

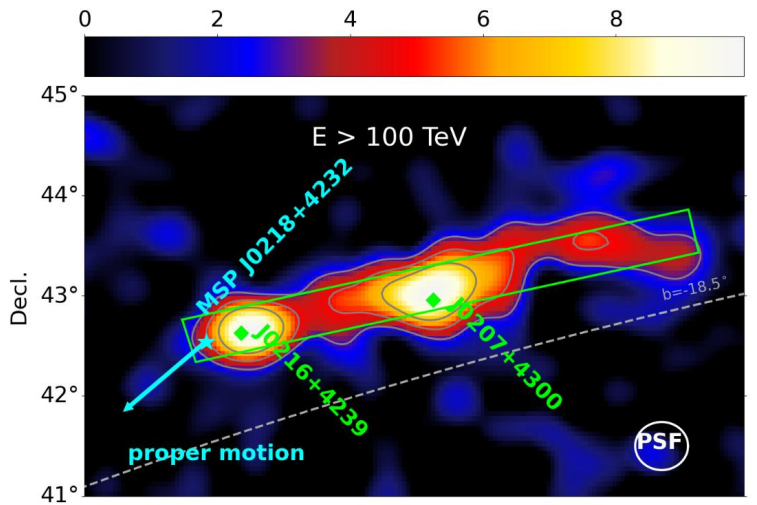
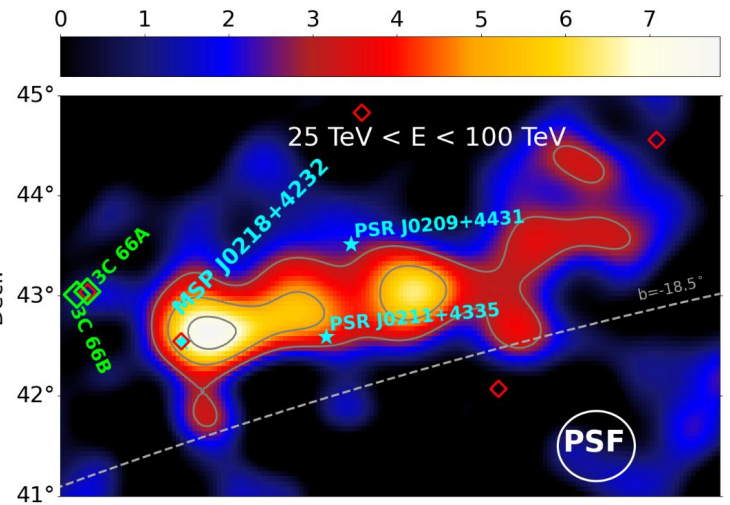
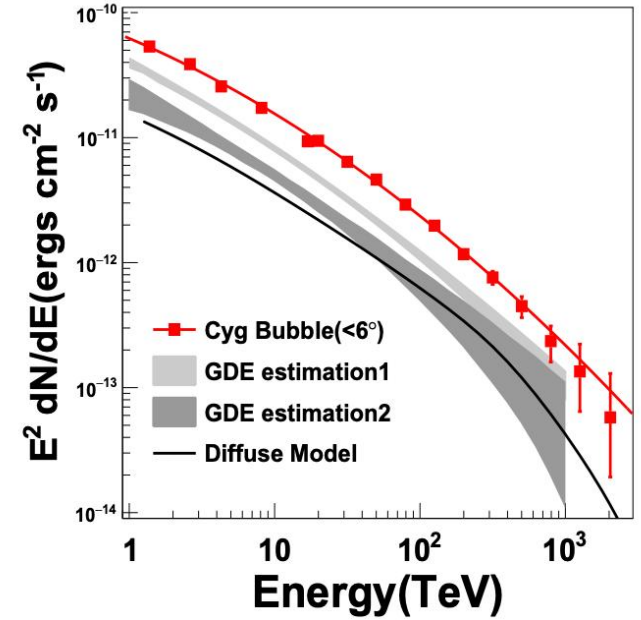
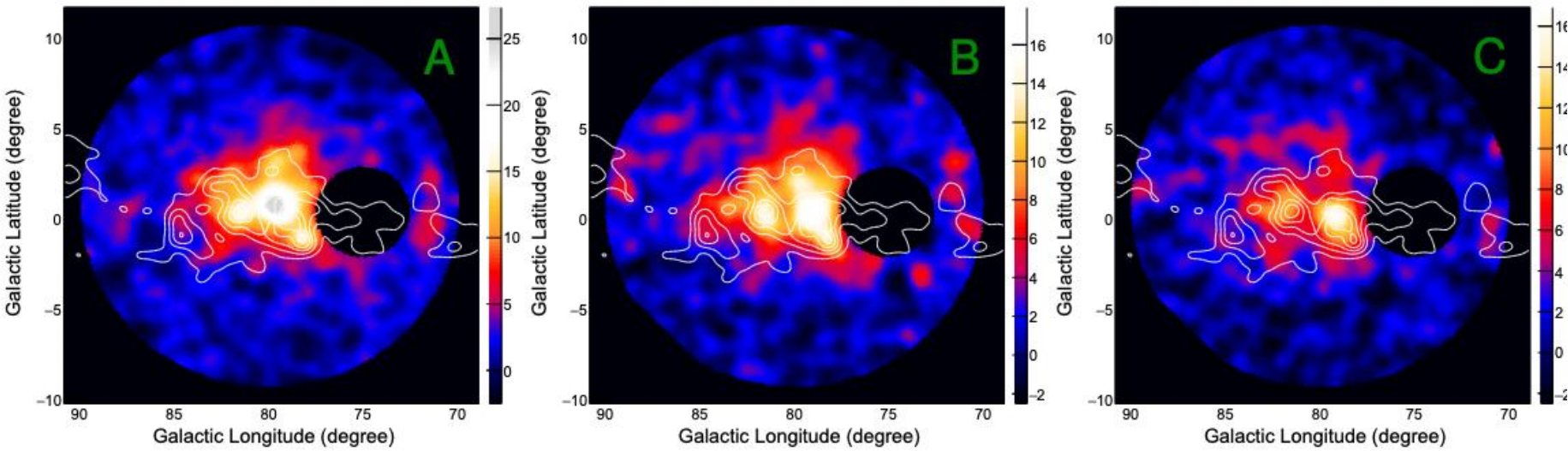
Ultrahigh-Energy Gamma-Ray Emission with an Elongated Morphology



Speaker: Tianyang Li

Collaborators: Felix Aharonian, Cong Li, Shaoqiang Xi,
Yifan Xiao, Hao Zhou

Search for Galactic PeVatrons with LHAASO



- LHAASO has unprecedented sensitivity.
- Sources with hard spectra may indicate the presence of PeVatrons.
- Extended gamma-ray morphology can reveal cosmic-ray propagation.

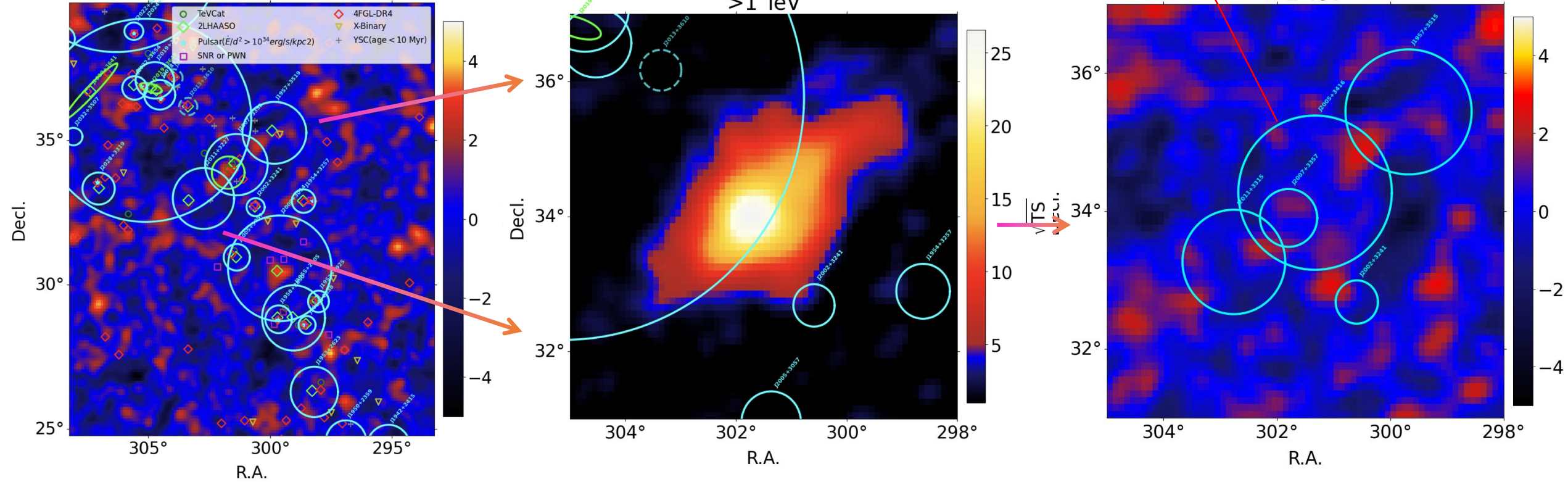
Data configuration

- Pass 5 data: updated to 2025-07-31
 - WCDA: ~ 1484.36 days
 - KM2A: ~ 1944.30 days
- Angular resolution
 - WCDA: $0.50^\circ @ 1\text{TeV}$
 - KM2A: $0.36^\circ @ 40\text{TeV}$

Primary Fitting

See Fangyu Liu's talk
yesterday

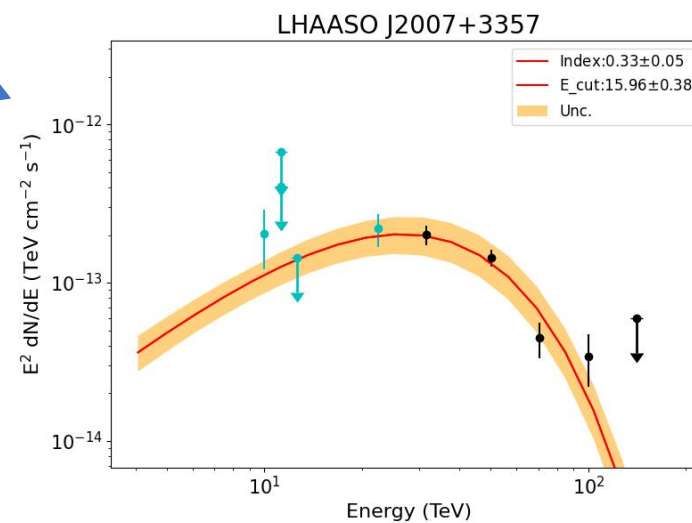
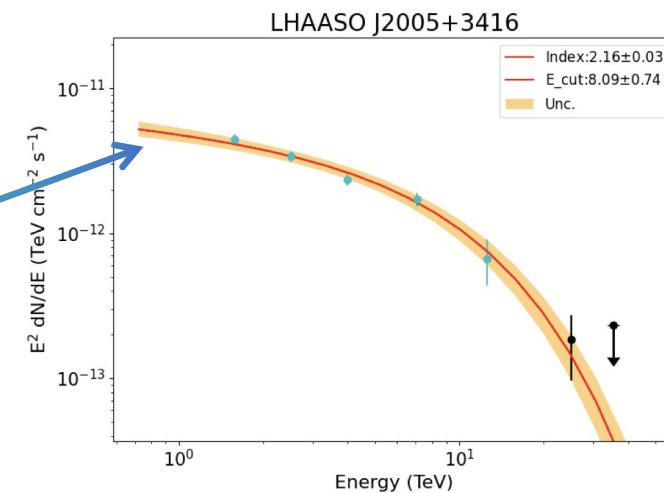
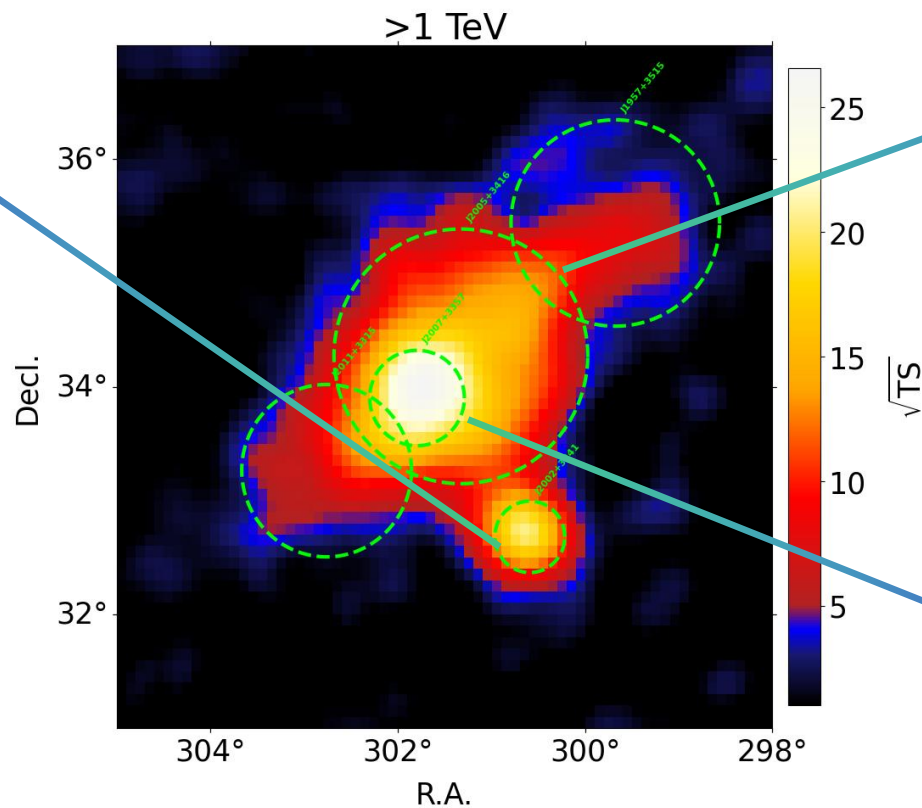
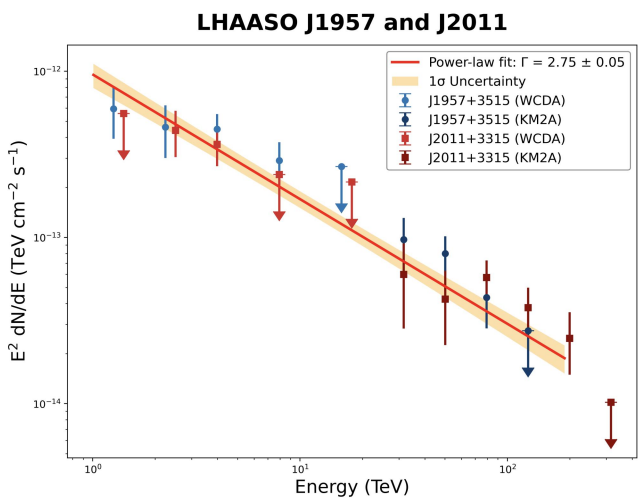
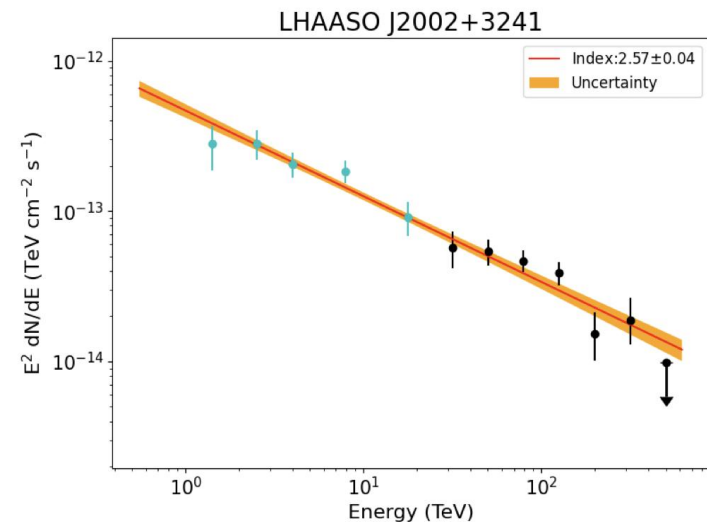
Following 1 LHAASO catalog procedure, add source with $TS > 25$
>1 TeV



- roi:
 - ra: [293.25, 308.25]
 - dec: [24.77, 39.77]

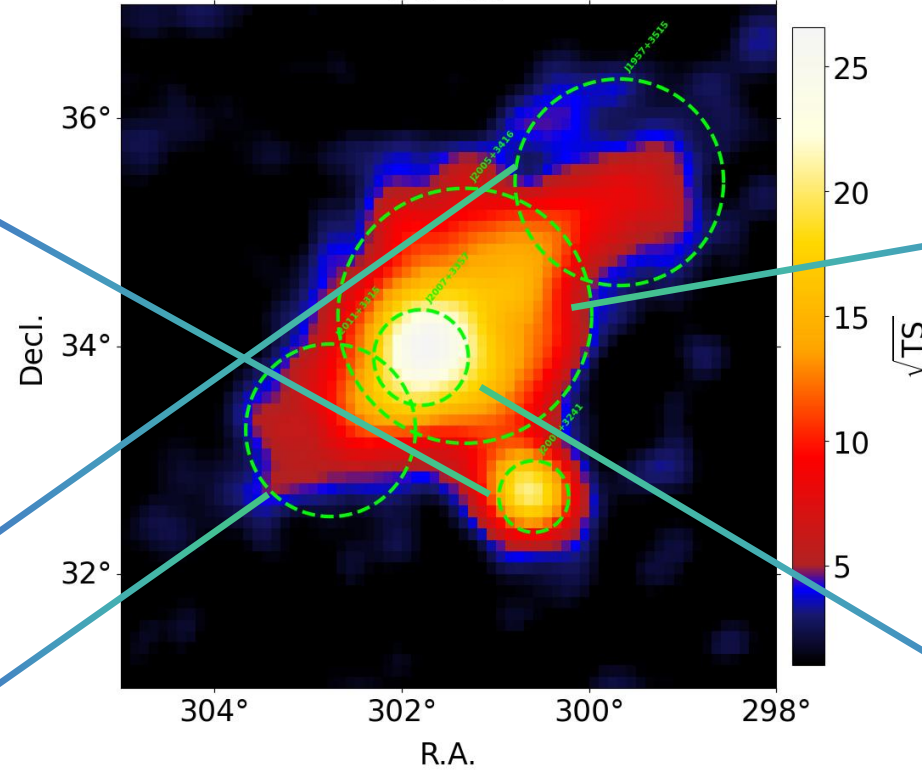
- roi:
 - ra: [298, 305]
 - dec: [31, 37]

Refitting in Zoomed Region

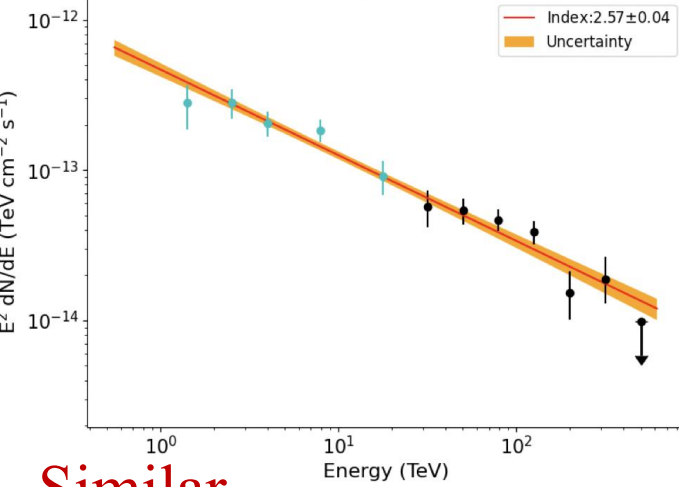


Refitting in Zoomed Region

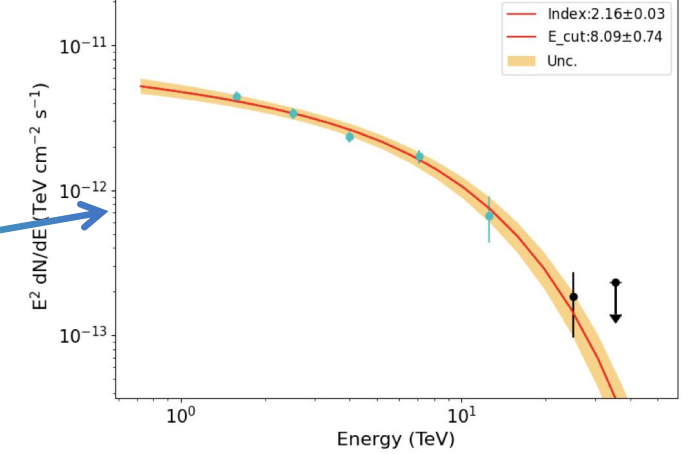
>1 TeV



LHAASO J2002+3241

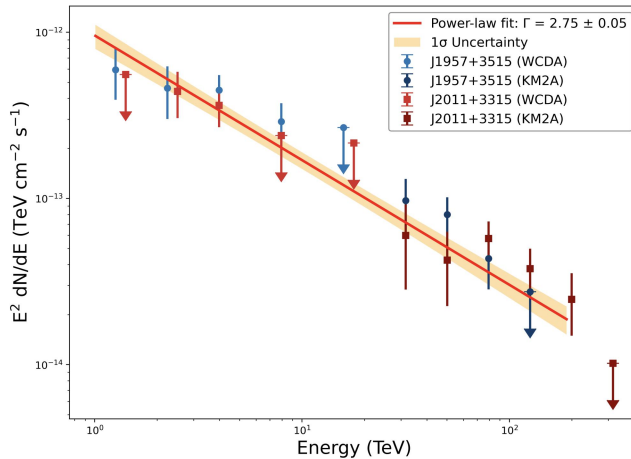


LHAASO J2005+3416

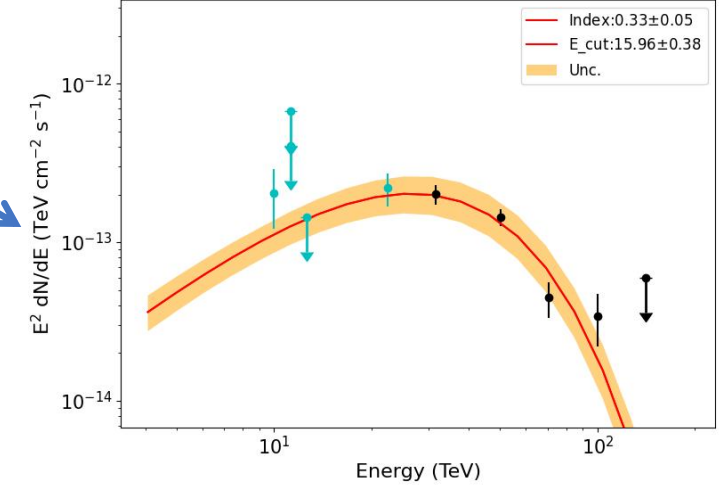


Similar

LHAASO J1957 and J2011



LHAASO J2007+3357



	$F0 \cdot 1e-15 (\text{TeV}/\text{cm}^2/\text{s})$	Index
J1957+3515	1.700 ± 0.195	2.7501 ± 0.0523
J2011+3315	1.356 ± 0.179	2.6757 ± 0.0572
J2002+3241	1.2558 ± 0.0731	2.5699 ± 0.0365

Morphology

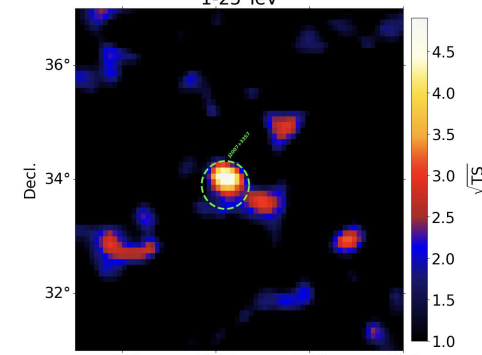
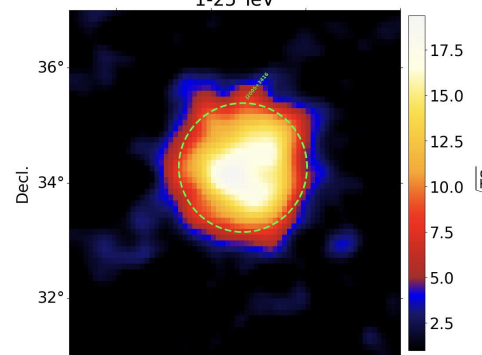
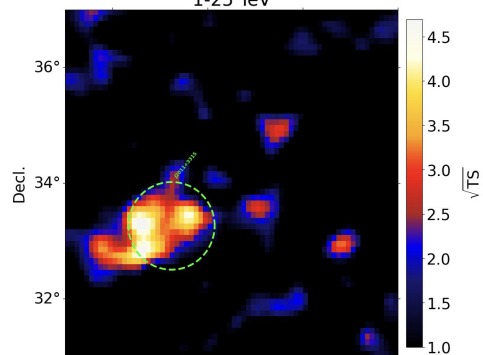
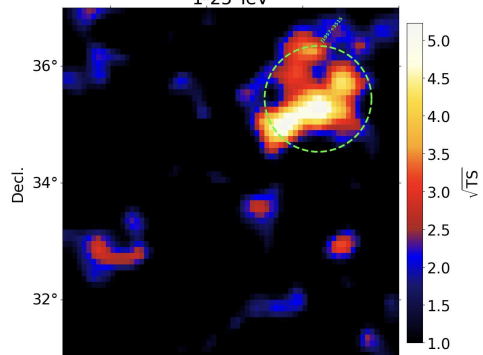
J1957+3515
1-25 TeV

circle is unsuitable J2011+3315
1-25 TeV

J2005+3416 **wcda bright**
1-25 TeV

J2007+3357
1-25 TeV

Energy

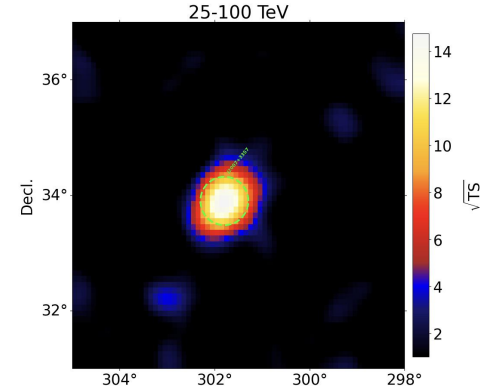
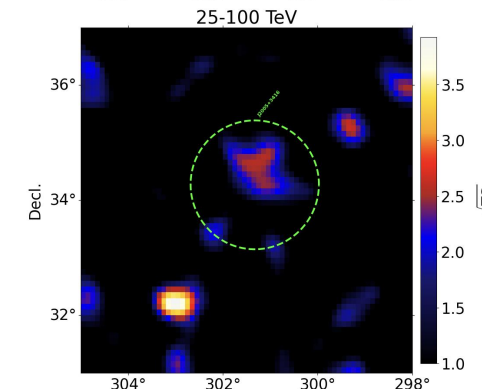
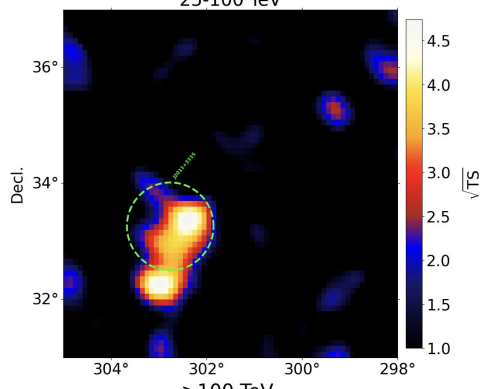
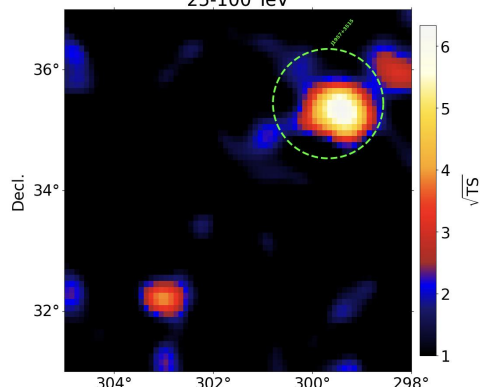


25-100 TeV

25-100 TeV

25-100 TeV

25-100 TeV

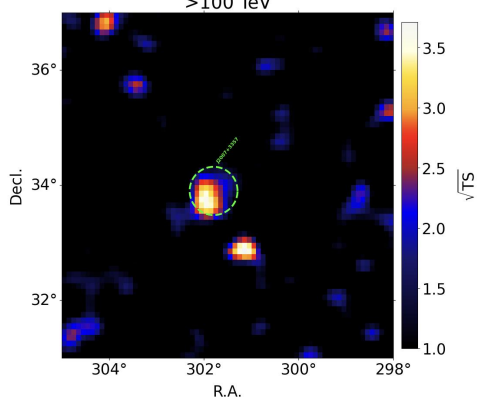
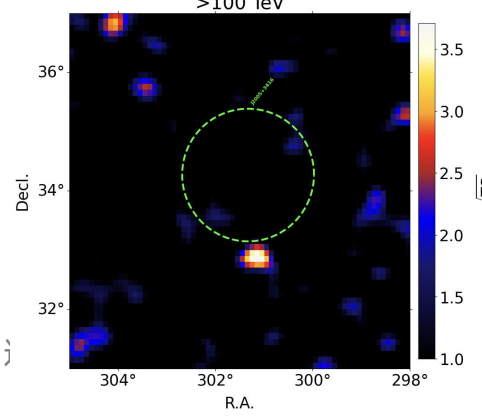
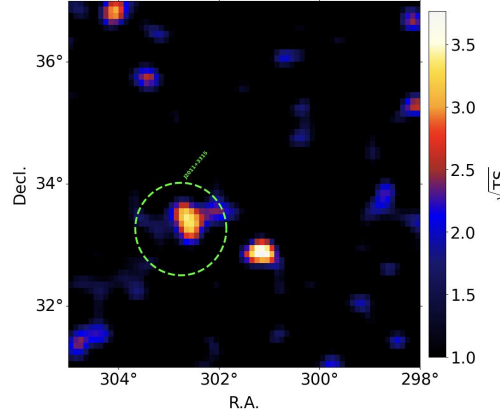
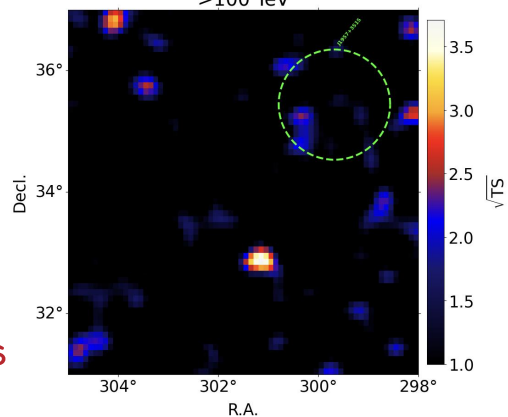


>100 TeV

>100 TeV

>100 TeV

>100 TeV

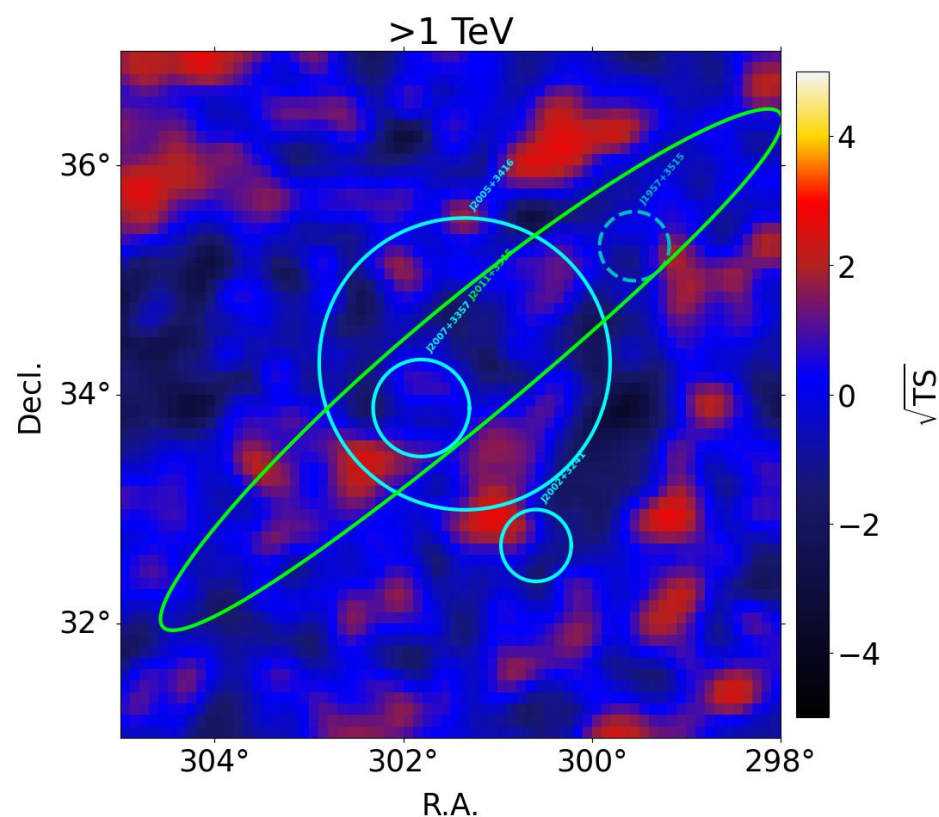
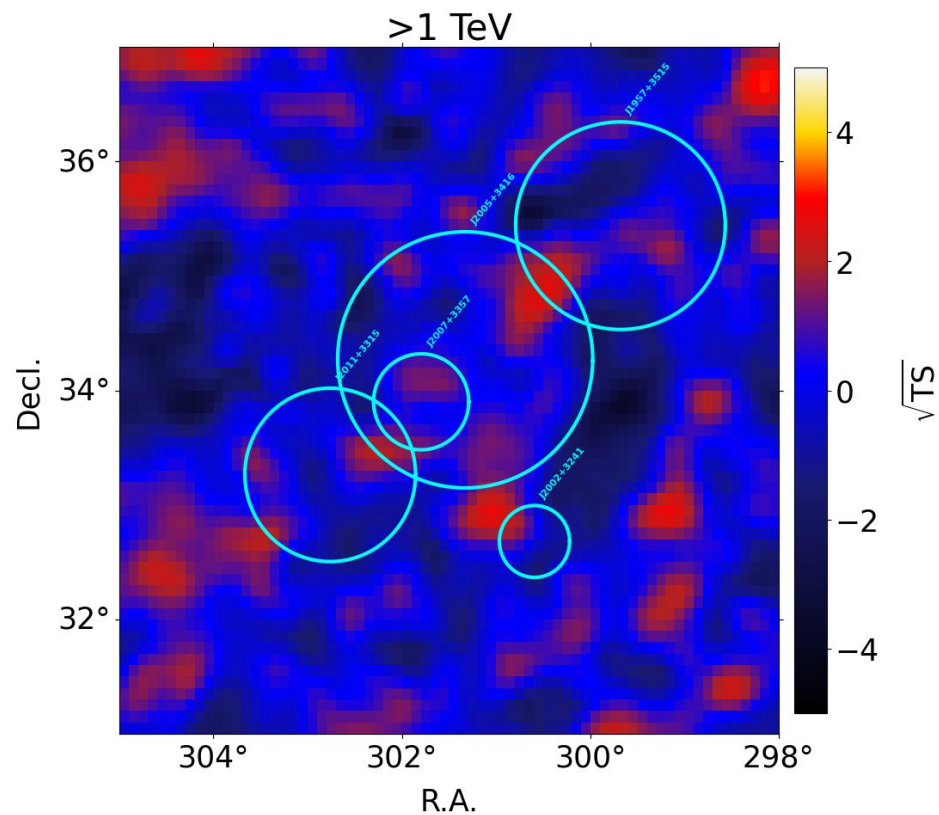


Ts

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Fitting test

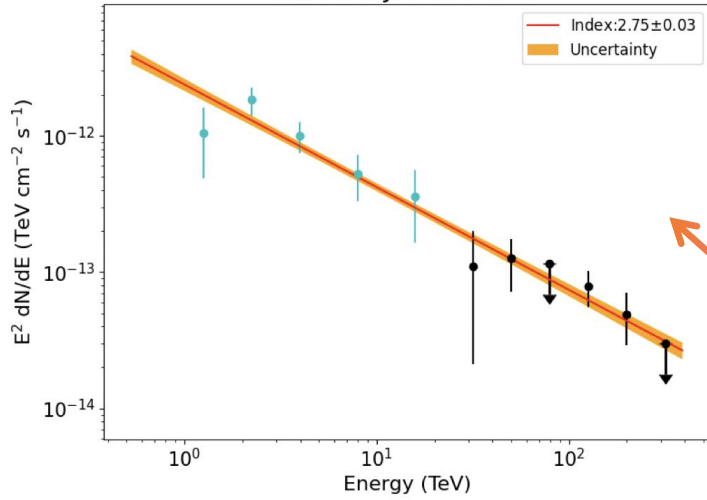
Best fit



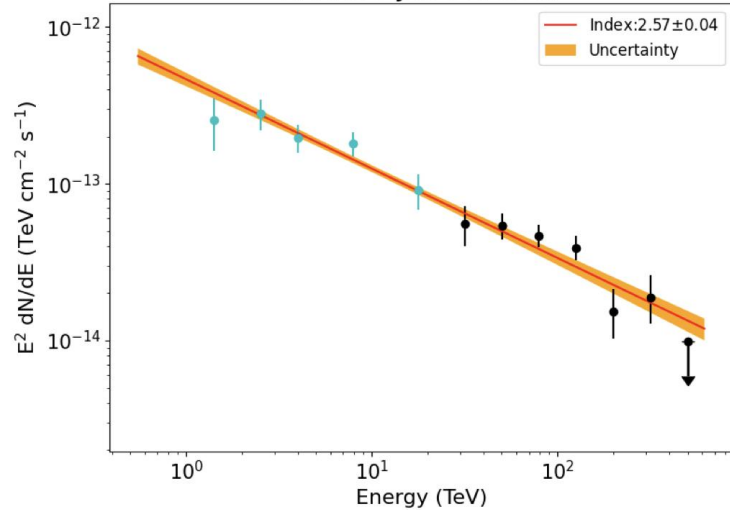
Description	Neglikelihood	ΔAIC	Dof
4-gaus	-17834.68	0	22
2-gaus+1-ellip+1ps(PLC)	-17846.59	-19.81	24

Energy spectrum

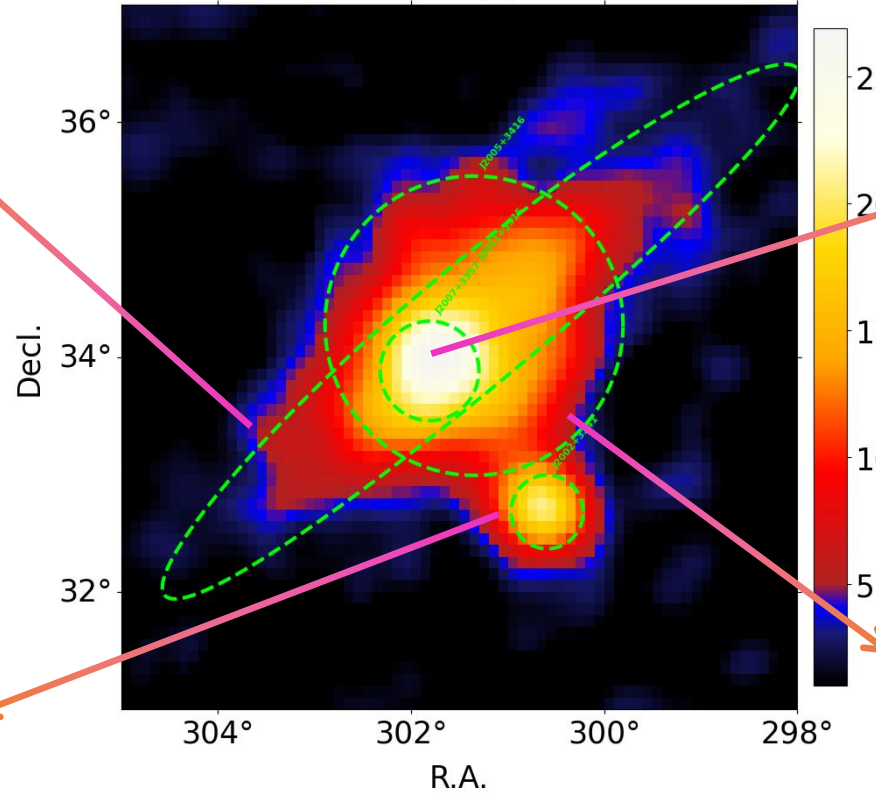
LHAASO J2011+3315



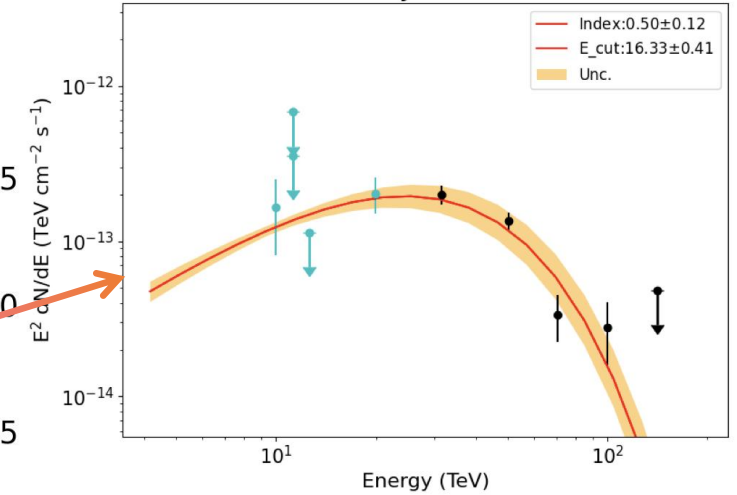
LHAASO J2002+3241



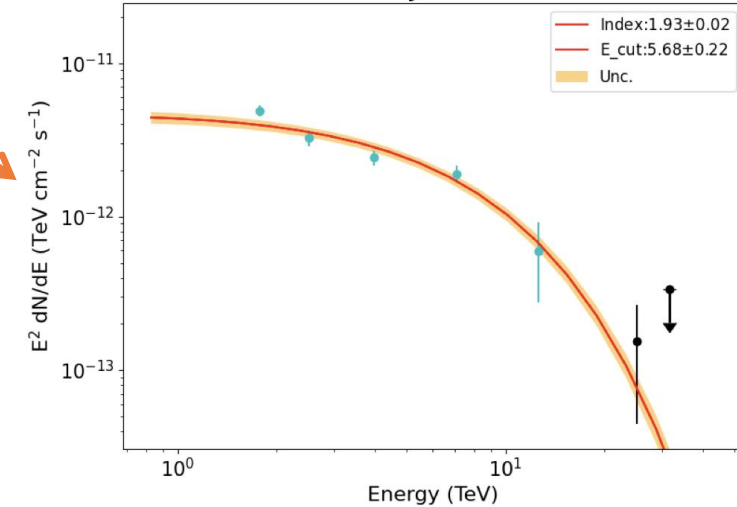
>1 TeV



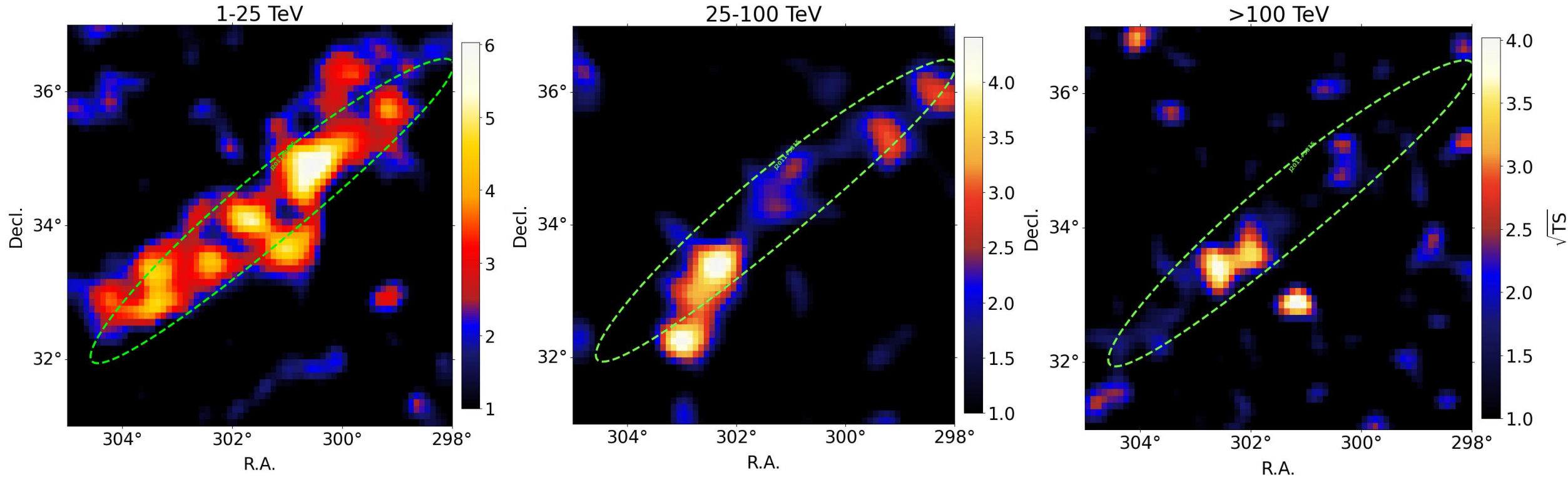
LHAASO J2007+3357



LHAASO J2005+3416

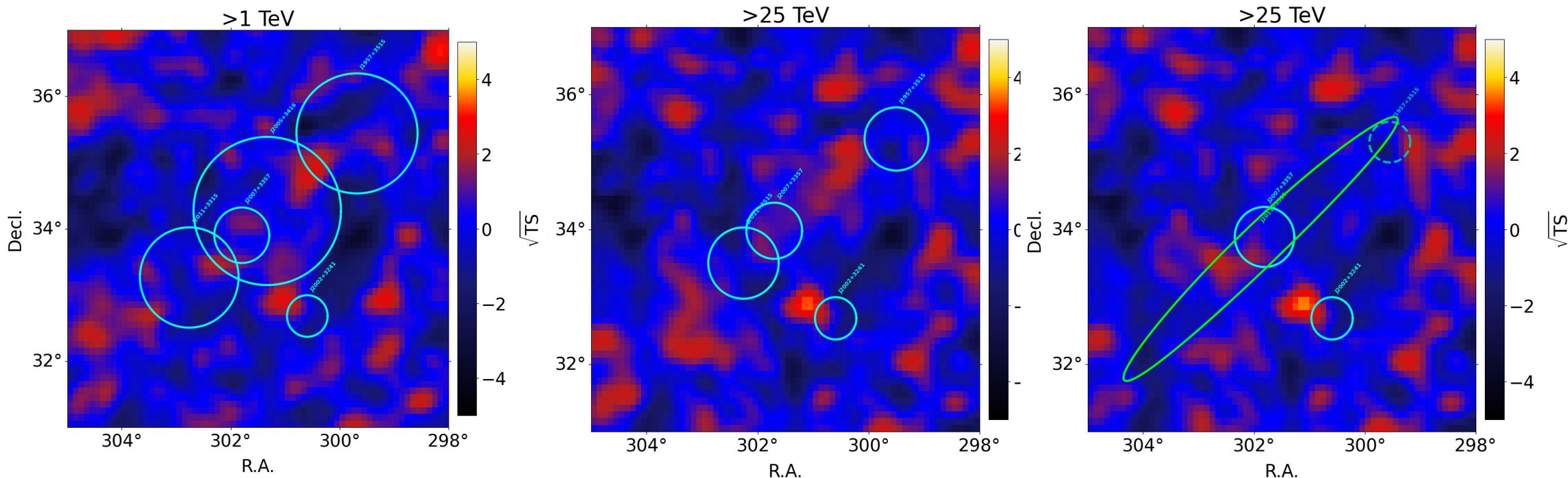


Morphology



- An elongated structure is observed in WCDA data.
- The brightest positions differ between WCDA and KM2A.
- An elliptical morphology is preferred overall, but the optimal model (ellipse vs. Gaussian) may vary with energy.

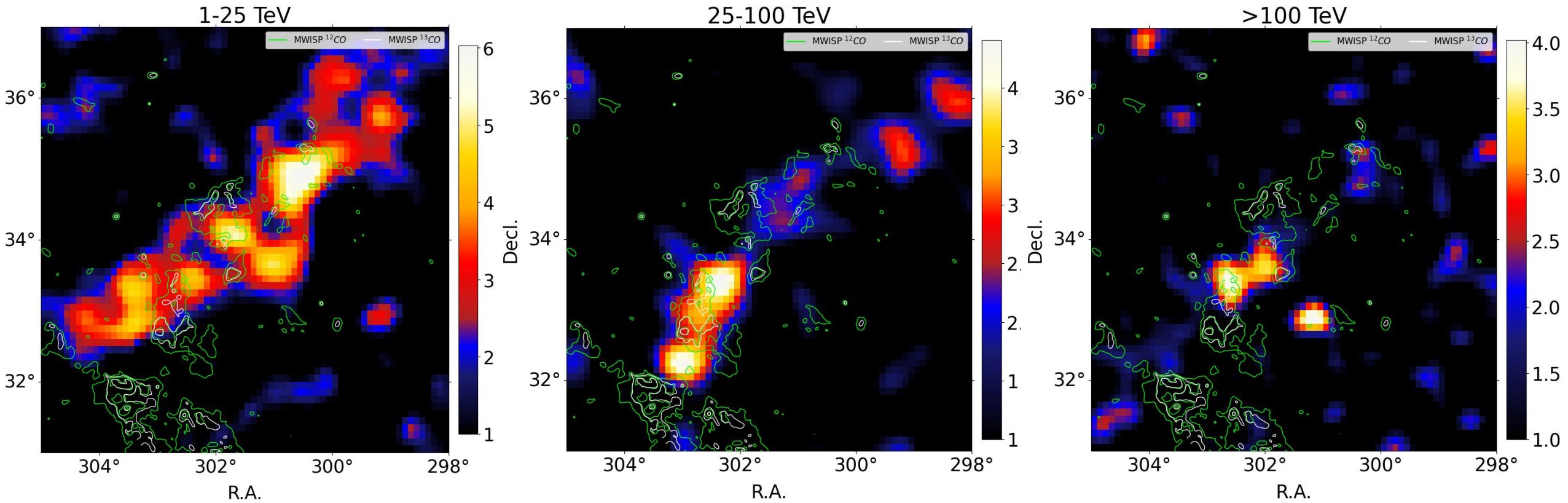
Model Comparison in KM2A



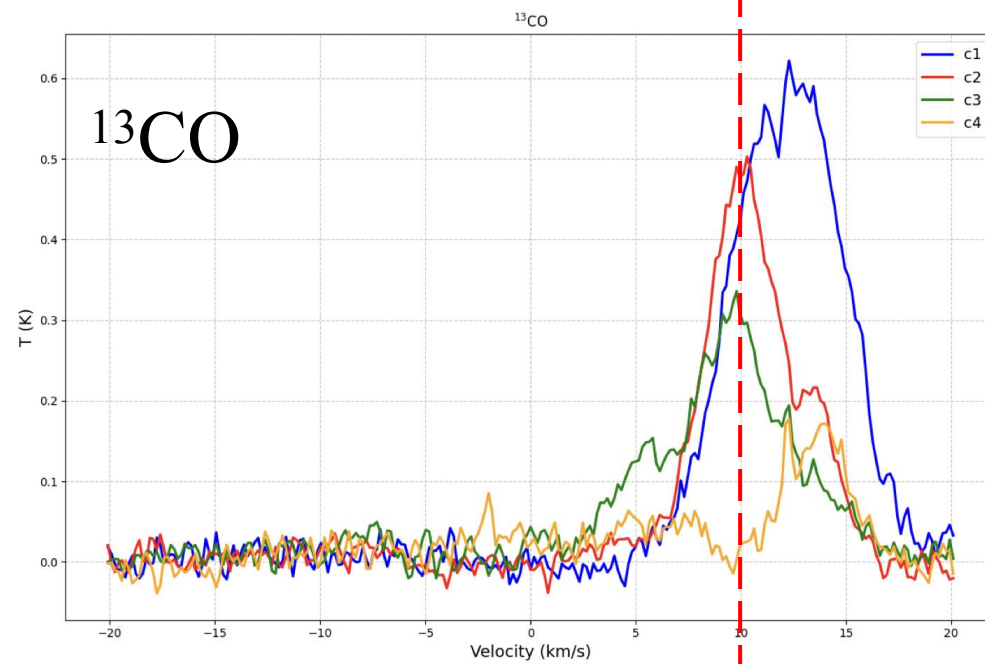
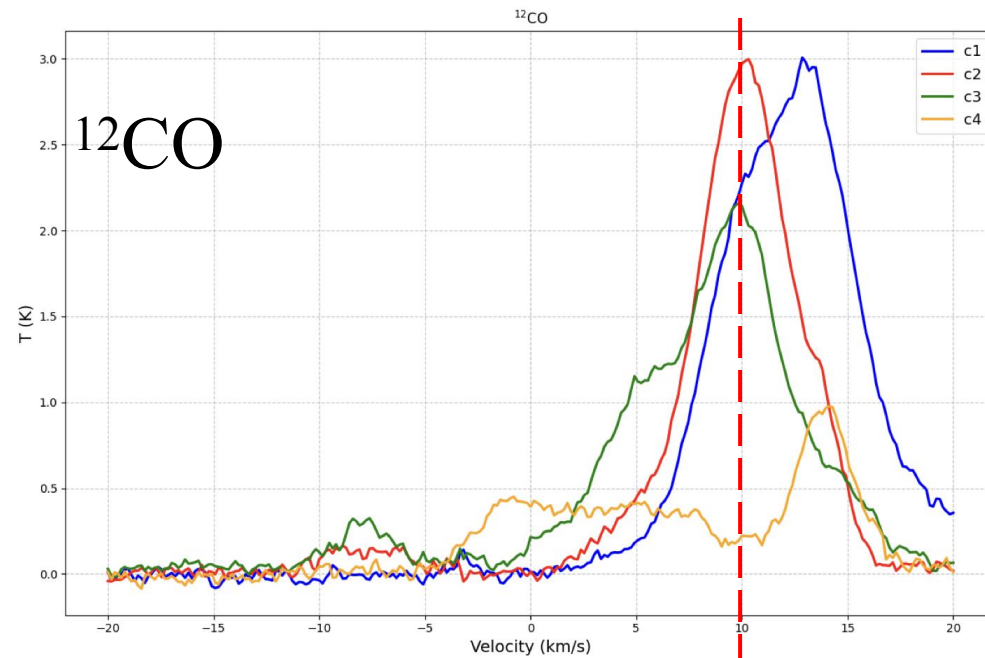
Description	Neglikelihood	ΔAIC	Dof
3-gaus	-8962.20	0	16
1-gaus+1-ellip+1ps(PLC)	-8968.89	-9.38	18

CO contour

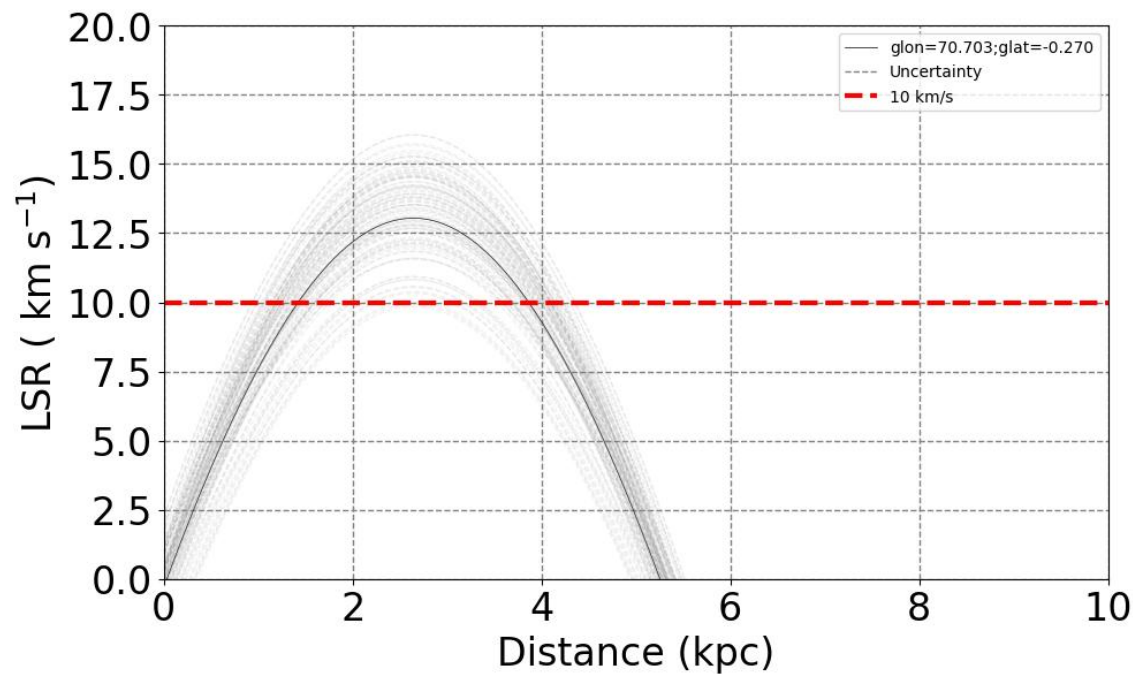
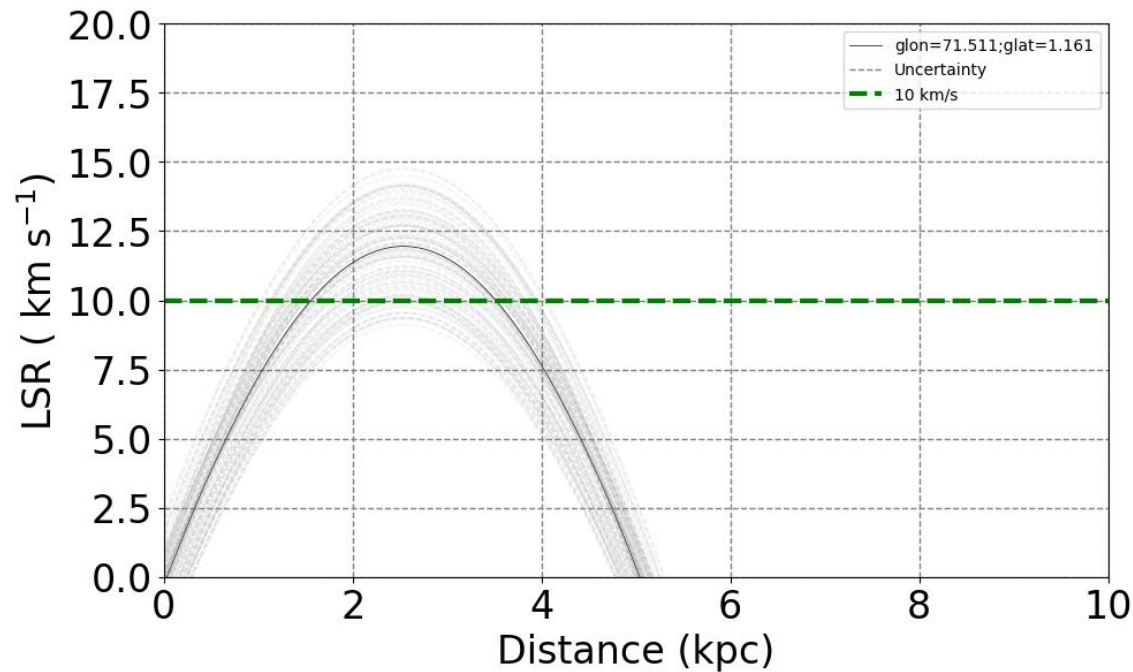
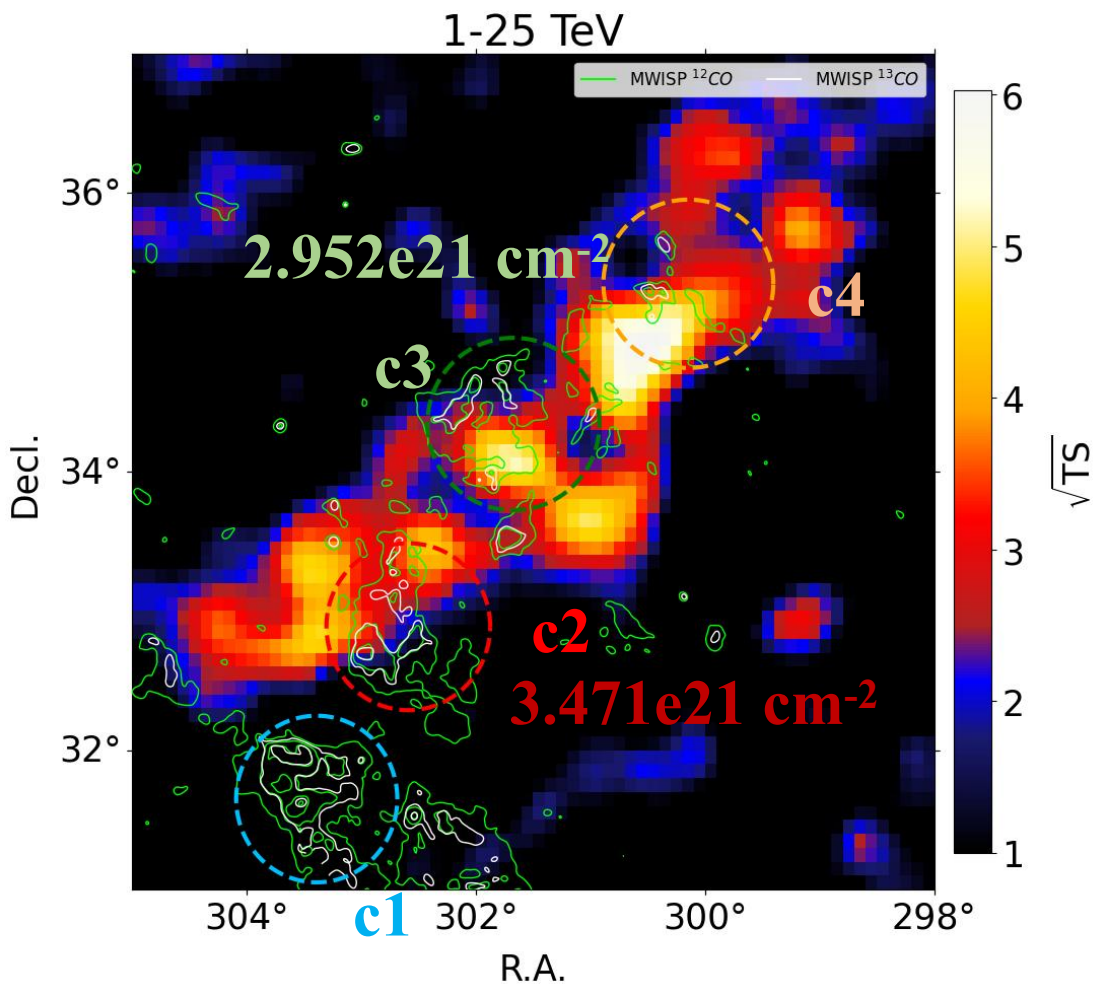
MWISP: ^{12}CO green; ^{13}CO white; velocity: 5-20 km/s



CO distribution

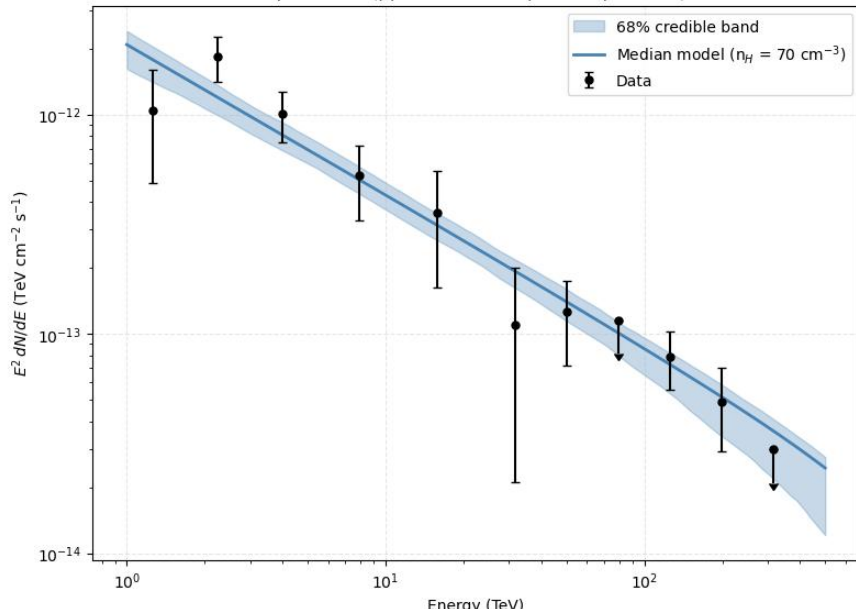


velocity-distance

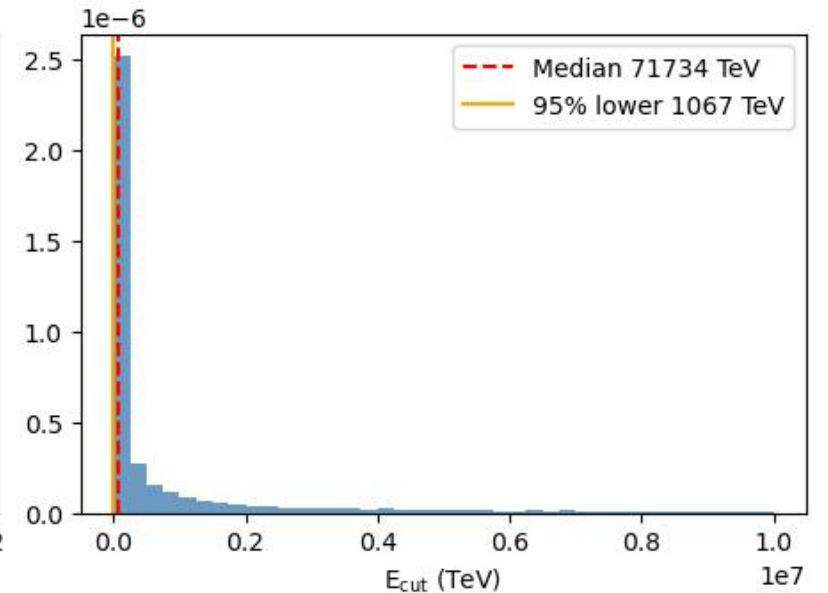
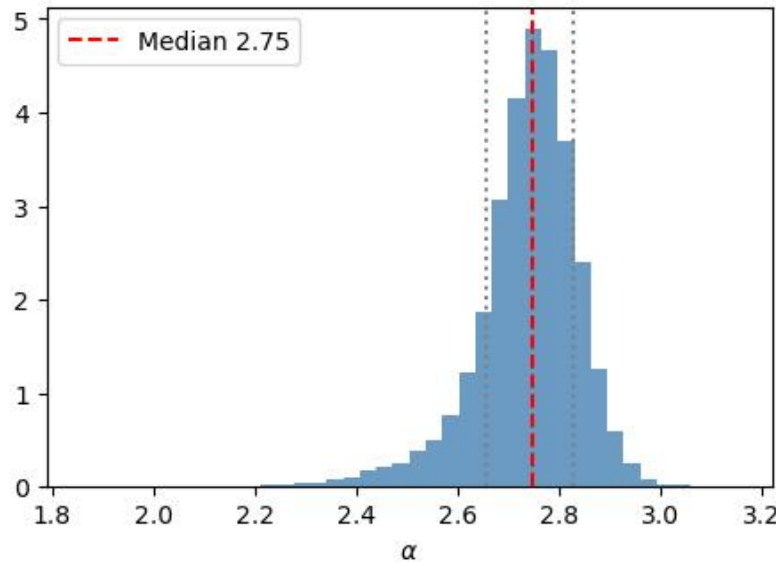
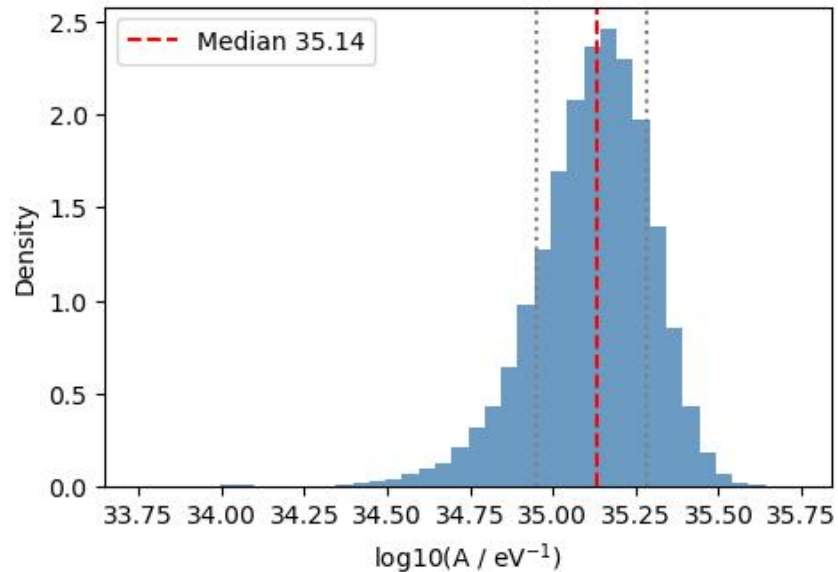


PP interaction

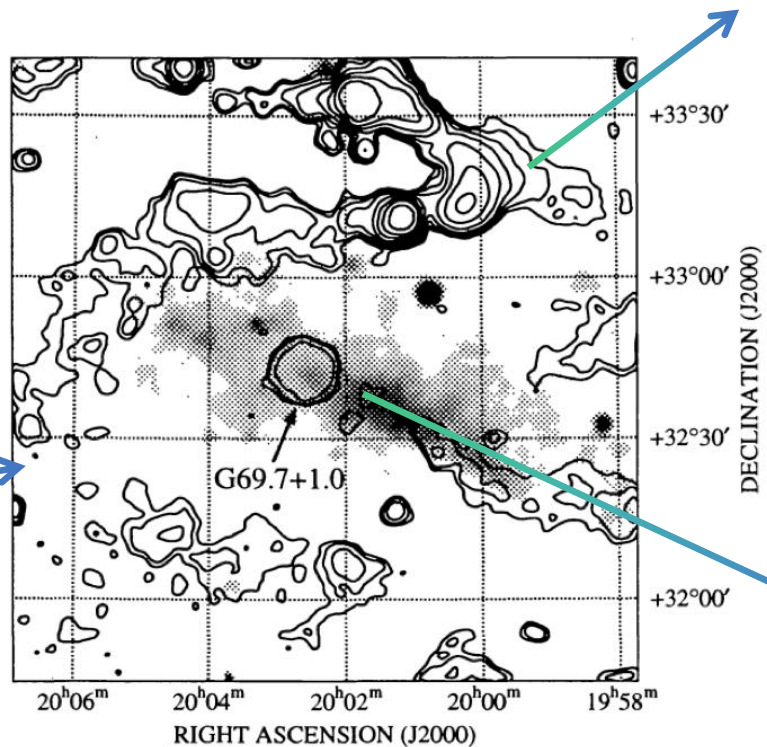
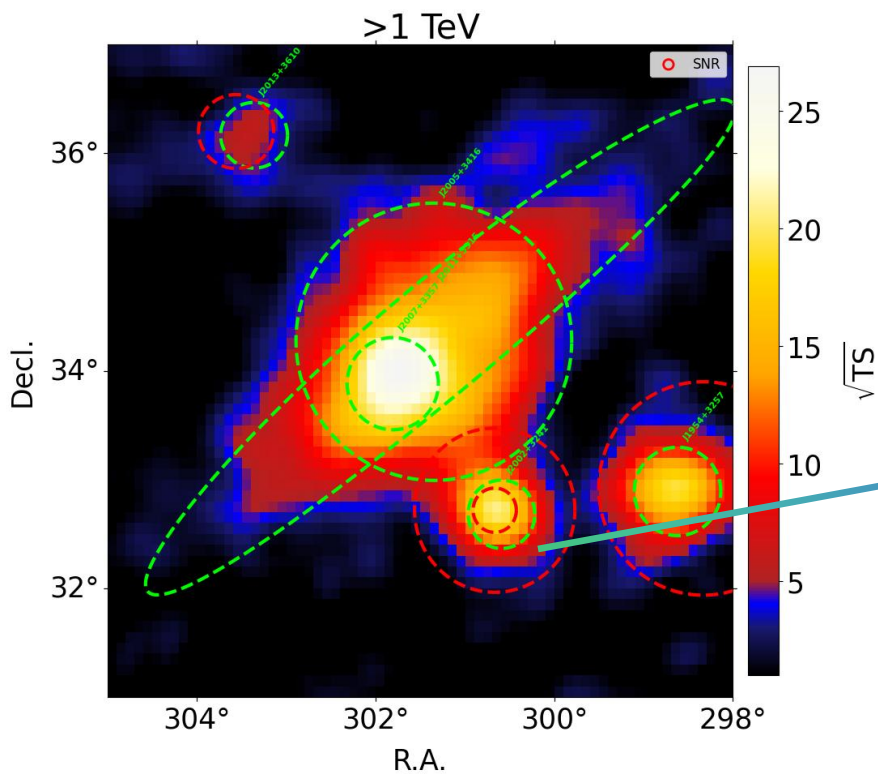
Spectral fit (pp model, ECPL proton spectrum)



- Distance: 1.5 kpc
- n_H : 70 cm^{-3}
- Total Energy: $W_p \sim 2.90 \times 10^{47} \left(\frac{d}{7 \text{ kpc}}\right)^2 \left(\frac{n}{70 \text{ cm}^{-3}}\right)^{-1} \text{ erg}$
- E_{cut} (lower limit): 1.1 PeV

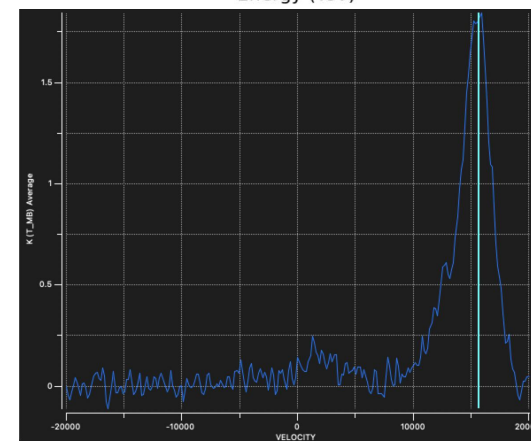
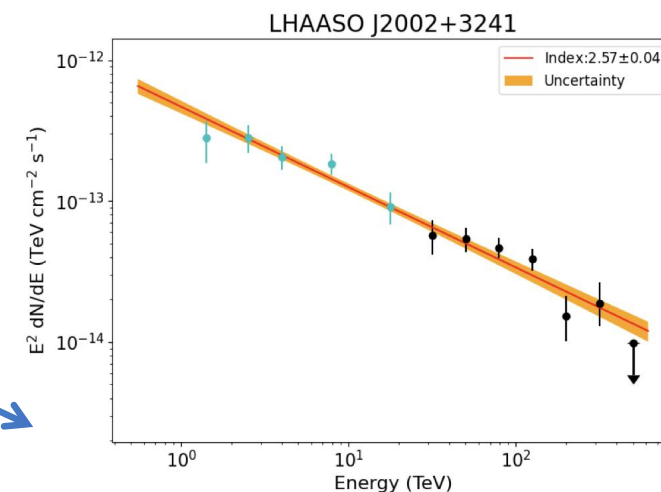


SNR in the roi



~2.5kpc

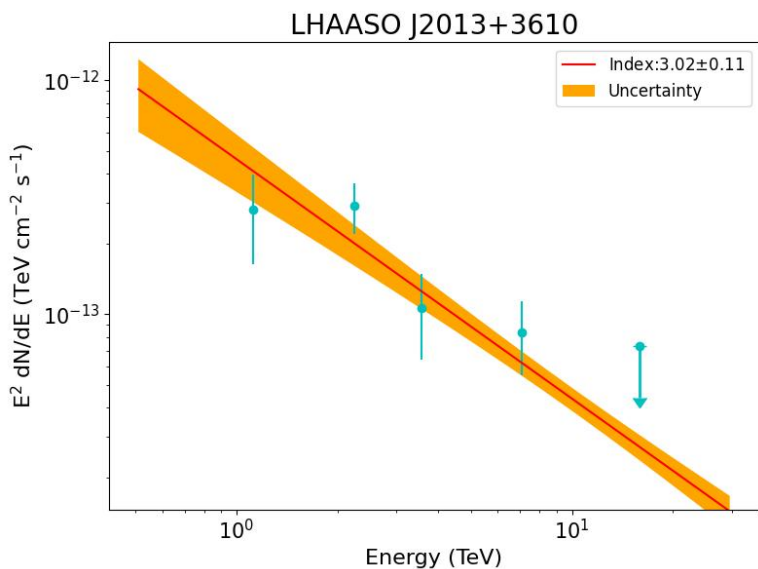
- G069.4+1.2: ~1 deg
 - 2.5 kpc and ~37 kyr (Yoshita et al. 2000)
 - non-thermal emission not detected



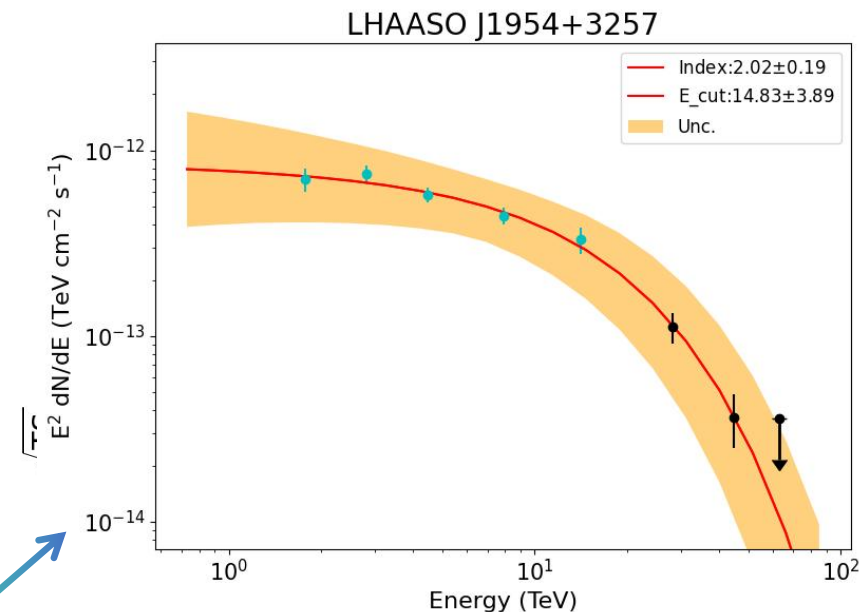
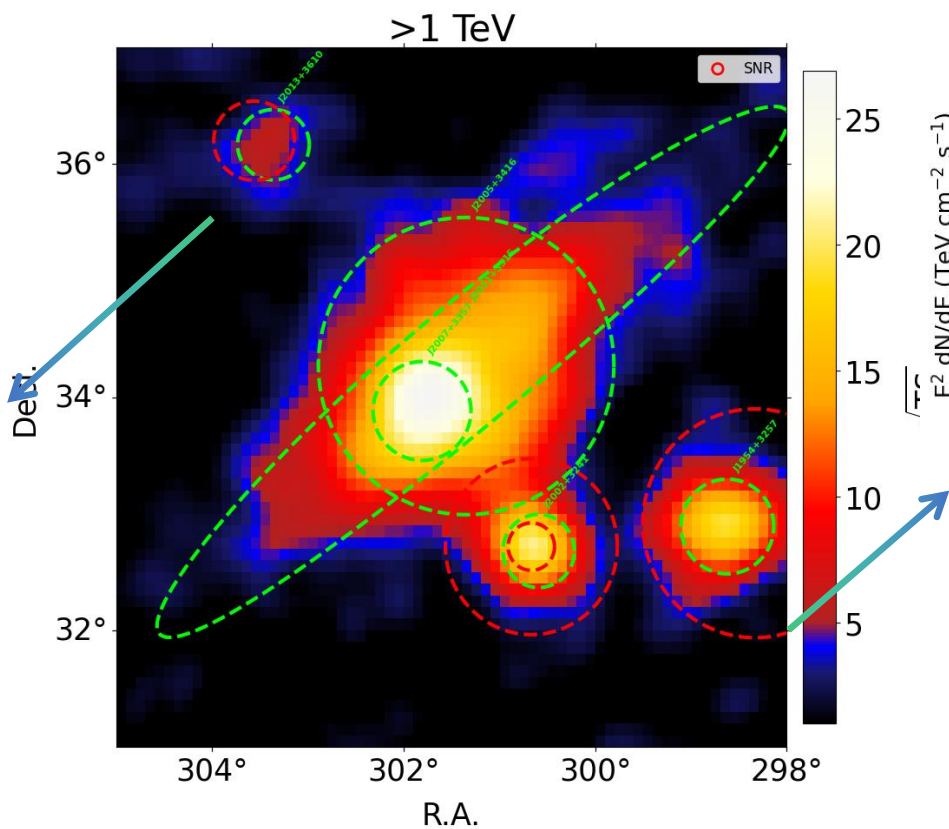
<http://snrcat.physics.umanitoba.ca/>

SNR in the roi

G073.9+00.9

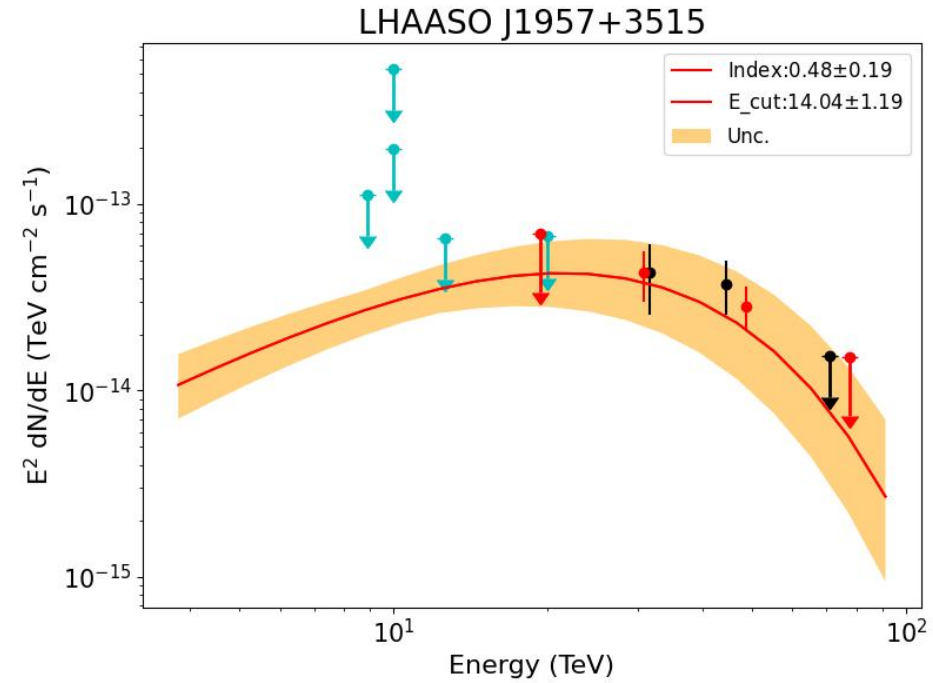
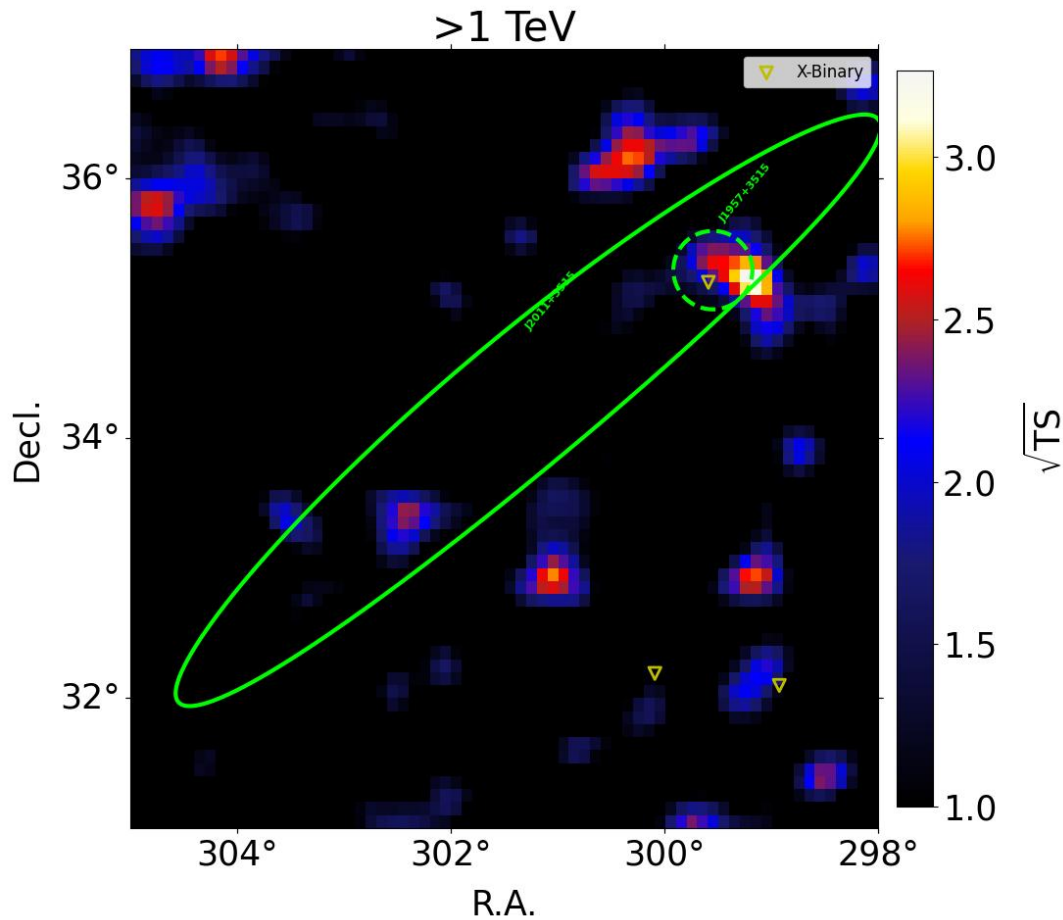


- Age: ~ 11 kyr (Lozinskaya et al., 1993)
- Distance: $1.25 \sim 4.0$ kpc



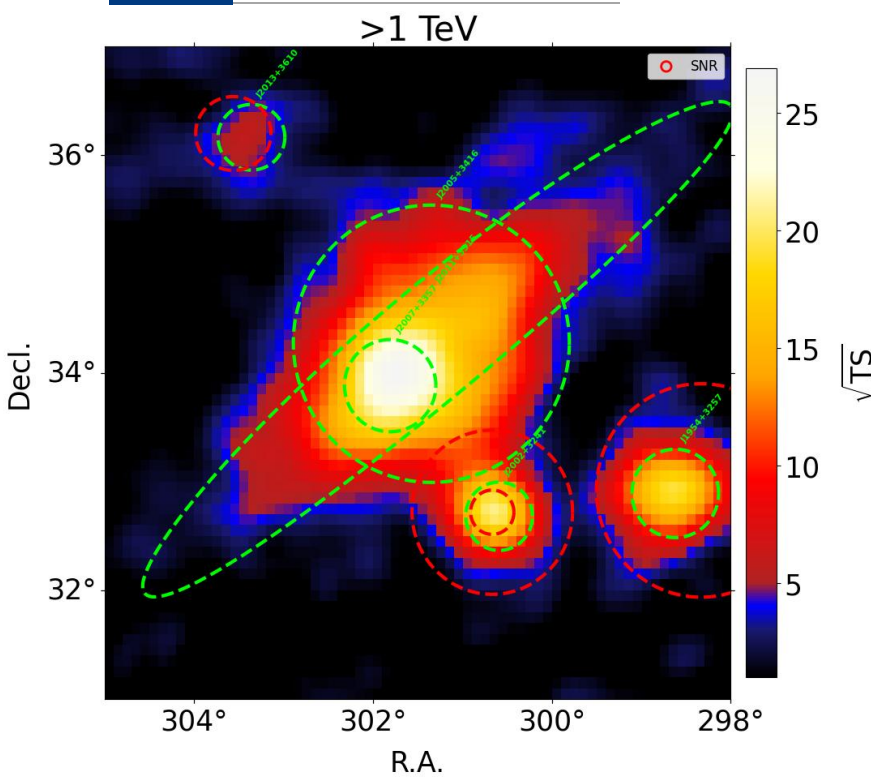
- Dynamic age: 60 kyr (Hewitt et al., 2023)
- Distance: $1.6 \sim 4.6$ kpc

Cgynus X1

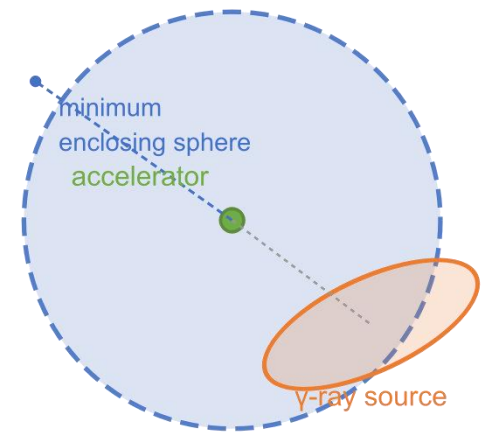


- Distance: 2.2 ± 0.2 kpc
- BH mass: 20 M_{sun}
- Age: 4.8-7.6 million yr
- L_x : $\sim(0.4-4) \times 10^{37}$ erg/s

Energy estimation



SNR is supposed to be at 1.5 kpc to the observer

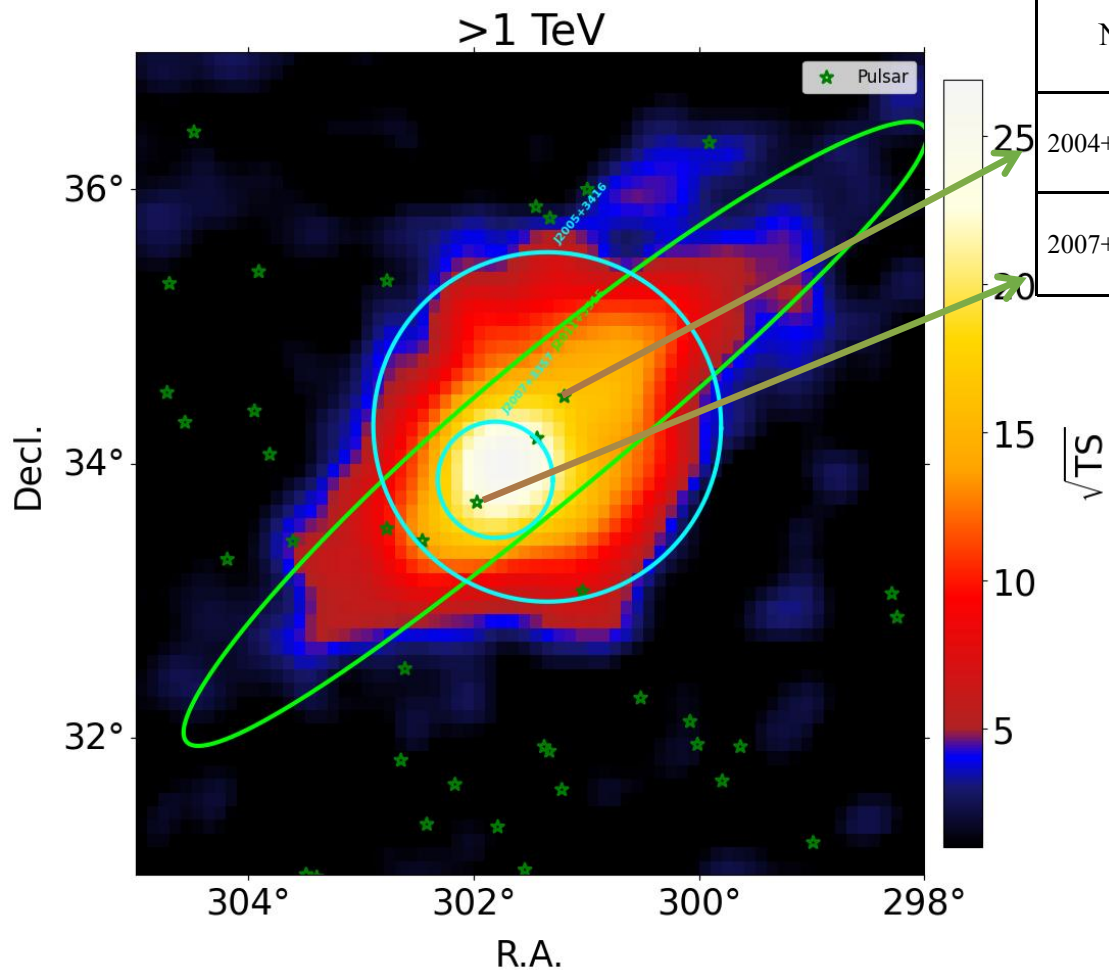


- PP parameters:
 - Distance: 1.5 kpc
 - nH : 70 cm^{-3}
 - Total Energy: $\sim 2.90e+47 \text{ erg}$
 - E_{cut} (lower limit): 1.1 PeV

SNR (burst injection)
Uniform CR density inside sphere

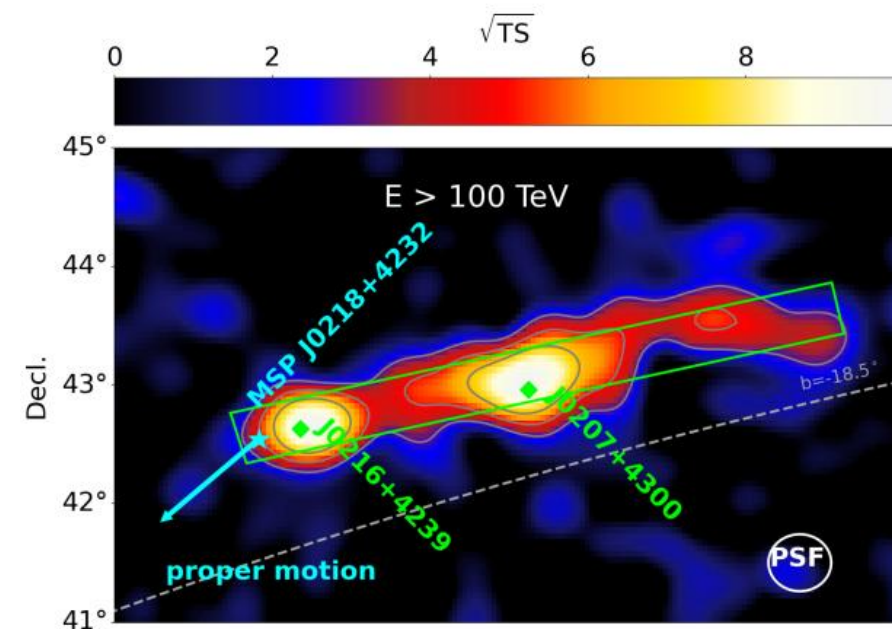
Name	LHAASO source	$E_{\text{injection}}$ (erg)	Ref Distance (kpc)
G069.7+01.0	J2002+3241	$1.41e+48$	2.5 (large uncertainty)
G073.9+00.9	J2013+3610	$5.89e+48$	1.25 - 4
G069.0+02.7	J1954+3257	$7.40e+48$	1.6 - 4.6

Pulsar observation



Name	Ra	Dec	P0(s)	Dist(kpc)	Dist_DM(kpc)	Edot(ergs/s)	Age(yr)
2004+3429	301.20	34.49	0.24	10.84	10.84	5.8E+35	1.85E+04
2007+3343_P	301.97	33.72	0.003	6.81	6.81		

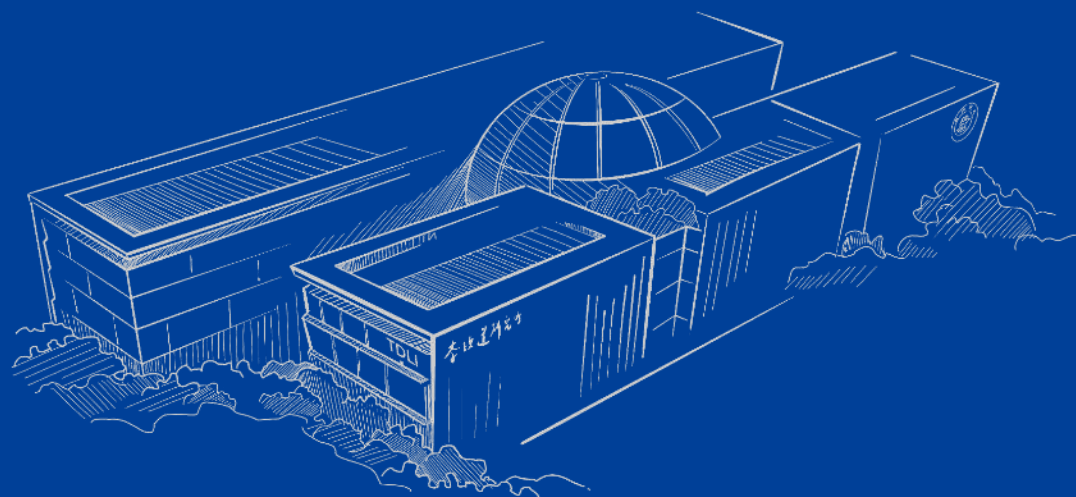
A millisecond pulsar at ~3 kpc



- We report the discovery of an UHE gamma-ray source J2011+3315.
- The morphology of J2011+3315 is complex and requires further investigation.
- The source exhibits a hard spectral shape.
- Dense CO gas distributions are found to be spatially associated with J2011+3515.
- These results suggest a possibility that particles escape from potential accelerators and illuminate multi-targets.



谢 谢

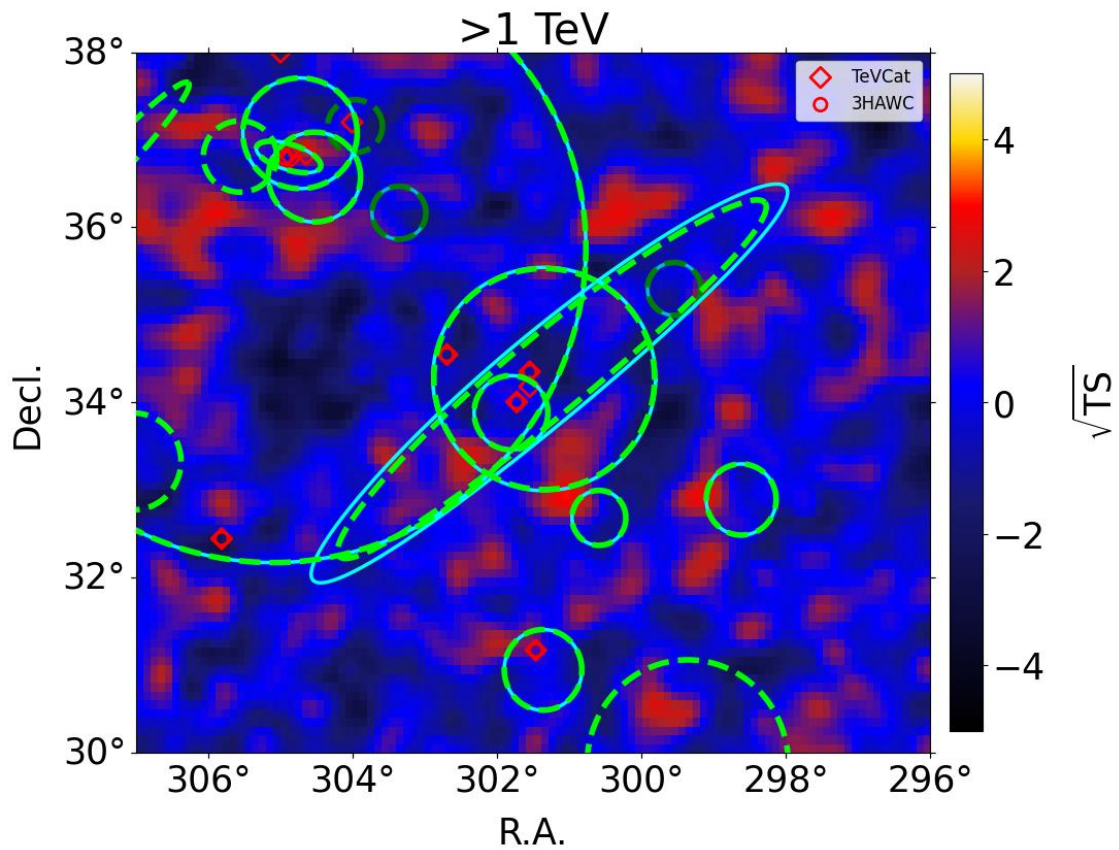




04

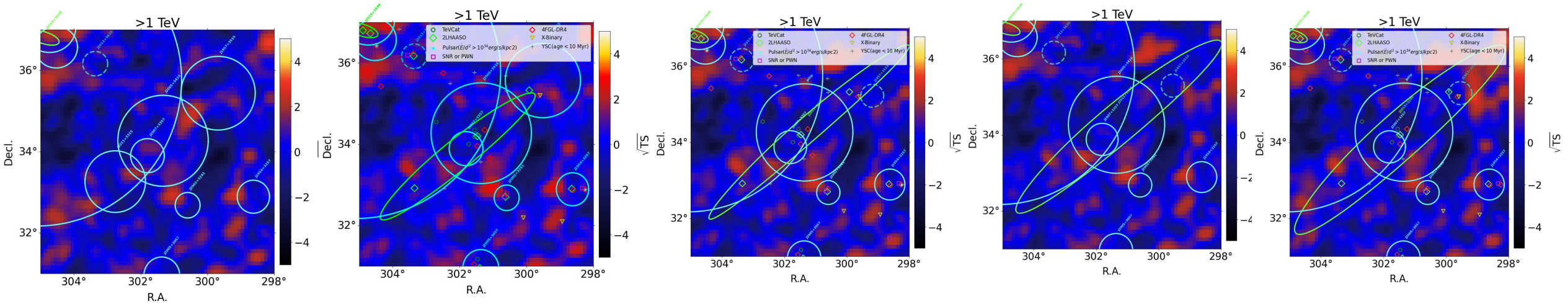
backup

larger roi



cyan: small roi result
green: large roi result

Fitting test



Description	Neglikelihood	ΔAIC	Dof
4-gaus	-17834.68146	0	22
3-gaus+1-ellip	-17841.40694	-9.4509600	24
2-gaus+1-ellip+1ps(PL)	-17843.47258	-15.582240	23
2-gaus+1-ellip+1ps(PLC)	-17846.58669	-19.81	24
2-gaus+1-ellip(disk)+1ps(PLC)	-17838.42632	-3.4897200	24

Morphology

J2011+3315

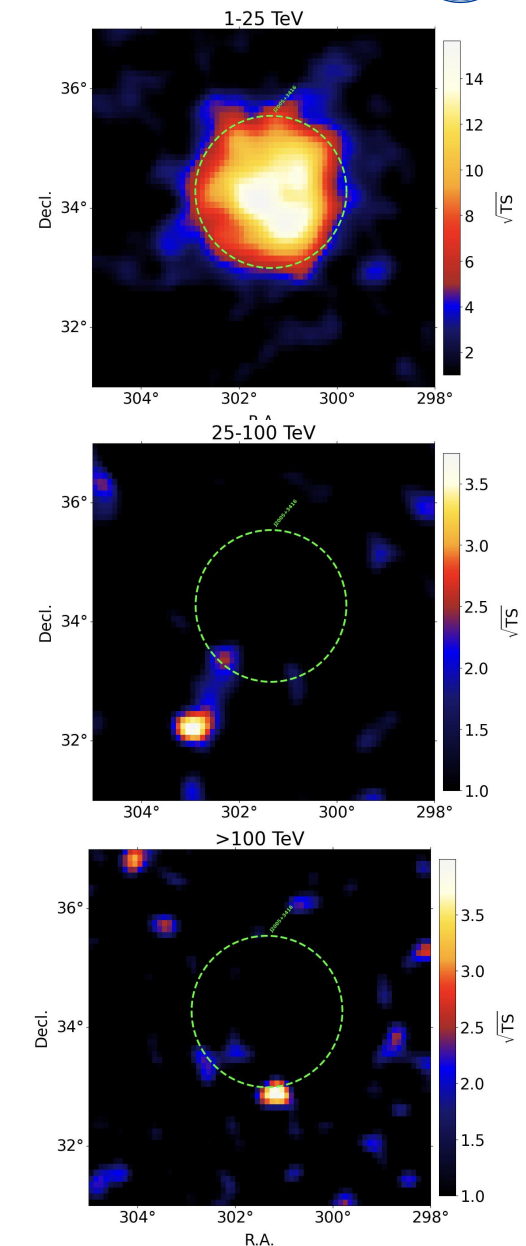
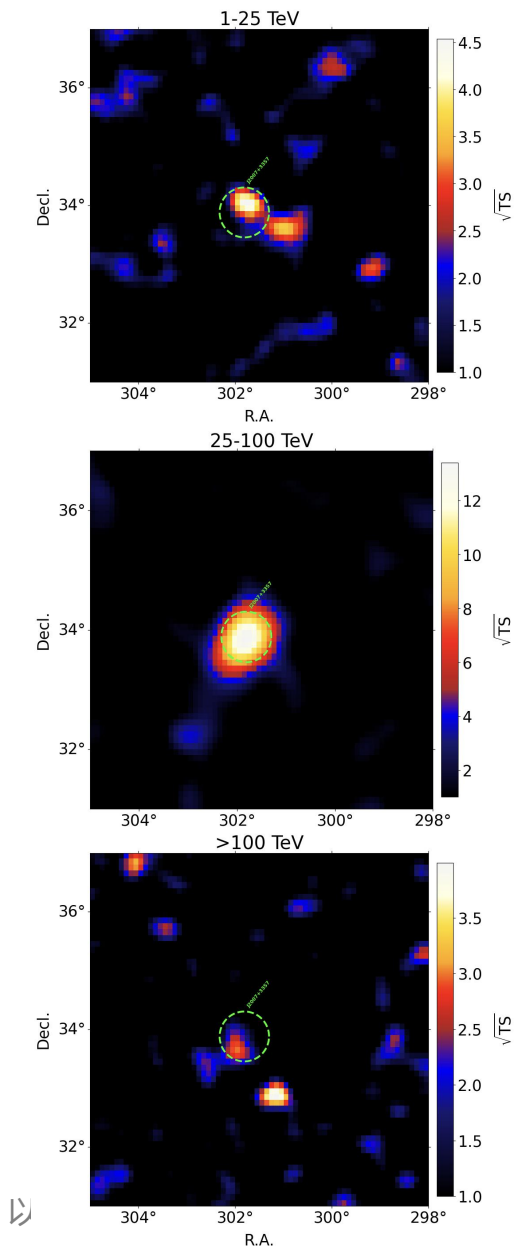
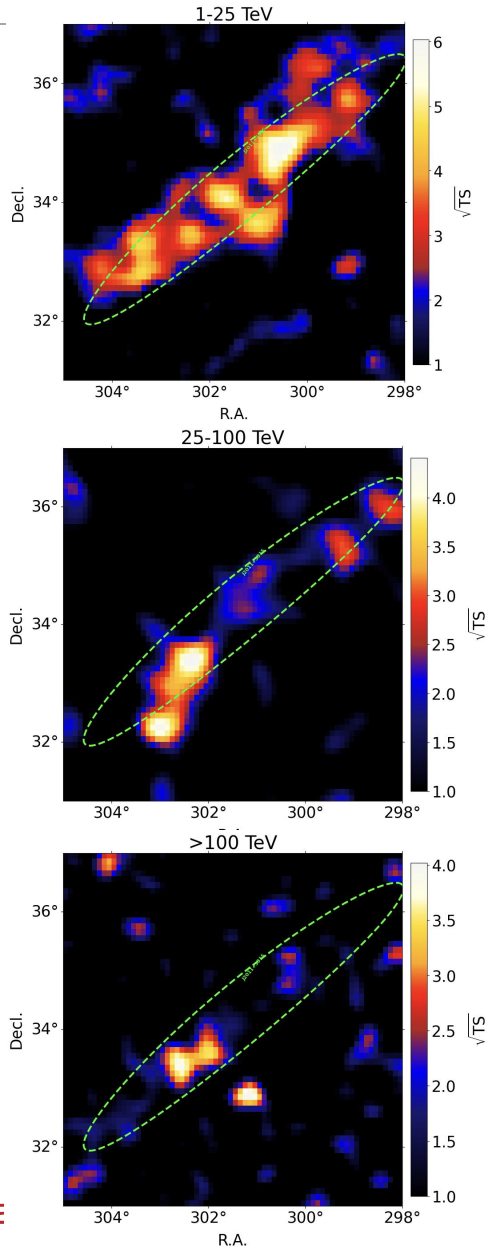
J2007+3357

J2005+3416



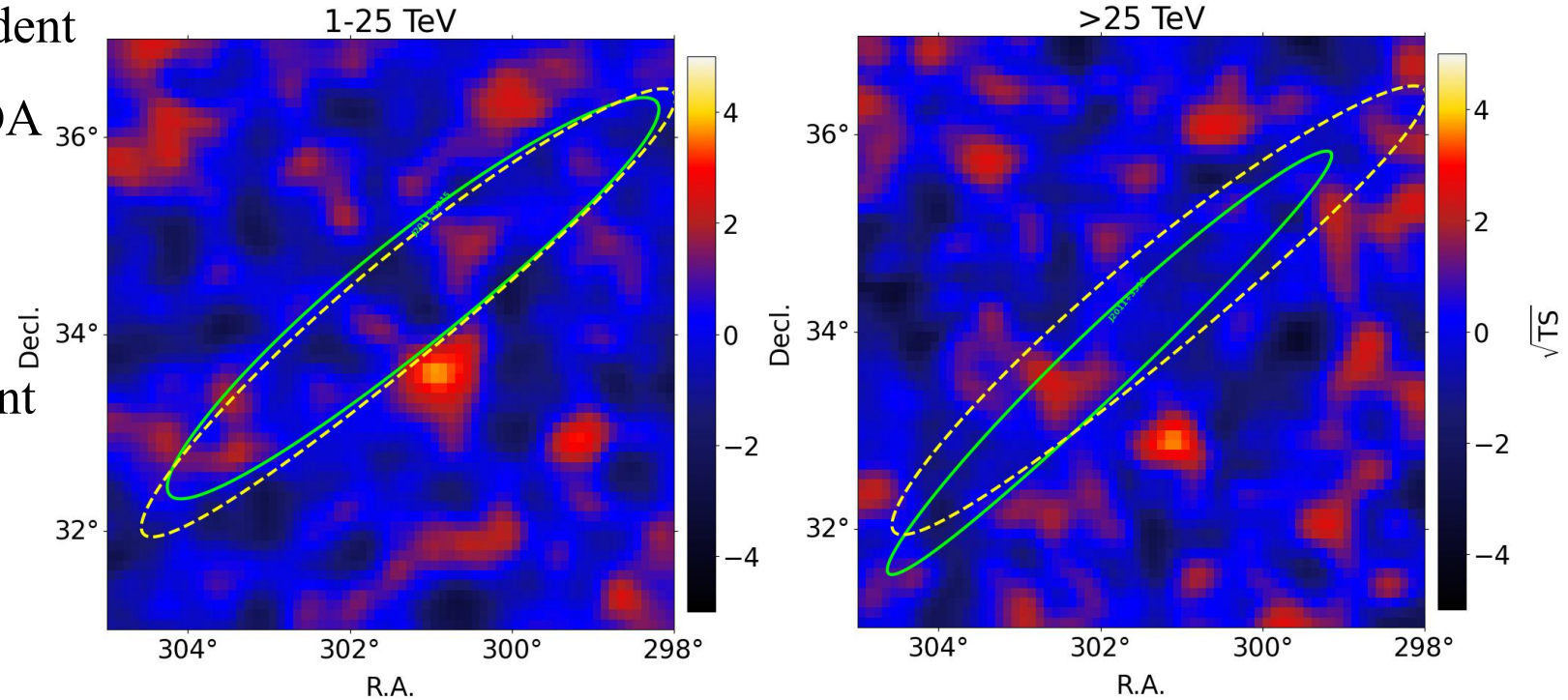
李政道研究所
TSUNG-DAO LEE INSTITUTE

Energy



Morphology evolution test

- H0: Ellipse shape is energy-independent
 - Same shape parameters in WCDA and KM2A
 - 5 paras
- H1: Ellipse shape is energy-dependent
 - Different shape parameters in WCDA and KM2A
 - 10 paras
- $\Delta TS = 9.29$, $\text{sig}=1.29\sigma$

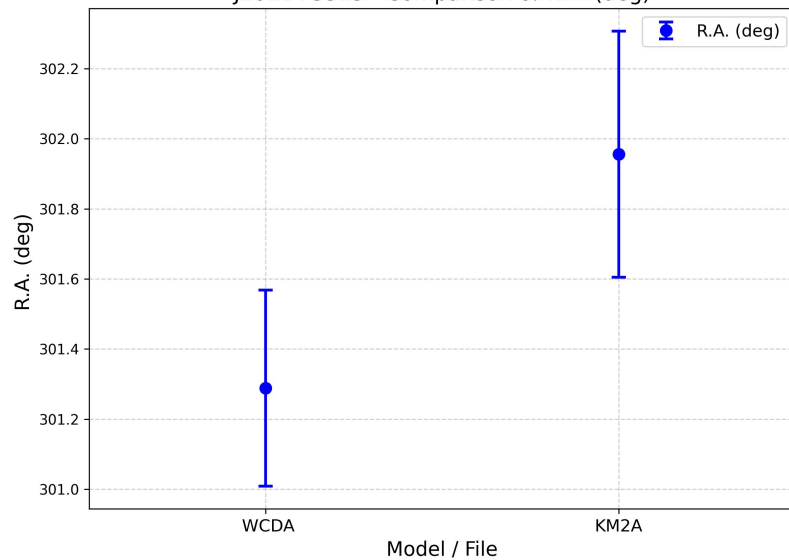


WCDA ΔTS : 2.88

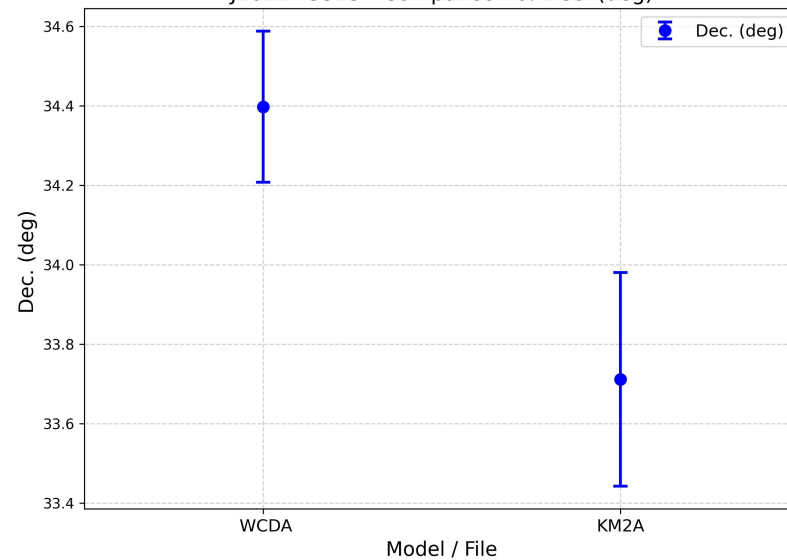
KM2A ΔTS : 6.41

Parameter evolution

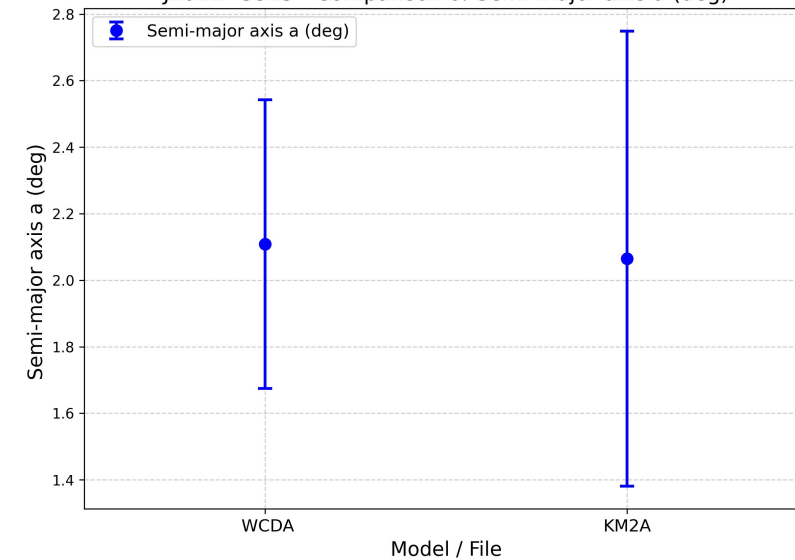
J2011+3315 - Comparison of R.A. (deg)



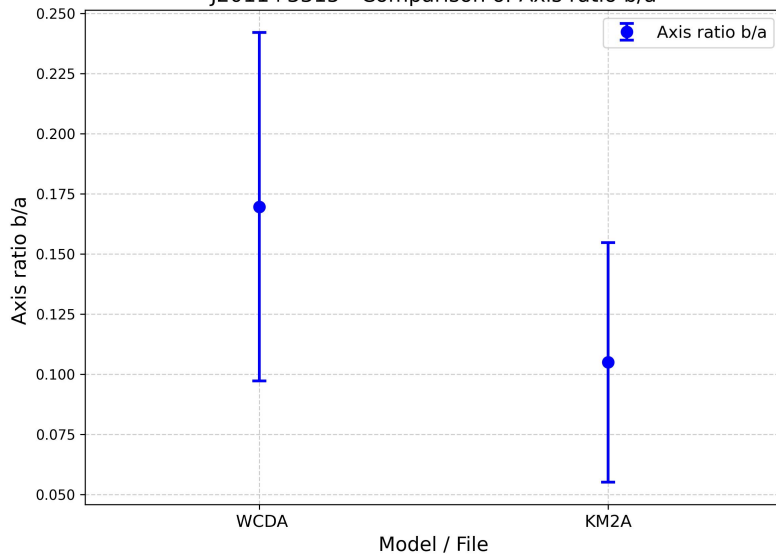
J2011+3315 - Comparison of Dec. (deg)



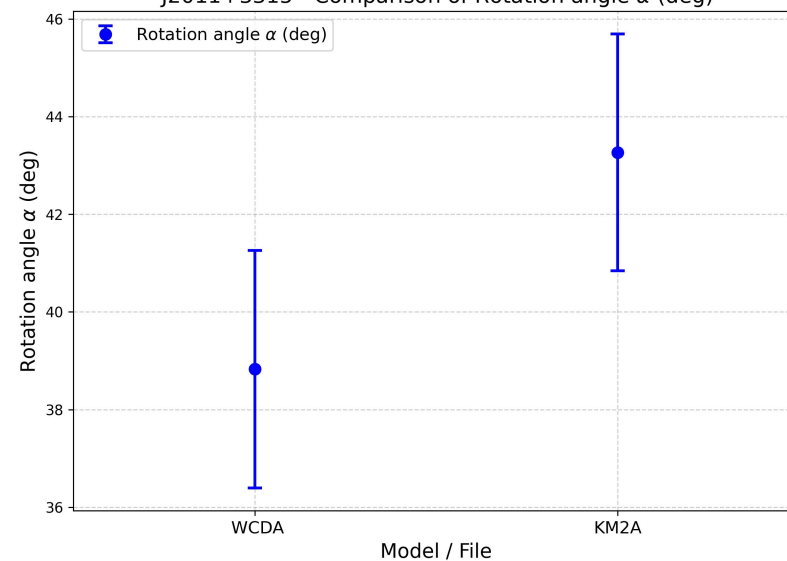
J2011+3315 - Comparison of Semi-major axis a (deg)



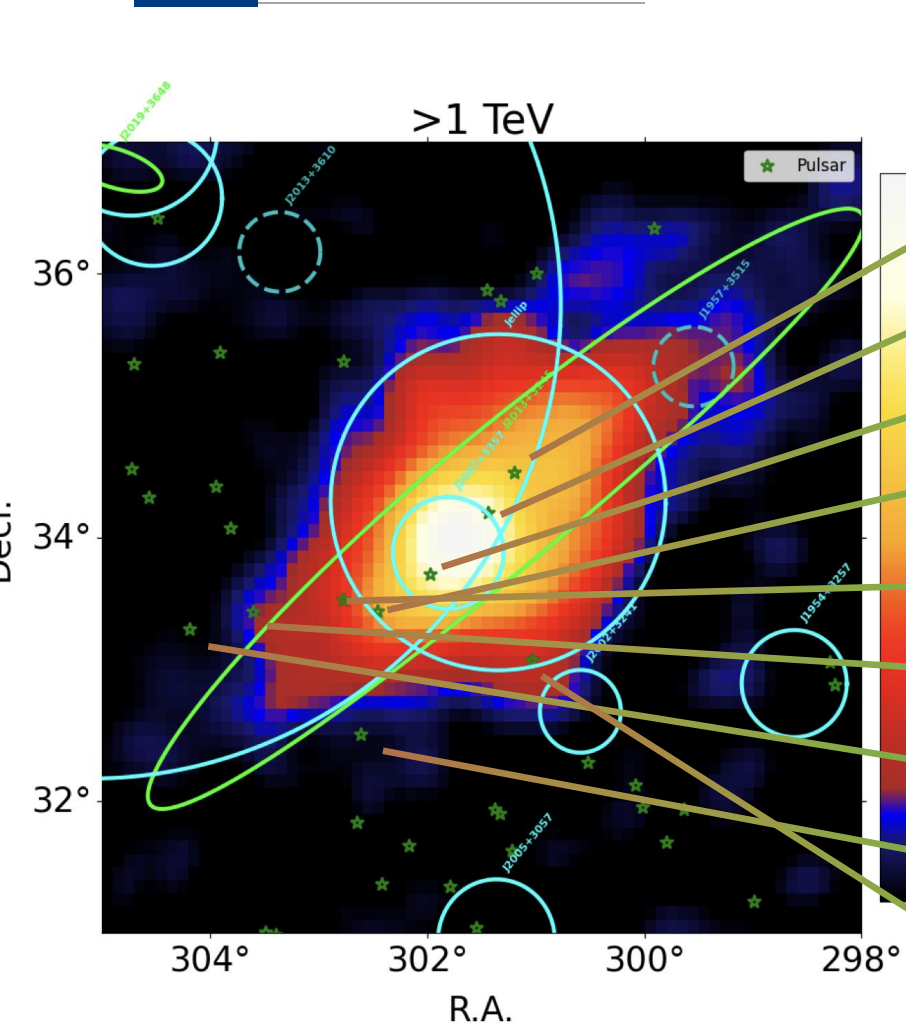
J2011+3315 - Comparison of Axis ratio b/a



J2011+3315 - Comparison of Rotation angle α (deg)



Pulsar observation



Name	Ra	Dec	P0(s)	Dist(kpc)	Dist_DM(kpc)	Edot(ergs/s)	Age(yr)
2004+3429	301.20	34.49	0.24	10.84	10.84	5.8E+35	1.85E+04
2005+3411_P	301.44	34.18	0.65	16.67	16.67		
2007+3343_P	301.97	33.72	0.003	6.81	6.81		
2009+3326	302.46	33.44	1.44	7.30	7.30	1.9E+31	1.55E+07
2011+3331	302.77	33.52	0.93	8.60	8.60	8.7E+31	8.27E+06
2014+3326_P	303.60	33.43	0.98	10.73	10.73		
2016+3318_P	304.19	33.30	2.18	17.85	17.85		
2010+3230	302.61	32.50	1.44	13.03	13.03	4.8E+31	6.32E+06
2004+3304_P	301.03	33.07	1.19	13.41	13.41		