Hadronic Scenario for Galactic PeVatron LHAASO J1912+1014u Supported by Fermi-LAT gamma-ray Data and FUGIN CO Data

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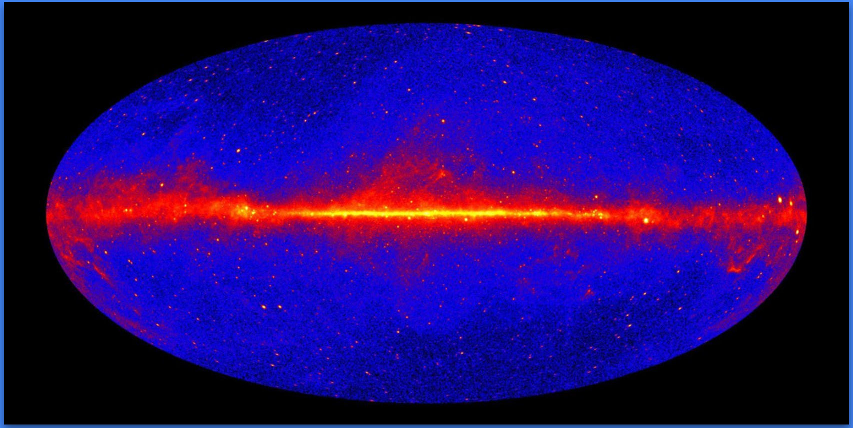
2026.08.31 TeVPA2026, Yamagata (Tendo), Japan

(Mizuno+26, ApJ 1006, 77)



Role of Fermi & CO Obs. in Studying Proton PeVatron

There are ~50 sub-PeV srcs being proton or electron PeVatrons (e.g., Cao+24)

Multi-λ data is crucial to examine CR type and spectrum. Correlation with dense CO clouds is key to identify proton PeVatrons

Complementary

Observatory	Energy Range	Angular Resol.	FOV
LHAASO, Tibet AS-gamma, HAWC	0.01-1 PeV (excellent ✓✓)	~0.5 deg (so-so)	~15% of the sky (good ✓)
IACTs (e.g., H.E.S.S. MAGIC, VERITAS, CTA)	0.1-100 TeV (good ✓)	~0.08 deg (excellent ✓✓)	a few deg (so-so)
Fermi-LAT	1-300 GeV (so-so)	0.1 deg in >10GeV (good ✓)	~20% fo the sky, all sky coverage (excellent ✓✓)

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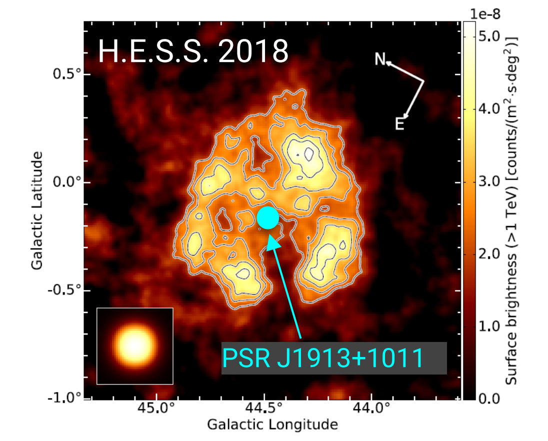
Wide energy coverage allows characterizing CRs (particle type, α_{CR}, and W_{CR}); Fermi-LAT plays crucial role in multi-λ study of proton PeVatrons

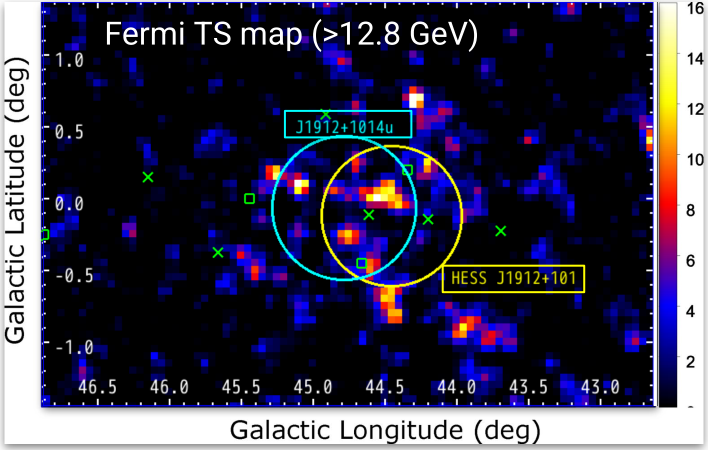
1LHAASO J1912+1014u in TeV/GeV Gamma-rays

1LHAASO J1912+1014u is extended (r_{39}~0.5 deg) sub-PeV source (Cao+24)

It positionally coincides with HESS J1912+101; likely radio-dark SNR (e.g., Yasuda+21) or PWN (PSR J1913+1011)

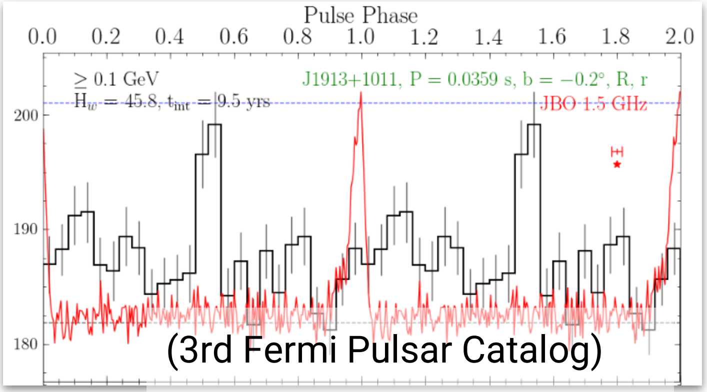
We developed dedicated background model for Fermi-LAT and found hard excess toward the LHAASO/H.E.S.S. source



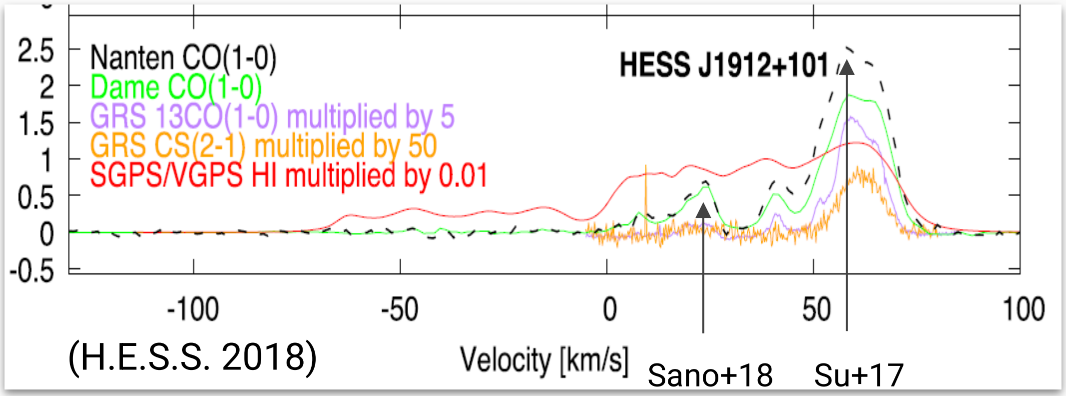


Two Scenarios for Fermi/LHAASO/H.E.S.S. Source

- PWN powered by PSR J1913+1011 (center of TeV emission)
  - Old (t_{sd}=170 kyr), powerful (L_{sd}=3e36 erg/s) pulsar at D_{DM}=4.5 kpc
- Putative SNR suggested by shell morphology in TeV
  - CO data toward HESS J1912+101 exhibit two peaks; v=60 km/s proposed by Su+17, and v=25 km/s proposed by Sano+18
- We prepared several templates and tested them against LAT data



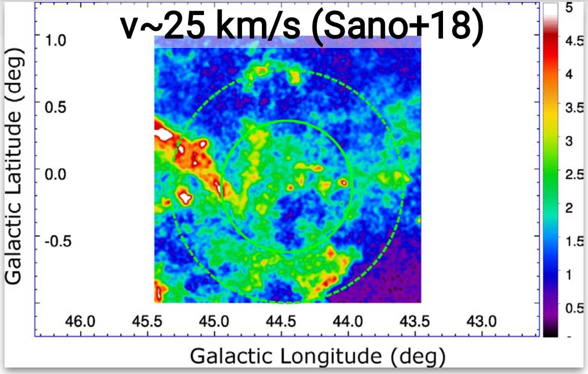
(3rd Fermi Pulsar Catalog)

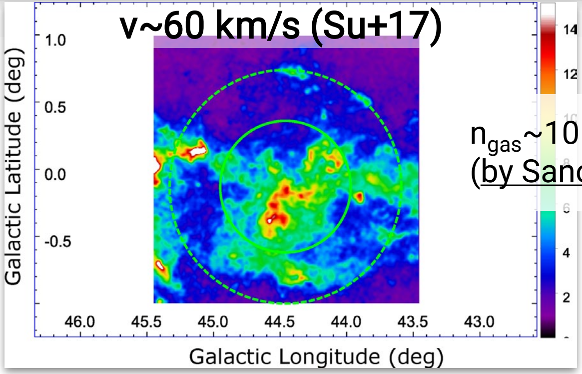


(H.E.S.S. 2018)

Sano+18 (D=1.7pkc Su+17 4.6kpc)

Two Scenarios for Fermi/LHAASO/H.E.S.S. Source





n_{gas}~10 cm^{-3}
(by Sano, Murase)

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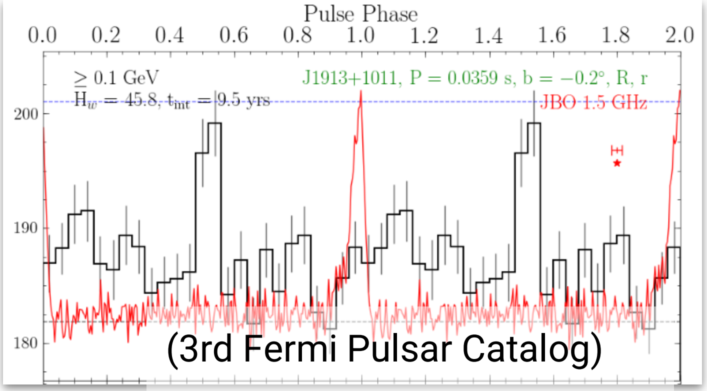

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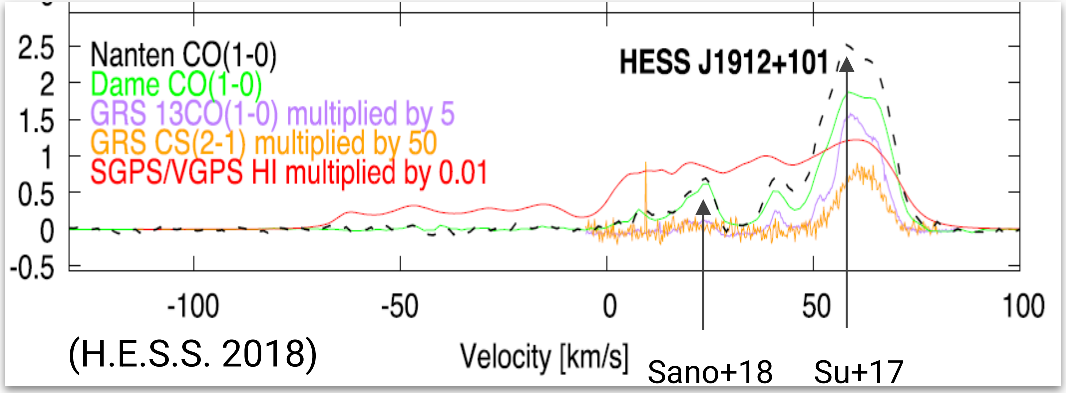


(H.E.S.S. 2018)

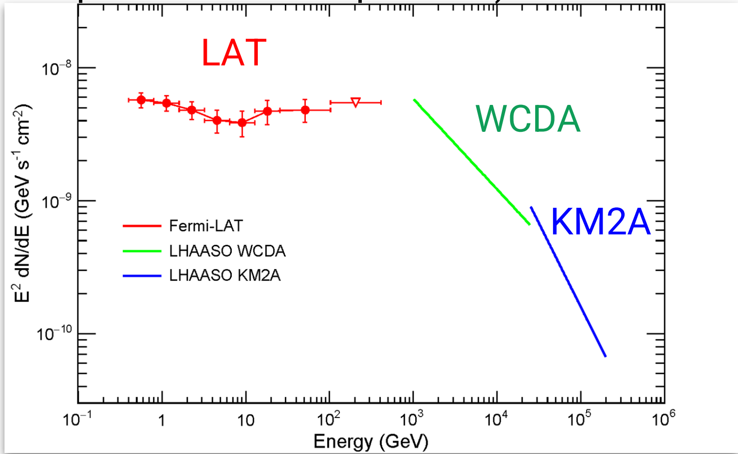
Sano+18 (D=1.7pkc
Su+17 4.6kpc)

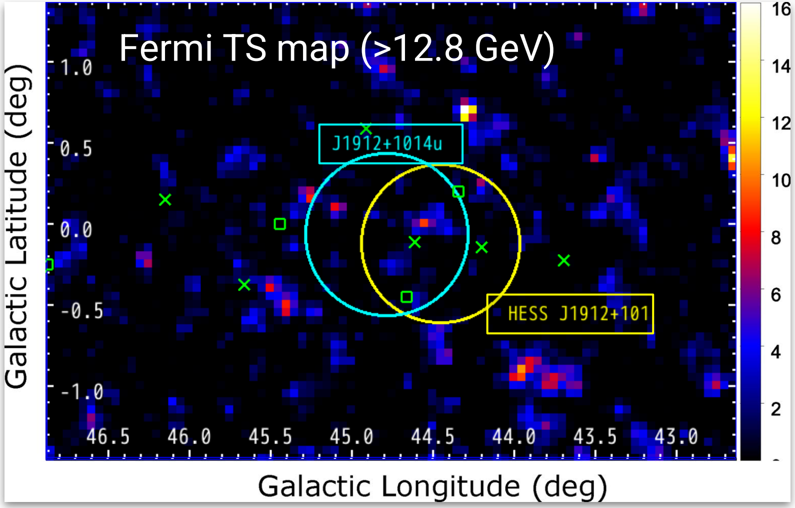
Modeling GeV Counterpart for the Source

Three models are equally good: Su+17 HI+CO (N_p) map, Sano+18 N_p map (SNR scenario), and LHAASO KM2A Gaussian (PWN scenario)

Will distinguish leptonic and hadronic scenarios based on SED incl. H.E.S.S. and HAWC results (employed Sano+18 Np map to derive GeV spectrum)

Model	ΔAIC	index
Radial Disk	88.6	2.08 ± 0.01
H.E.S.S. int. map	74.6	2.11 ± 0.01
Su et al. (2017) N_p map	95.6	2.08 ± 0.01
Sano et al. (2018) N_p map	94.8	2.06 ± 0.01
WCDA Gaussian	86.4	2.09 ± 0.01
KM2A Gaussian	94.4	2.08 ± 0.01



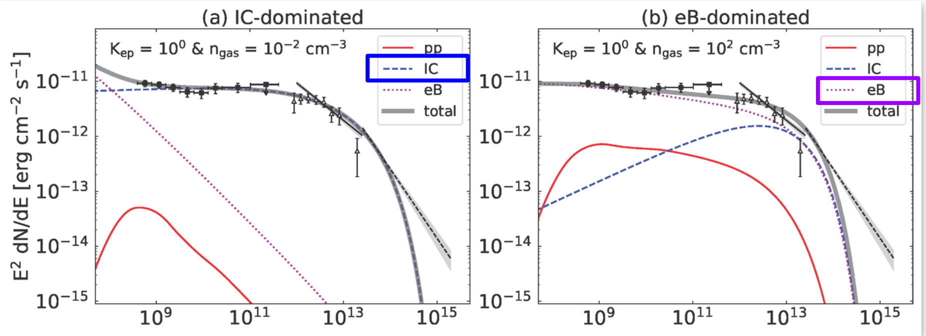


Discussion of CR Type and Properties

Performed comprehensive fit to SED to characterize CRs by scanning wide range of K_{ep} and n_{gas} (let norms, index and E_{cut} vary freely); considered both D=1.7 kpc and 4.6 kpc

1. no electron cooling

- PWN scenario = IC-dominated case (large K_{ep} and small n_{gas}) can reproduce SED, but is rejected in terms of energetics (even w/ PSR J1913+101)
- eB-dominated case (large K_{ep} and n_{gas}) w/ $E_{cut,e}$=50TeV is OK for now)

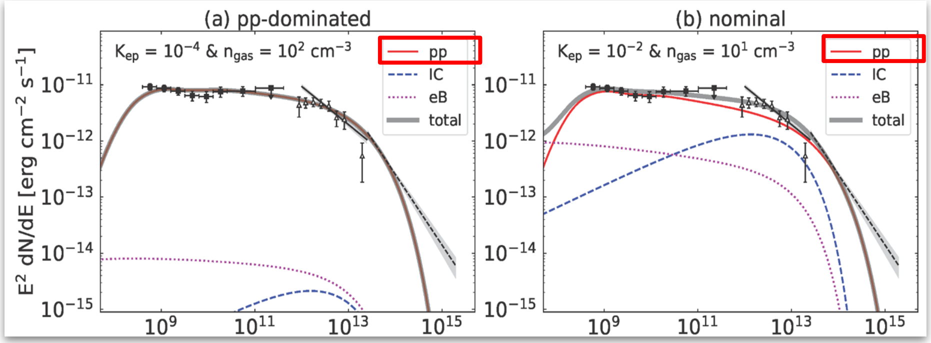


(by T. Oka) Energy (eV)

Performed comprehensive fit to SED to characterize CRs by scanning wide range of K_{ep} and n_{gas} (let norms, index and E_{cut} vary freely); considered both D=1.7 kpc and 4.6 kpc

2. considering cooling

- Putative SNR’s age (>10 ky) gives $E_{cut,e}$≤30 TeV; eB-dom. case unlikely
- pp-dom. case (small K_{ep} & large n_{gas}) and nominal case (standard K_{ep} & n_{gas}) are OK; pi0-gamma is dominant from GeV to TeV



(by T. Oka) Energy (eV)

Discussion of CR Type and Properties (Cont'd)

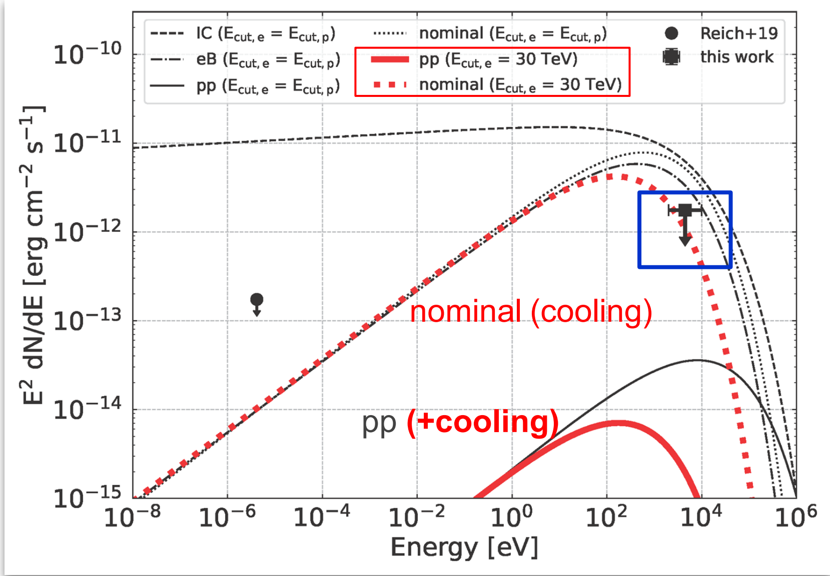
Performed comprehensive fit to SED to characterize CRs by scanning wide range of K_{ep} and n_{gas}

3. considering X-ray upper limit

- Constrained X-ray emission using Chandra data (Suzuki+20)
- eB-dom. case is rejected, supporting proton PeVatron scenario

case	energetics	cooling	X-ray UL
IC	NG	NG	NG
eB	✔	marginal	NG
pp	✔	✔	✔
nominal	✔	✔	✔

Synchrotron model spectrum (by Suzuki, Oka)



α_p=2.2, $E_{cut,p}$=320 TeV, W_p=1e49 erg (nominal & 1.7 kpc)

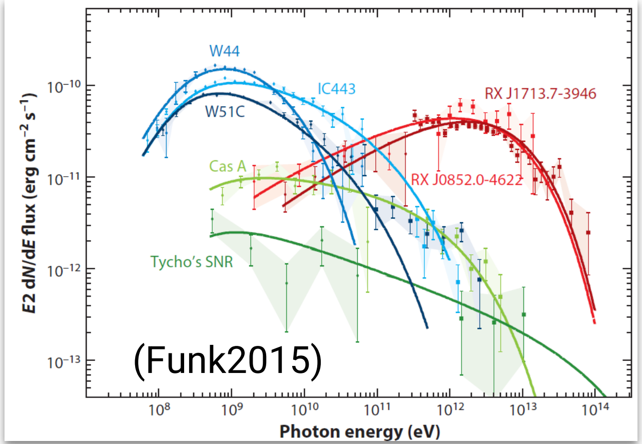
Comparison with Other SNRs

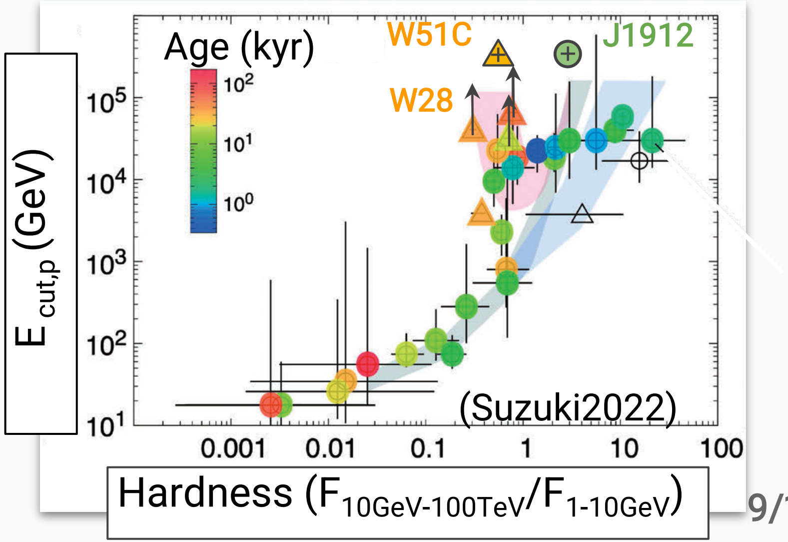
(α_p=2.2, $E_{cut,p}$=320 TeV, W_p=1e49 erg)

Interpret J1912 as an SNR which accelerated CR_p up to PeV

SNRs show softening as they become older (CR_p escape); some middle-aged SNRs show no apparent cutoff ($E_{cut,p}$>30 TeV) or large $E_{cut,p}$ (>300 TeV)

With deeper obs. in GeV/TeV, <u>we can investigate “relic” CRs</u> of proton PeVatrons (in low-surface-brightness emission like J1912)





Summary

Investigated 1LHAASO J1912+1014u (HESS J1912+101) and revealed GeV emission (by Fermi-LAT) associated with ISM gas (by FUGIN survey)

Performed comprehensive fit to SED to characterized CRs responsible for GeV/TeV emission

- GeV/TeV SED (+ X-ray UL) support proton PeVatron scenario
- SNR with α_p=2.2, $E_{cut,p}$=320 TeV, and W_p=1e49 erg (D=1.7 kpc)

Deeper obs. in GeV/TeV (+ search for LSB emission) will reveal relic CRs of proton PeVatrons

Thank you for your attention

References

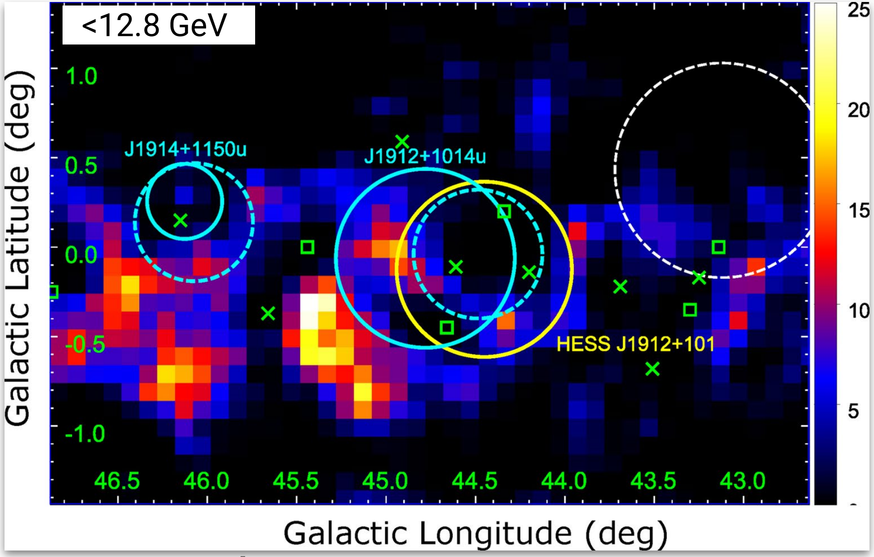
- Aharonian et al. 2008, A&A 484, 435
- Amenomori et al. 2021, Nature Astronomy 5, 460; MAGIC Collaboration 2023, A&A 671, 12 (SNR G106.3)
- Brand&Blitz 1993, A&A 275, 67
- Cao et al. 2024, ApJ 271, 25
- Funk 2015, ARNPS 65, 245
- H.E.S.S. Collaboration 2018, A&A 612, 8
- LHAASO Collaboration 2024, Science Bulletin 69, 2833
- Ranasinghe&Leahy 2023, ApJS 265, 53
- Sano et al. 2018, ASJ meeting (ISM-oriented paper in prep.)
- Smith et al. 2019, ApJ 871, 78 (LAT PSR catalog)
- Su et al. 2017, ApJ 845, 48
- Suzuki et al. 2020, ApJ 893, 147; Suzuki et al. 2022, ApJ 924, 45; Suzuki 2024, Astronomical Herald 117, 489

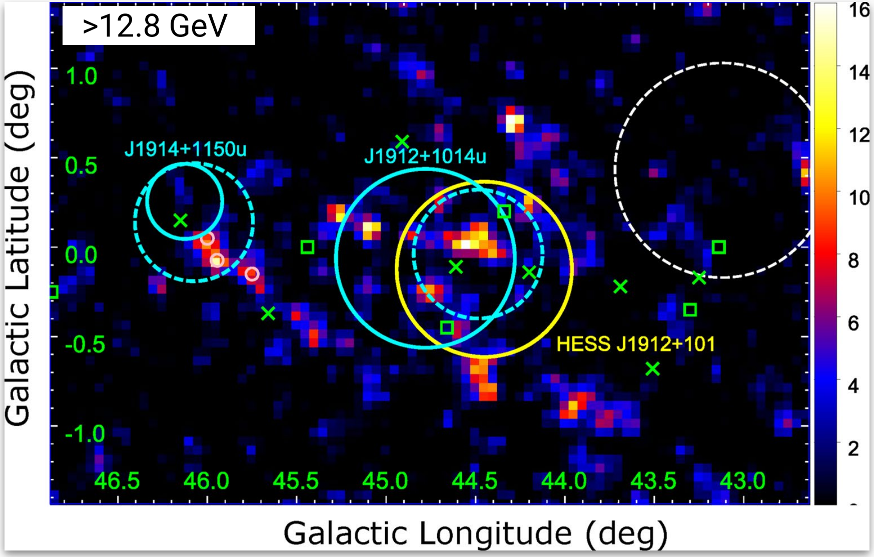
Backup Slides (Appendix)

Developing Baseline Model

Standard analysis (gll_iem_v07 & 4FGL sources) gives large residuals around the source below and above 10 GeV that affect the past studies

We constructed baseline model by (1) adding DNM template to reduce LE residual and (2) modeling HE residual close to another sub-PeV source phenomenologically





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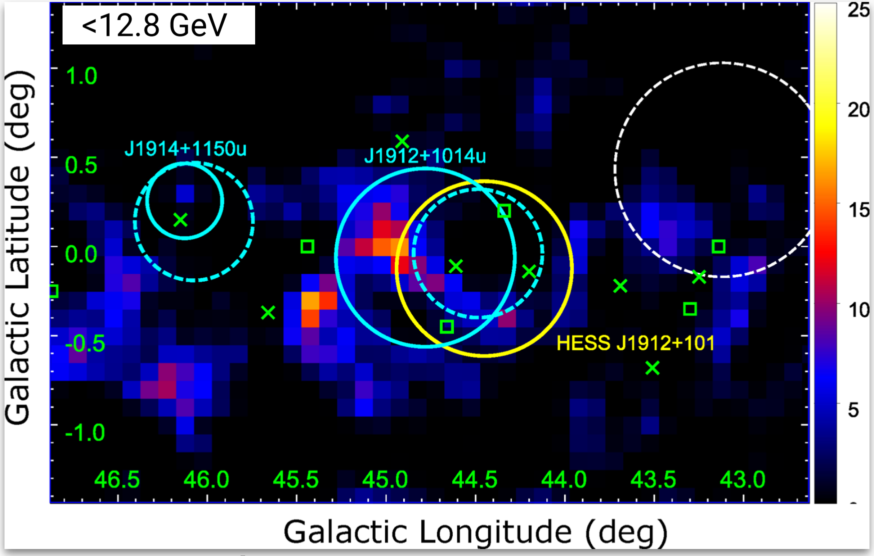

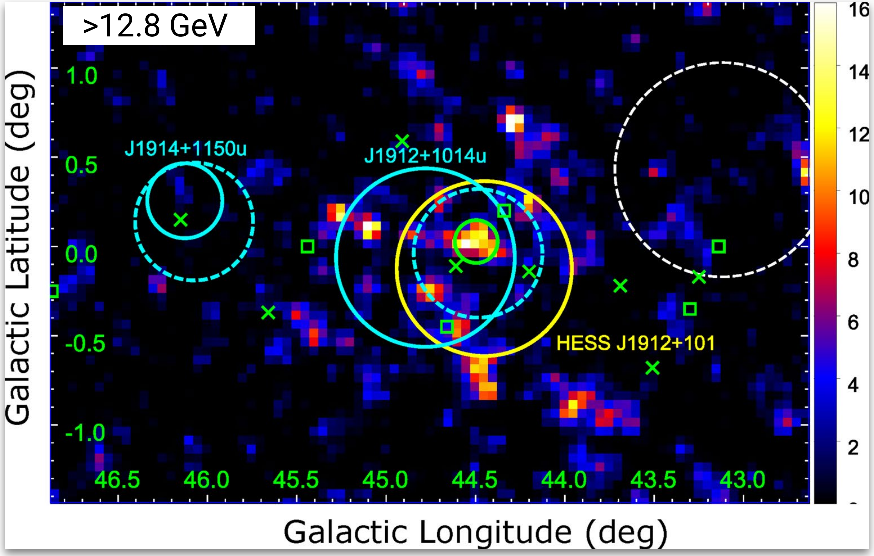

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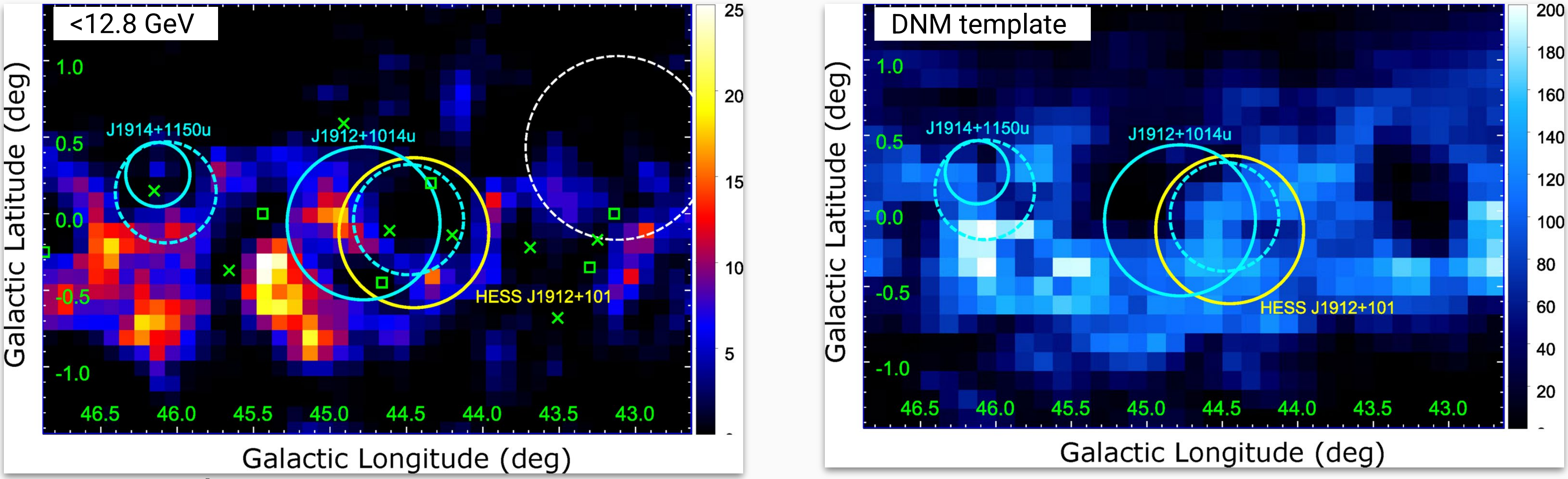


Alternative Scenario (Sano+18)

Su+17 proposed CO cloud with v~60 km/s is associated with HESS J1912+101

Sano+18 proposed alternative scenario (CO cloud with v~25 km/s) based on the following:

- expanding gas motion is observed
- good spatial correlation with H.E.S.S. source is observed
- (ISM-oriented paper in prep.)

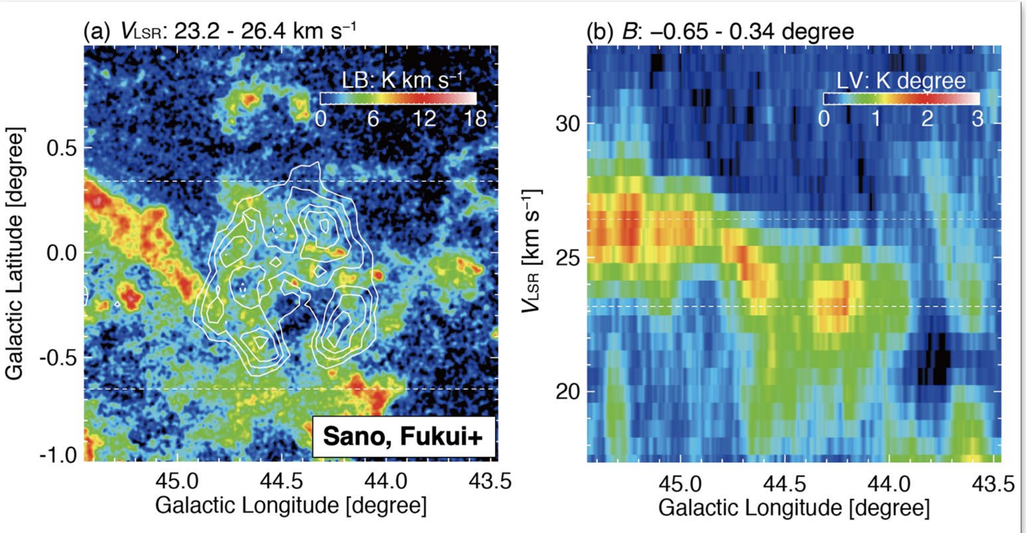
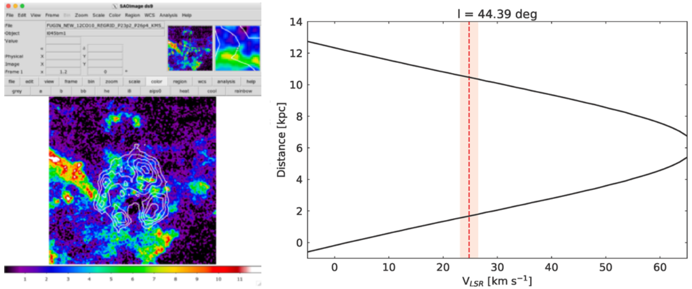


Image: FUGIN ^{12}CO(1–0), Contours: H.E.S.S. TeV gamma-ray

Distance to the Source

We refer to rotation curve by Brand&Blitz 1993 and adopt the distances of near side

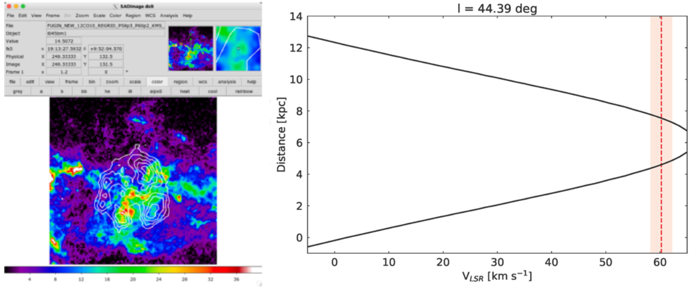
✓ **Sano+18 CO model**: V_{LSR} = +23.2 - 26.4 [km/s]



D=1.7 +/- 0.1 kpc

D=10.5 +/- 0.1 kpc

✓ **Su+17 CO model**: V_{LSR} = +58.3 - 62.2 [km/s]



D=4.6 +/- 0.2 kpc

D=7.5 +/- 0.2 kpc

(by T. Oka)

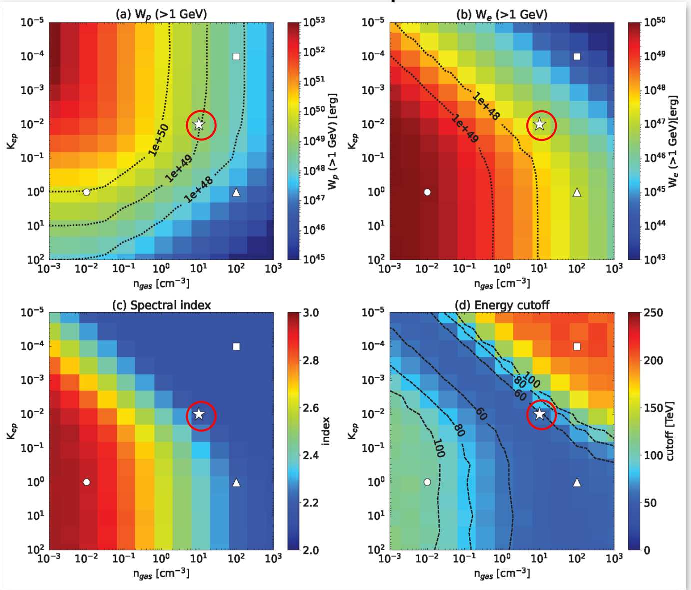
✓ **PSR J1913+1011**: D = 4.6 kpc

If the LHAASO (and LAT) source is SNR, D=1 deg corresponds to

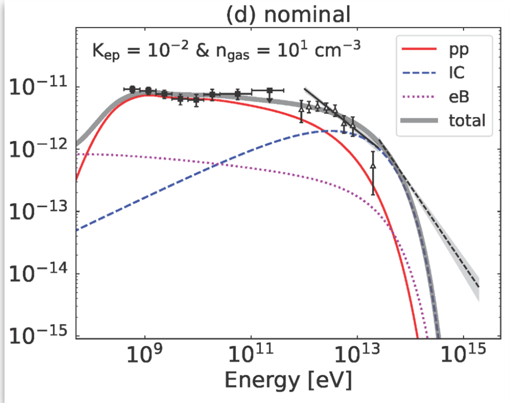
- ~30 ps (t~13 kyr) for Sano+18
- ~80 pc (t~120 kyr) for Su+17 (D=9.5$t^{0.44}$ pc; Ranasinghe&Leahy 23)

Discussion of CR Type and Properties

We carried out a comprehensive fit to GeV and TeV spectrum by scanning wide range of K_{ep} and n_{gas}; we consider both d=1.7 kpc (Sano+18 N_p map) and 4.6 kpc (Su+17 N_p map)



- Free params: N_p, N_e, α_p=α_e, E_{cut}
- Fit GeV/TeV SED using NAIMA with IC+eB+pp for each (K_{ep}, n_{gas})
- Example for nominal case (K_{ep}=0.01 and n_{gas}=10/cc)

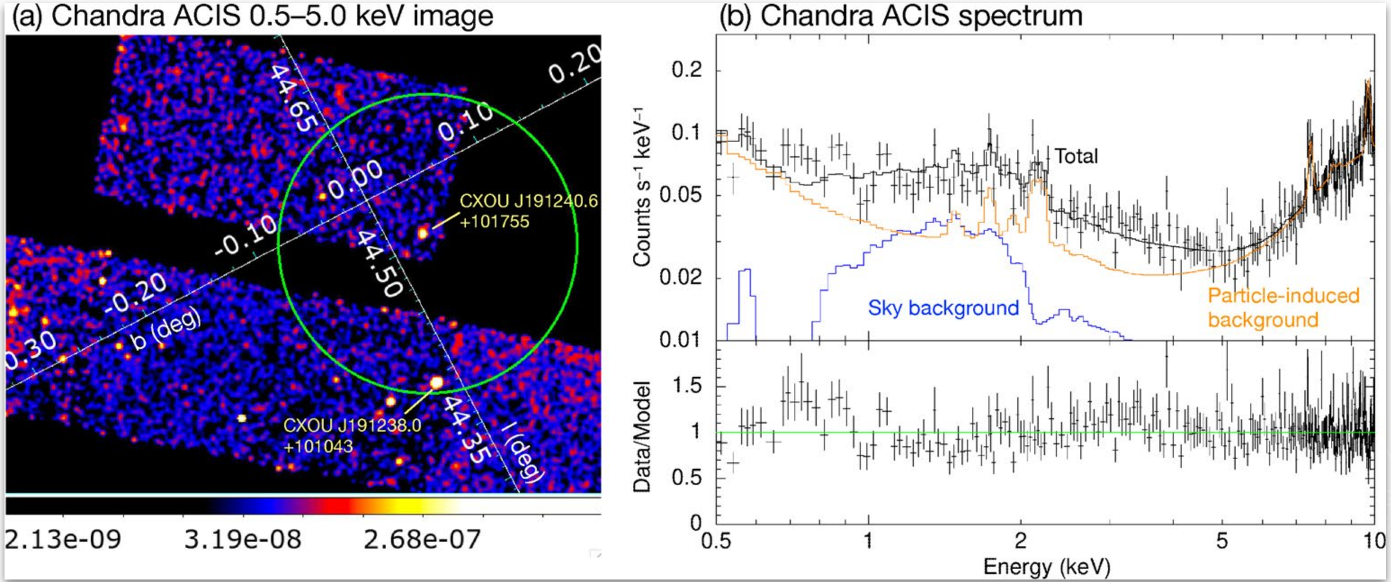


(by T. Oka)

X-ray Upper Limit

Position at the center of HESS J1912+101 observed by Chandra

Diffuse X-ray is well explained by instrumental BG + sky BG + Galactic ridge emission, strongly constraining additional non-thermal X-ray



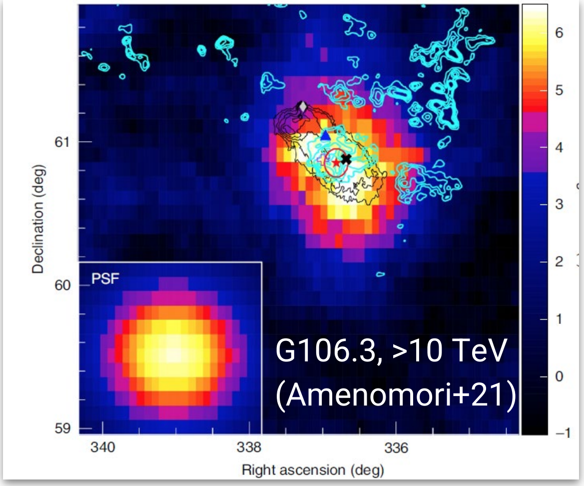
(by H. Suzuki)

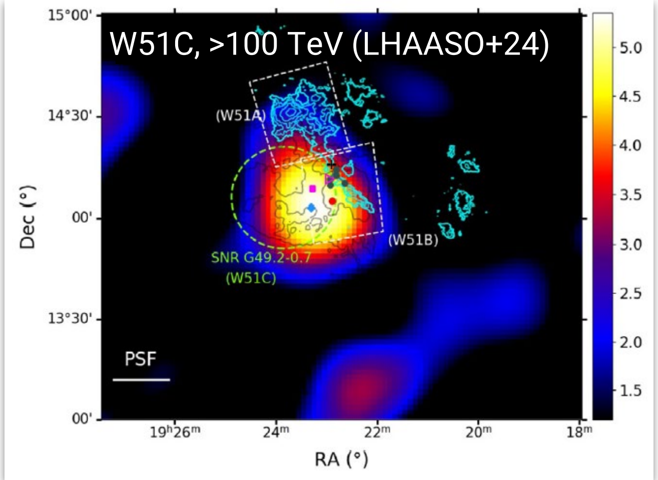
SNR as Sub-PeV Source

Several middle-aged SNRs accelerated CRp up to PeV (Ecut,p > a few 100 TeV). Some others could have accelerated (no apparent cutoff)

- If escaped PeV protons coincide with dense clouds, or entire population is associated with clouds of moderate density, they are detected as sub-PeV src

Good fraction of SNRs are likely PeVatrons and will be detected as sub-PeV src in future





Source	α_p	Ep,cut (TeV)	Wp (erg)	Ngas (cm^{-3})
SNR G106.3+2.7	1.70	1000	1.7e46	200
W51C	2.55	380	1.3e50	100
1LHAASO J1912+1014u	2.20	320	1.1e49	10