Investigating hadronic PeVatrons with X-ray and CO observations

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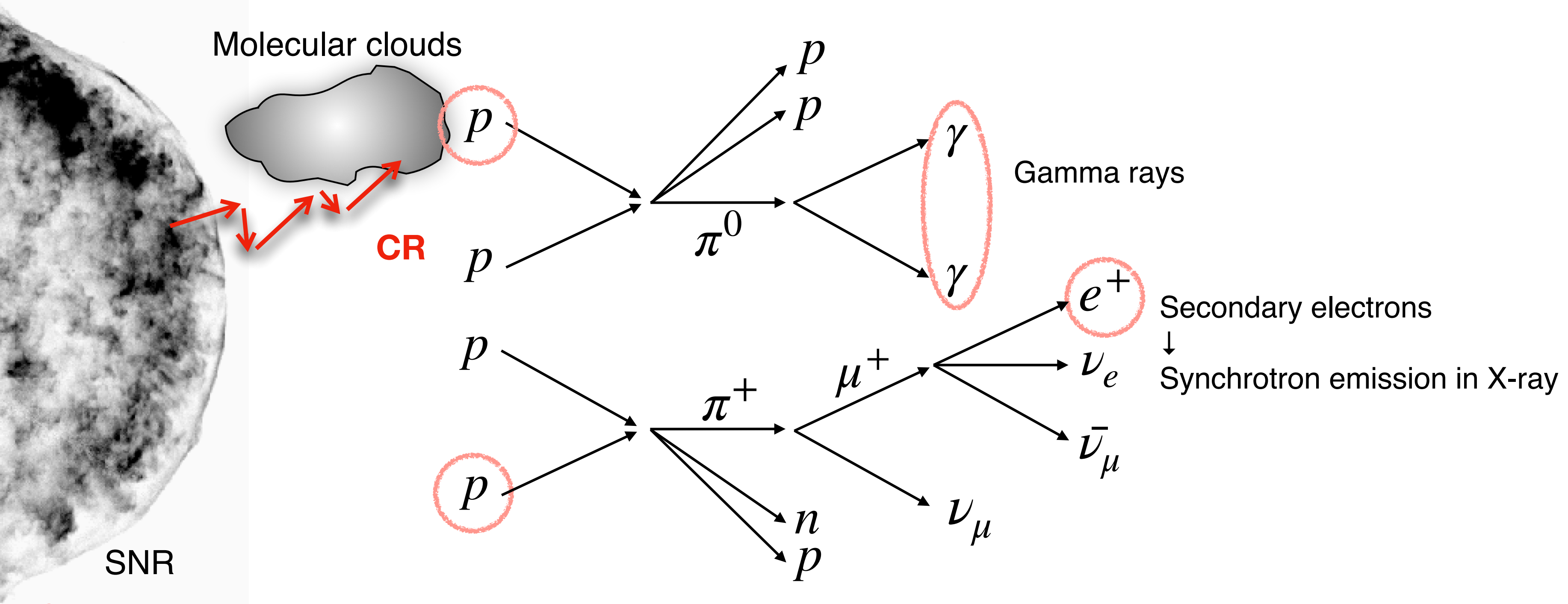
Hadronic gamma-ray emission

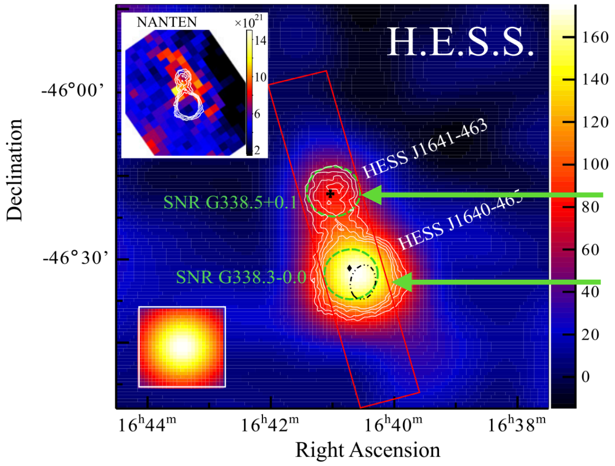


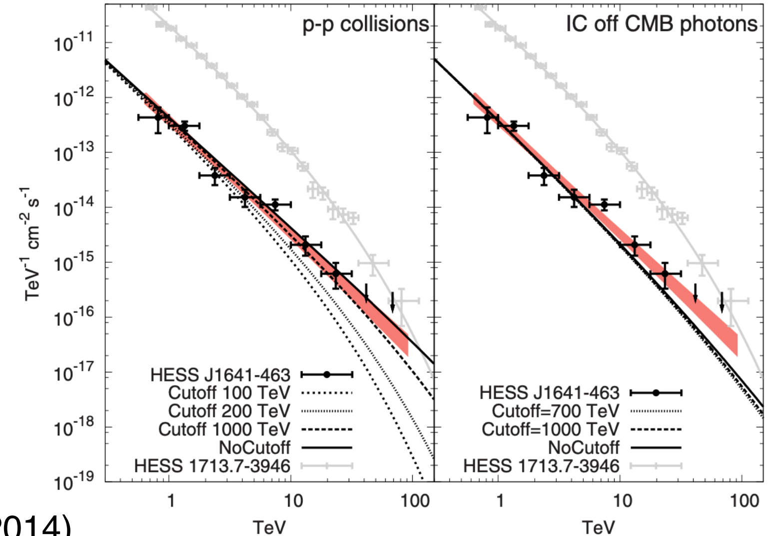
[this talk] search for secondary synchrotron emission (X-ray observation) and molecular clouds (CO observation)

HESS J1641-463

- Unidentified, extended TeV gamma-ray source on the Galactic plane
- Hard TeV gamma-ray spectrum (Γ=2.07) → $E_{p,c}$ > 100 TeV → PeVatron candidate!
- Coincides with a radio SNR, G338.5+0.1
- X-ray domain has been unexplored

Excess map of HESS (>4 TeV)

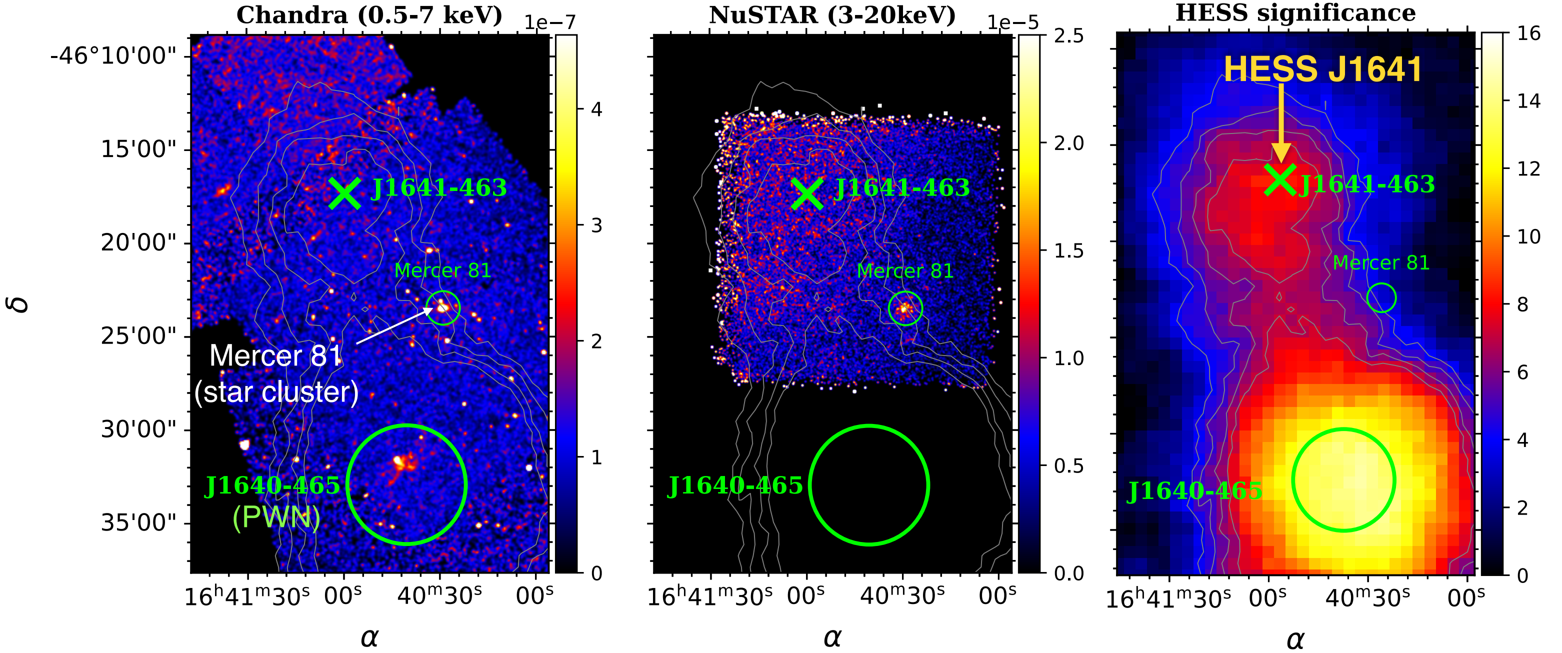




(HESS Collab. 2014)

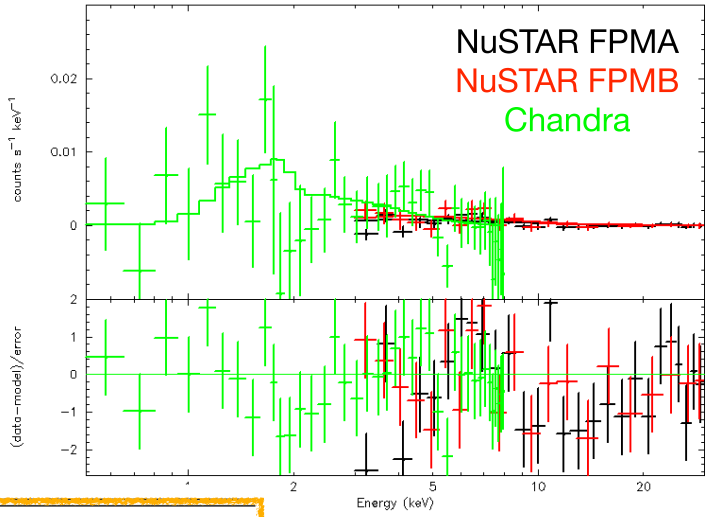
X-ray observation and image

- Analyzed new NuSTAR data (80 ks) and archival Chandra data (60 ks in total)
- No significant X-ray emission from HESS J1641



X-ray spectrum of HESS J1641

- Fitting model: absorbed power law
  - $N_H = 2\times10^{22}$ cm^{-2} and $\Gamma = 2$ (fix)
- 2σ flux upper limit
  - (6–7)x10^{-13} erg/cm^2/s in 2–10 keV
  - ~3 x10^{-13} erg/cm^2/s in 10–20 keV
  - Roughly consistent with Mares+ 2021



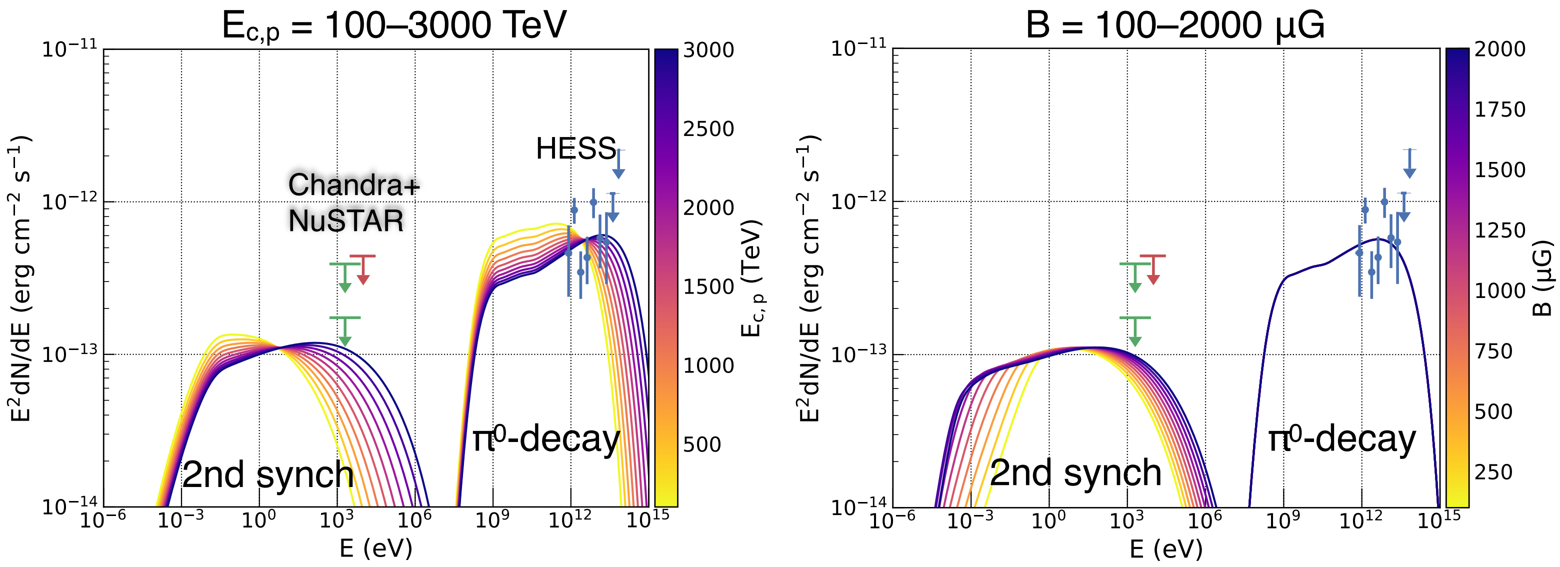
	Size (arcmin^2)	Detector	F_{2-10}	F_{10-20}	Scaled F_{2-10} (10^{-13} erg/cm^2/s)	Scaled F_{10-20} (10^{-13} erg/cm^2/s)
NuSTAR	18.1	FPMA	4.0	1.7	6.2	2.7
	28.3	FPMB	7.1	3.0	7.1	3.0
Chandra (12508)	22.8	ACIS-S (BI)	5.1	—	6.3	—
Chandra (11008)	15.35	ACIS-I	1.5	—	2.8	—

Flux scaled to HESS's extension

Modeling

Tsuji et al 2024 *ApJ* 967 138

Synchrotron X-ray from secondary e± in pp interaction



n (cm^{-3})	100
B (μG)	300
Age (kyr)	5
d (kpc)	11
Index	2
$E_{c,p}$ (PeV)	1
Wp (erg)	1.5×10^{48}

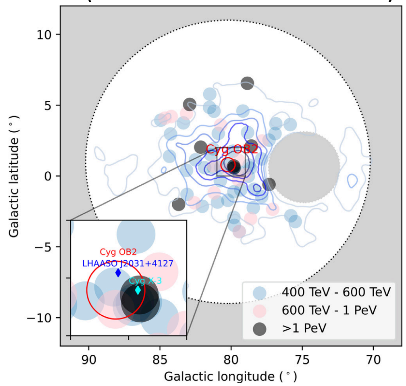
- X-ray upper limits (this work) cannot place tight constraint
- X-ray emission, if detected, might be able to determine $E_{max,\,p}$

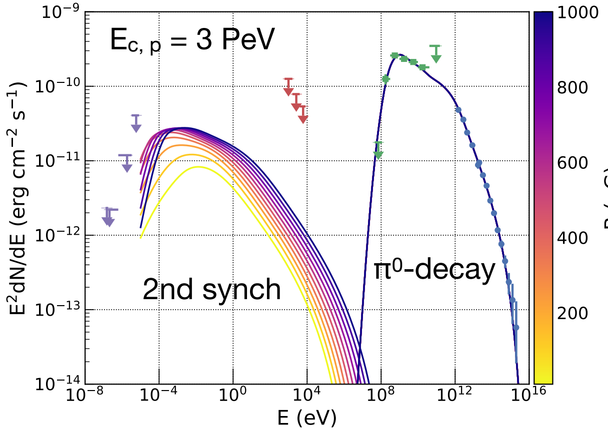
Detectability of 2nd electrons

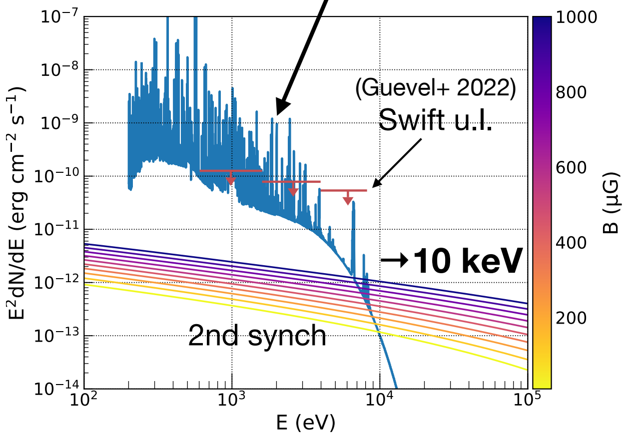
Cygnus cocoon/OB2

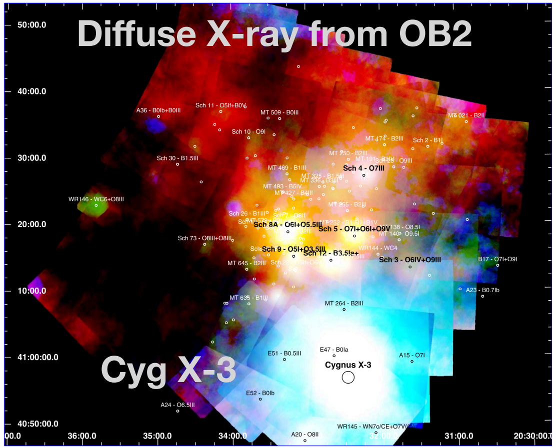
- >PeV emission
  - ~6 deg bubble and ~0.3 deg core (including OB2 and Cyg X-3)
  - Hadronic origin → 2nd synchrotron depends on only B-field
- Thermal diffuse emission (kT= 0.1–1 keV) from OB2 region
  - 2nd synch becomes dominant at >10 keV

(LHAASO Collab. 2024)





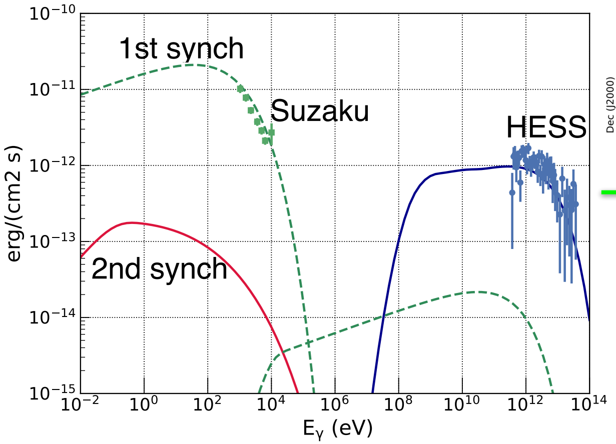


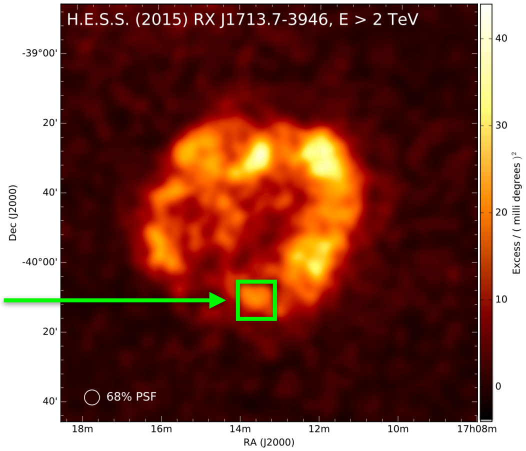


(Albacete-Colombo+ 2023)

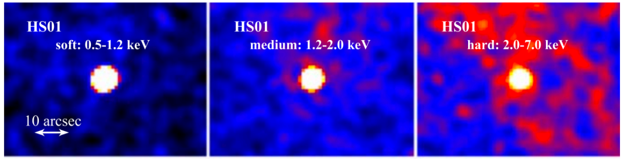
Detectability of 2nd electrons

SNR RX J1713.7-3946

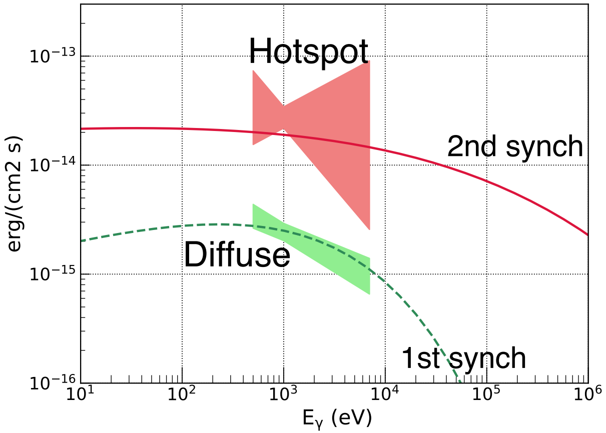




Many X-ray "hotspots" in NW shell: cores of molecular clouds?



(Higurashi, NT, Uchiyama, 2020)



- South region
  - ~5x5 arcmin² (HESS Collab. 2018)
  - Hadronic fraction >70% (Fukui+ 2021)
  - Primary synchrotron component is dominant

- Hotspots
  - ~5 arcsec in radius
  - 2nd synchrotron component (~10^{-14} cgs)
  - Angular resolution should be <15 arcsec
    - Otherwise, 1st synchrotron dominates

Detectability of secondary electrons

Future prospect

- What is the best target?
  - Hard TeV gamma-ray spectrum and low thermal/synchrotron X-ray flux

	Example	Size	Notes
1. UnID gamma-ray source	HESS J1641-463	3 arcmin	△ Needs deep observation
2. Star forming region	Cygnus bubble	~6 deg	✕ Too largely extended
	Cygnus OB2	~0.3 deg	○ Detectable at >10 keV
3. SNR	RX J1713's diffuse	~5 arcmin	✕ 1st synchrotron dominant
	RX J1713's hotspot	~5 arcsec	○ Requires <15" resolution

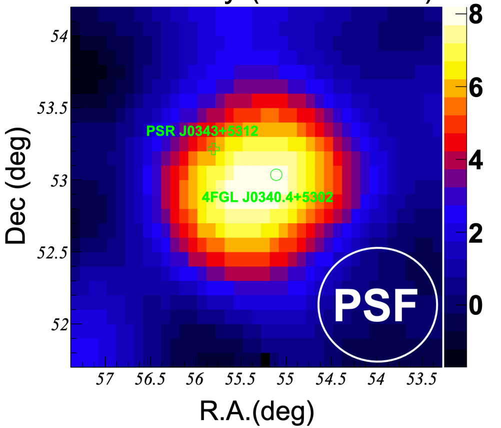
- Detectable by future hard X-ray telescope with good angular resolution (e.g., HEX-P)

Search for molecular clouds in LHAASO J0341 + 5258

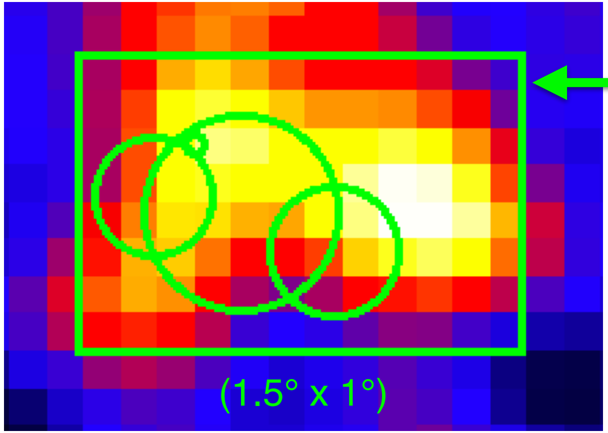
- LHAASO J0341+5258
  - Extended, unidentified source up to >100 TeV
  - E_{max} ~ 200 TeV (Cao+ 2021; Kar and Gupta 2022)

Name	Size (deg)		Γ	
	KM2A	WCDA	KM2A	WCDA
LHAASO J0341+5258	0.29	—	2.98	—
1LHAASO J0339+5307	<0.22	—	3.64	—
1LHAASO J0343+5254u	0.20	0.33	3.53	1.70

Gamma ray (Cao+ 2021)

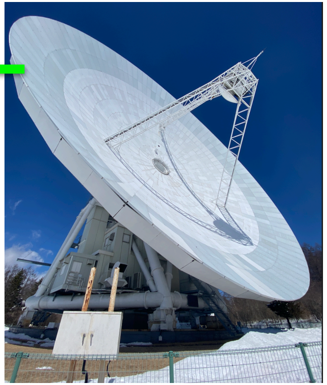


7 km/s ^{12}CO map (Dame+ 2001)



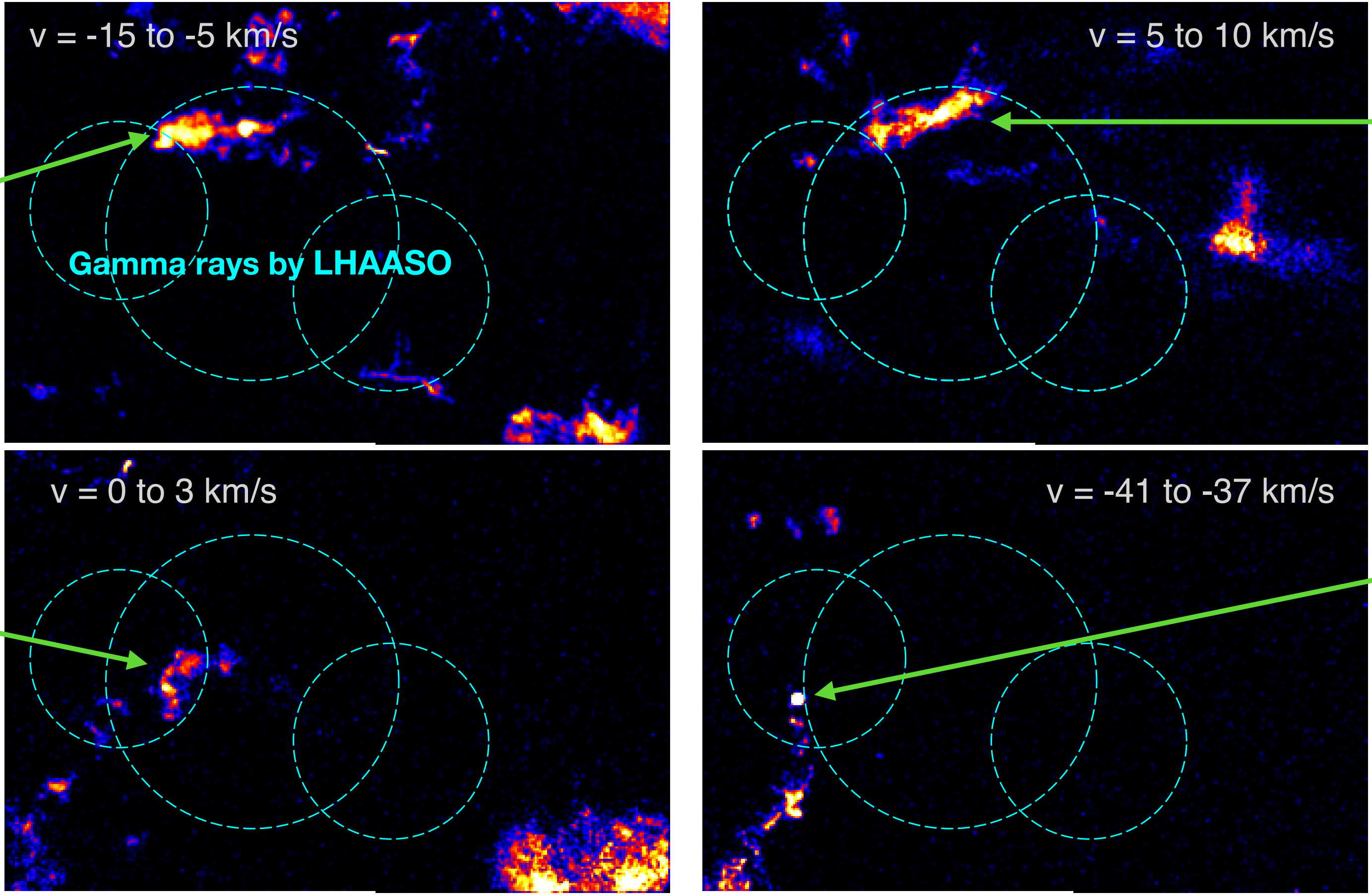
Observations of ^{12}CO, ^{13}CO, and $C^{18}O$ lines (J=1–0)

45-m Nobeyama radio telescope



(Tsuji+ in prep.)

^{12}CO map



Dense core, also detected in ^{13}CO and $C^{18}O$
- r = 1.6 pc
- d = 1 kpc
- M = 310 M_{sun}

- r = 0.9 pc
- d < 0.3 kpc
- M = 25 M_{sun}

“Half-shell” (Cao+ 2021)
- r = 0.5 pc
- d < 0.3 kpc
- M = 5.4 M_{sun}

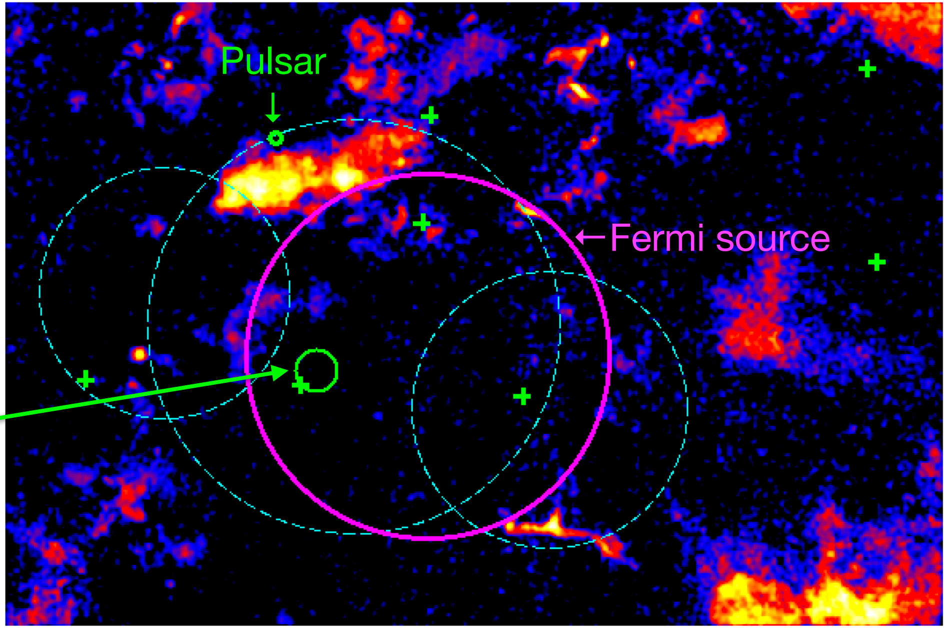
CO envelope of AGB star?
(IRAS 03392+5239)
- r = 1.2 pc
- d = 4 kpc
- M = 339 M_{sun}

Discussion

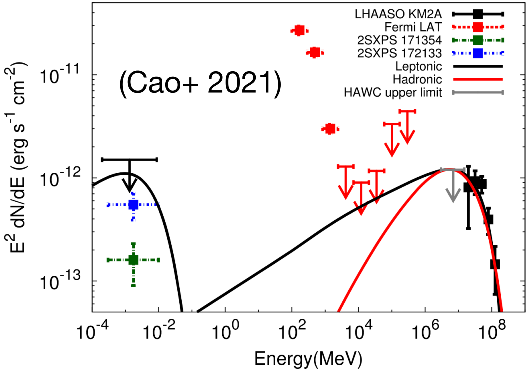
■ Counterparts

- X-ray: 4 ROSAT sources (Boller et al. 2016)
- Pulsar: PSR J0343+5312
- GeV: 4FGL J0340.4+5302

Nobeyama ^{12}CO image (-40 to 10 km/s)



Extended X-ray emission
in new XMM data in 2024
(Shuo Zhang et al.)



■ Leptonic: pulsar/PWN + halo

■ Hadronic: CR + clouds

Molecular clouds (this work)
- d < ~1 kpc
- n = 100–1000 cm^{-3}

$$W_p \sim 3 \times 10^{45} \left(\frac{d}{1\ \mathrm{kpc}}\right)^2 \left(\frac{n}{100\ \mathrm{cm}^{-3}}\right)^{-1}\ \mathrm{erg}$$

Summary

- X-rays (secondary synchrotron radiation) and molecular clouds could be probes of hadronic gamma rays
- Synchrotron emission from secondary electrons
  - Tested in HESS J1641-463, Cygnus cocoon/OB2, SNR RX J1713.7-3946
  - Future hard X-ray telescope might be able to detect the emission
- Molecular cloud search in LHAASO J0341+5258
  - ~30 hr observations by Nobeyama Radio Observatory
  - Most of detected clouds are nearby (<1 kpc), small (~1 pc), and light (5–300 M_{sun})
- Future plan
  - Ongoing analysis of XMM data and scheduled Nobeyama CO observations on 6 sources below

Source name	X-ray	CO
LHAASO J0341+5258	XMM in 2024	Nobeyama in 2024 (this talk)
LHAASO J2108+5157	XMM in 2023	De la Fuente+ 2023
1LHAASO J0500+4454	—	Nobeyama in 2025
1LHAASO J0622+3754	XMM in 2024	Nobeyama in 2025
1LHAASO J1956+2921	XMM in 2024	Nobeyama in 2024–2025
V4641 Sgr	—	Nobeyama in 2024

Collaboration with K. Mori, S. Takekawa, A. Mitchell, S. Zhang, P. Bangale, J. Gelfand, J. Alford, J. Woo, S. Safi-Harb, I. Sander, L. Olivera-Nieto, and E. de la Fuente,