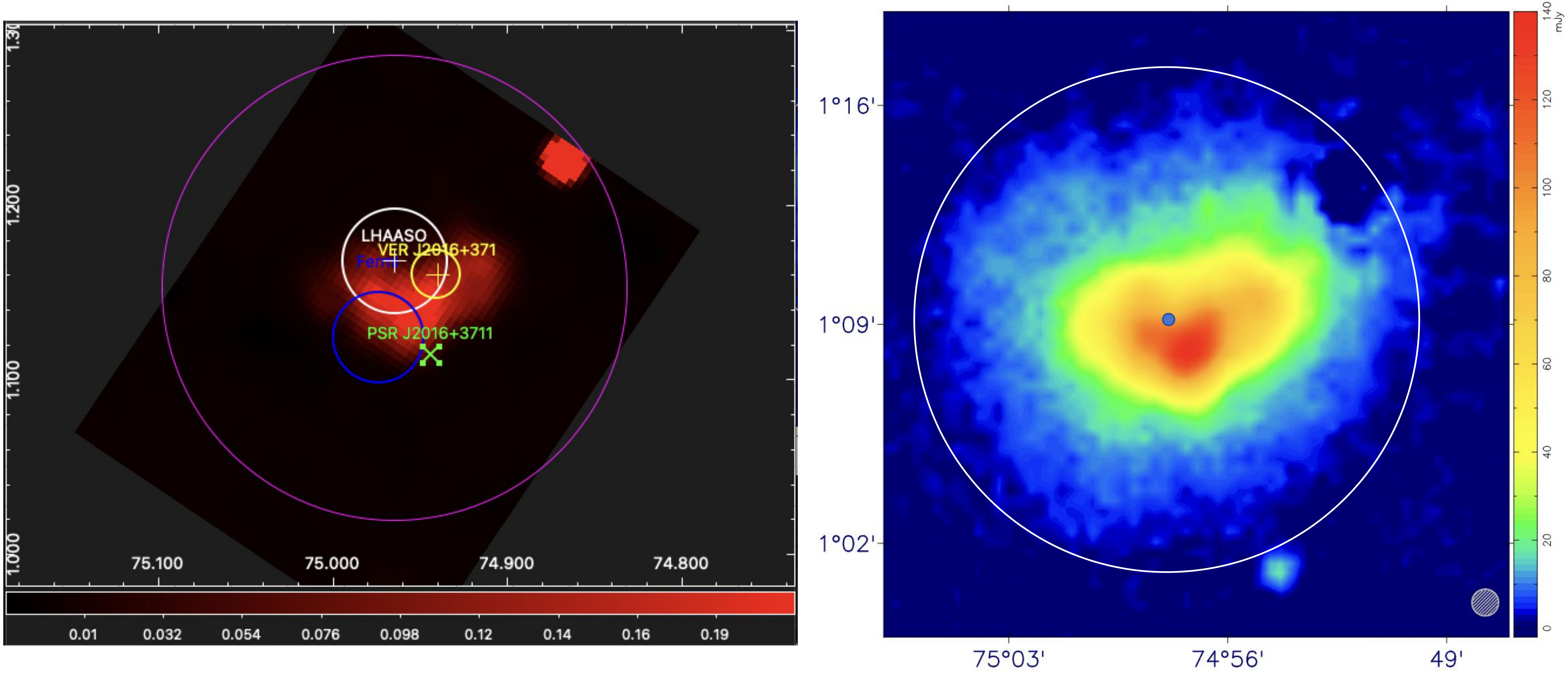
the energy density of IR [~0.4, ~0.8] eV/cm3 for *d* in [1, 7] kpc

U_{IR} ~ 0.6 eV/cm3 (*d* ~ 3.4 kpc) is adopted

■ The *t*-integrated spectrum of leptons (Zhang+2020)

$$\frac{dN}{dE_e} = A_e E_e^{-\alpha_1} \left[1 + \left(\frac{E_e}{E_b}\right)^s\right]^{\frac{\alpha_1 - \alpha_2}{s}} \exp\left[-\left(\frac{E_e}{E_{ecut}}\right)^\beta\right]$$

Parameters: $\beta = 3$, $s = 1$, α_1, α_2, E_b, E_c, W_e



LHAASO
VER J2016+371
Fermi
PSR J2016+3711
1.300
1.200
1.100
1.000
75.100
75.000
74.900
74.800
0.01
0.032
0.054
0.076
0.098
0.12
0.14
0.16
0.19
1°16'
1°09'
1°02'
75°03'
74°56'
49'
140
120
100
80
60
40
20
0
mJy

	Boomerang (G106)	CTB 87
P	51.65 ms	50.80 ms
Pdot	7.73871e–14	7.2471e–14
DM	205.1	428.0
d_DM	3.0	13.3
age	1.06e4	1.11e4
L_sd	2.2e37	2.2e37