Discovery of 100 TeV γ-rays from HESS J1702-420: a new PeVatron candidate

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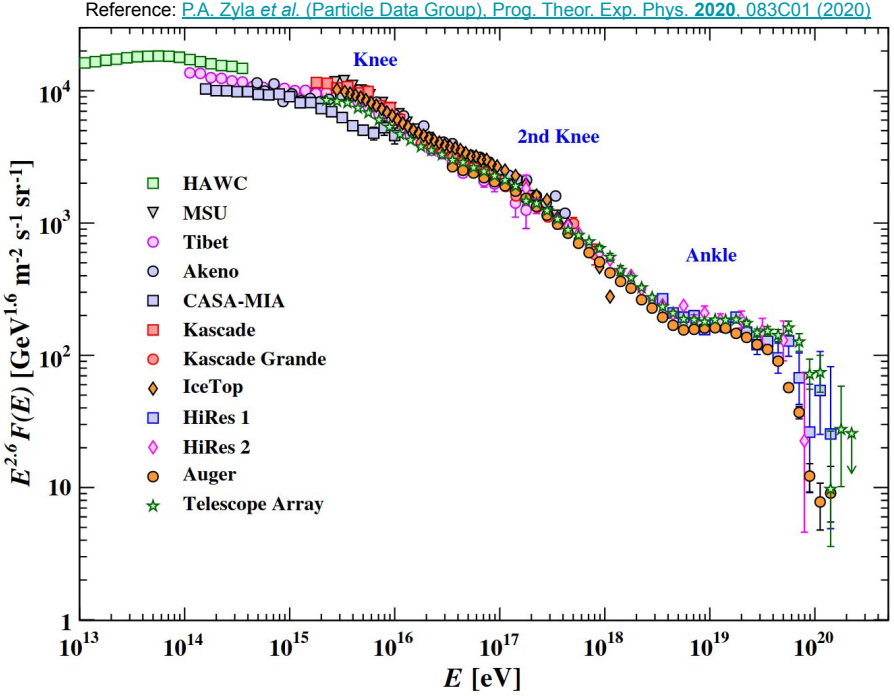
The quest for Galactic PeVatrons

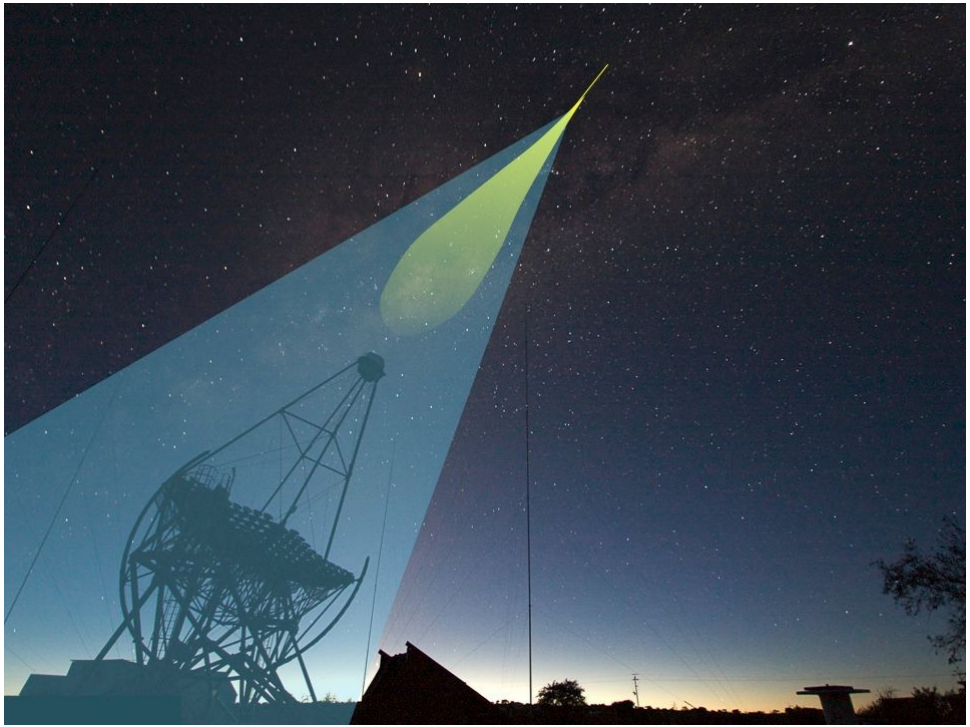
- The origin of CRs is a century-old problem
- It is believed that the bulk of cosmic rays at least up to the **knee** (3-4 PeV) is accelerated within the Galaxy, by unknown **proton PeVatrons**
- Several source populations have been proposed as PeVatron candidates (e.g. supernova remnants), but **no PeVatron has been firmly identified yet**
- The H.E.S.S. Collaboration has already reported evidence for the acceleration of PeV protons in the Central Molecular Zone around Sgr A* [1]

Reference: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)



The H.E.S.S. telescope array

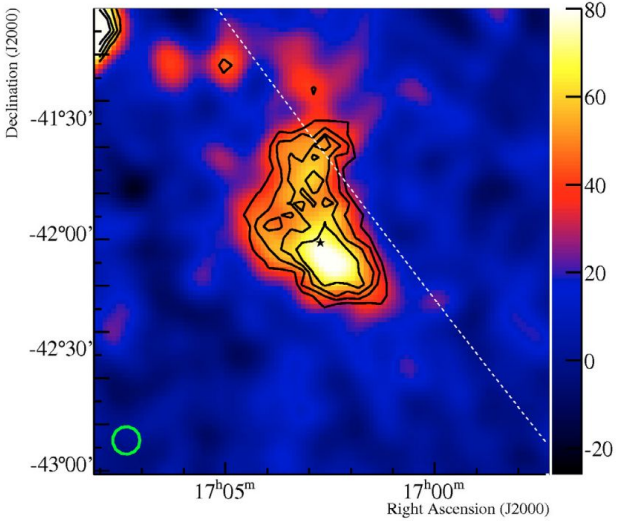
- H.E.S.S. is an array of 5 Imaging Atmospheric Cherenkov Telescopes (**IACTs**)
- It is located in Namibia, and is operational since 2003
- Array design: four 12 m diameter telescopes (CT1-CT4) at the corners of a 120 m × 120 m square, with cameras upgraded in 2017 [2]
- In 2012, a fifth 28 m diameter telescope (CT5) was added at the center of the grid. **This work makes use of CT1-CT4 data only.**

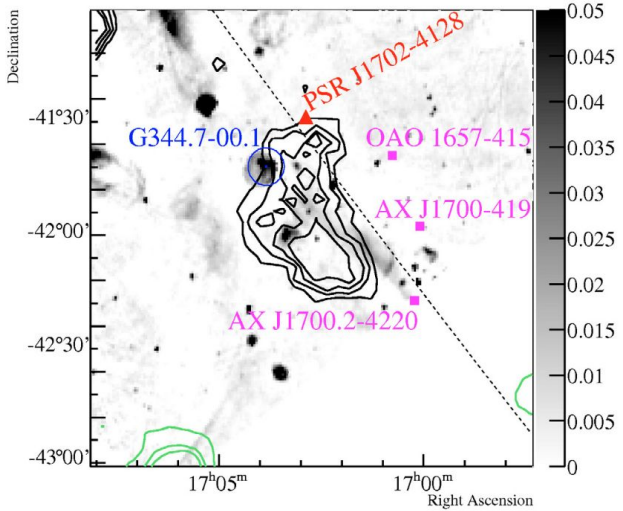


Previous H.E.S.S. publications of HESS J1702-420

- HESS J1702-420 is a **dark** TeV source (→ no counterpart found at other wavelengths)

- First detection in 2008 (12.8σ significance) [3]. Characteristics:
  - **Hard power law spectral index** (~2.07)
  - No sign of spectral cut-off
  - Significantly extended morphology (well described by a $0.30^{o} \times 0.15^{o}$ elliptical Gaussian)





An update on HESS J1702-420

We present **new observations** of HESS J1702-420, processed with **improved analysis** techniques.

H.E.S.S. observations:

- Period: 2004-2019
- On-source livetime: 44.9 h (**~35 h of new data**)

Analysis configuration:

- **Analysis optimized to enhance the collection area at the highest energies**
- The reduced data and IRFs were exported to **FITS** files complying with the GADF format

High-level analysis:

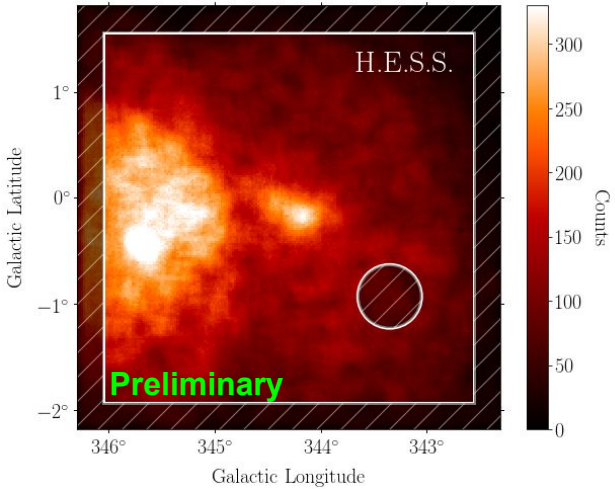
- All the high-level results (sky maps and spectra) were obtained using gammapy v0.17
- We applied a **3D likelihood analysis** to model a $4^o \times 4^o$ ROI centered on HESS J1702-420

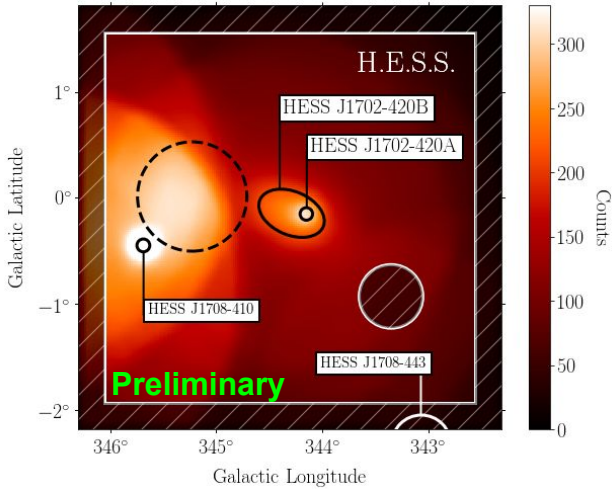
3D analysis of HESS J1702-420

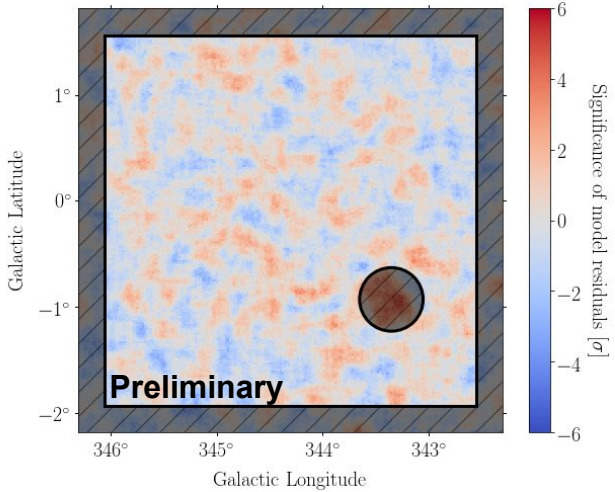
- We improved the first-guess source model (**HGPS**) by iteratively adding components
- The significance for the addition of a new component μ was estimated from the **likelihood ratio**

$$\mathrm{TS} = -2 \ln \left(\frac{\mathcal{L}_0^{\max}}{\mathcal{L}_\mu^{\max}} \right)$$

- The **3D analysis** separates HESS J1702-420 into **2 components** (TS=606, 42) with significantly different morphologies and spectra

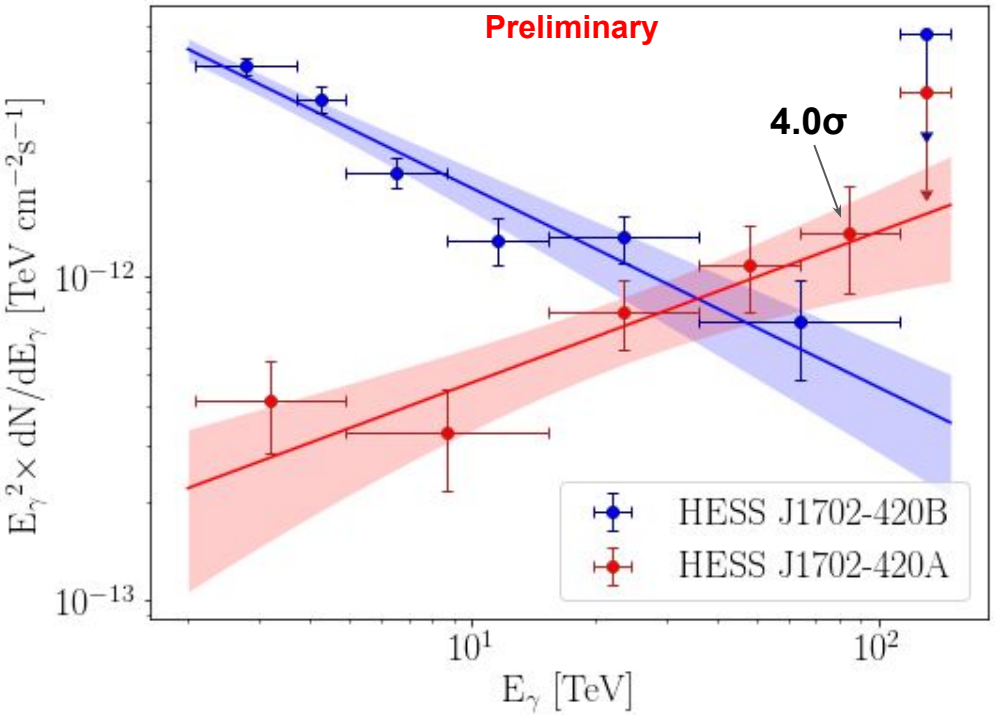






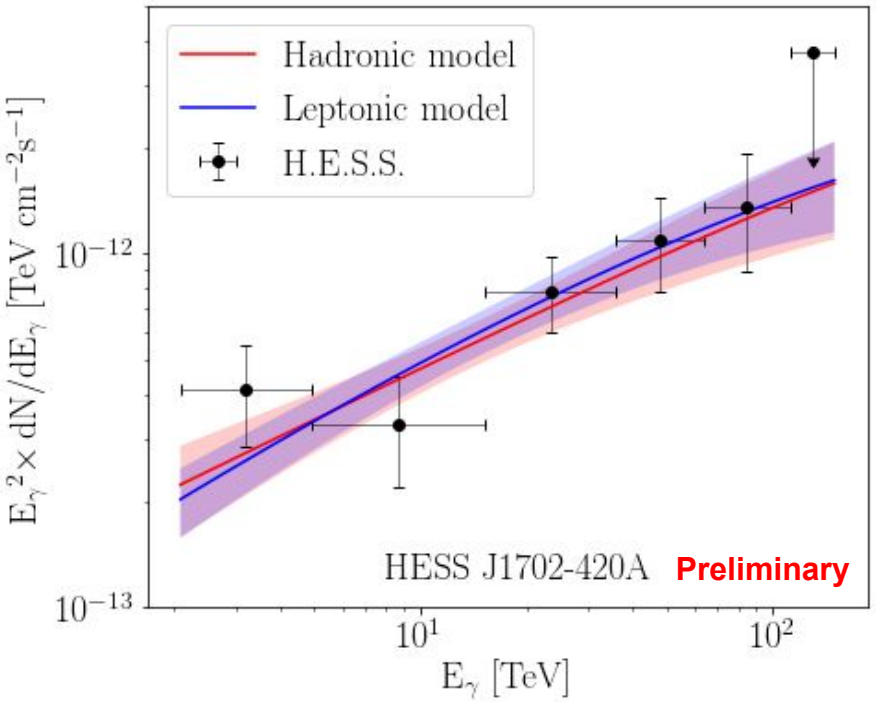
VHE γ-ray spectra of HESS J1702-420A and B

- HESS J1702-420A is a weak TeV source that is outshone (below ~40 TeV) by HESS J1702-420B
- The spectrum of HESS J1702-420A extends with the **hard index**
  Γ = **1.53** ± 0.19_{stat} ± 0.20_{sys}
  and **without curvature up to 100 TeV**
- HESS J1702-420B has a steep spectral index (Γ~2.62) and accounts for most of the HESS J1702-420 flux.



HESS J1702-420A: hadronic scenario (p-p + π^0 decay)

Scenario	PL index	E_{cut} (95% c. l.)	Total energy in particles (E>1 TeV)
Hadronic	$1.58 \pm 0.14_{stat}$	≥ 550 TeV	≥ 1.8 10^{47} erg @ d=3.5 kpc and nH=100 cm^{-3}

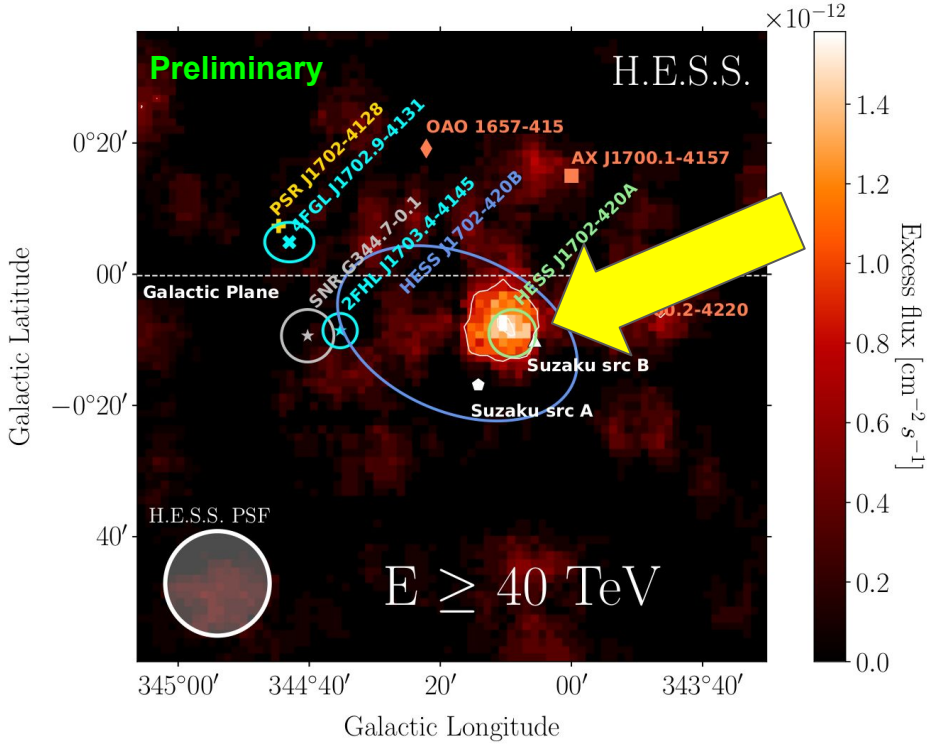


- In a simple hadronic emission scenario, HESS J1702-420A **likely harbors PeV protons**
- The exceptional spectral hardness over two energy decades is difficult to explain with standard DSA
- HESS J1702-420A may be a gas cloud illuminated by energetic runaway CRs from a nearby PeVatron [4]
- However, there is no evidence for dense gas clouds clearly correlated with HESS J1702-420A [5], which prevents a confirmation of the hadronic scenario

HESS J1702-420A: leptonic scenario (IC on CMB + ISRF)

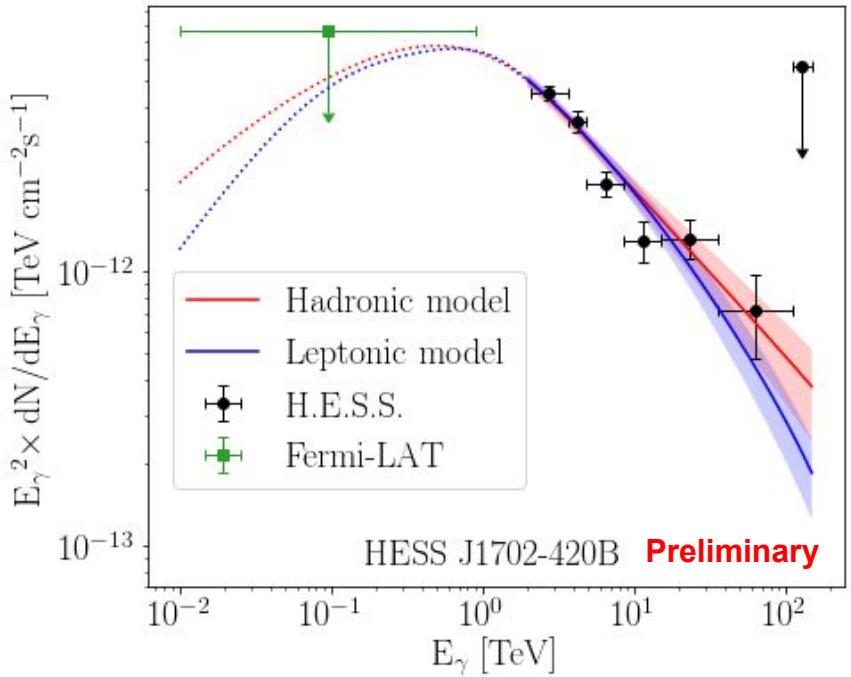
Scenario	PL index	E_{cut} (95% c. l.)	Total energy in particles (E>1 TeV)
Leptonic	$1.61 \pm 0.15_{stat}$	≥ 64 TeV	≥ 8.1 10^{45} erg @ d=3.5 kpc

- A simple one-zone leptonic (PWN) origin of HESS J1702-420A is **discouraged** by the non-detection of a spectral break associated with the rapid cooling of ~100 TeV electrons
- However, HESS J1702-420A is positionally close to the faint X-ray source ***Suzaku* src B** [6], which might be the compact object (pulsar) powering the TeV source
- Unfortunately, *Suzaku* could not measure the spectrum of src B, and its flux estimation suffered from strong systematics



HESS J1702-420B: hadronic scenario (p-p + π^0 decay)

Scenario	PL index ($E>E_{break}$)	E_{break} [TeV]	Total energy in particles (E>1 GeV)
Hadronic	$2.66 \pm 0.11_{stat}$	$6.77 \pm 3.64_{stat}$	~ $2.8\ 10^{48}$ erg @ d=3.5 kpc and nH=100 cm^{-3}

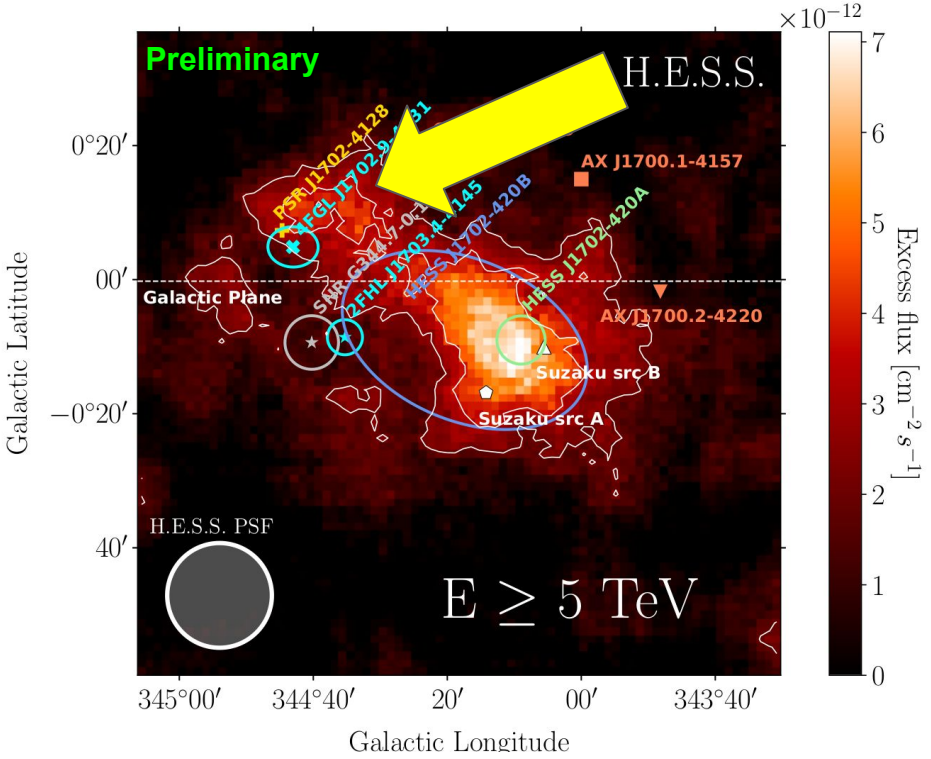


- In a hadronic scenario, HESS J1702-420B may be a proton accelerator whose spectral break around E_p~7 TeV is due to the **energy-dependent escape** of CRs
- In this case, the hard γ-ray spectrum of HESS J1702-420A could be the signature of **delayed emission** from the highest energy runaway protons, hitting target material in the ISM.

HESS J1702-420B: leptonic scenario (IC on CMB + ISRF)

Scenario	PL index ($E>E_{break}$)	E_{break} [TeV]	Total energy in particles (E>1 GeV)
Leptonic	$3.39 \pm 0.11_{stat}$	$4.19 \pm 1.25_{stat}$	~4.5 10^{47} erg @ d=3.5 kpc

- In a leptonic scenario, HESS J1702-420A and B could be different emission zones of a single **PWN**
- However, the only known nearby pulsar (**PSR J1702-4128**, $\dot{E}=3.4 \times 10^{35}$ erg s^{-1}) would need a 19% conversion efficiency (extremely high!) to power the whole TeV emission
- It remains possible that the PSR J1702-4128 powers at least part of HESS J1702-420B
- Indeed, **significant VHE γ-ray emission is detected by H.E.S.S. near the pulsar position**



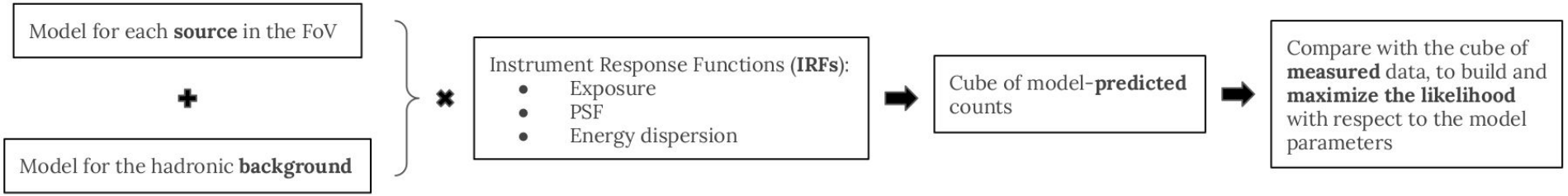
Conclusions

- We reported on new H.E.S.S. observations of the PeVatron candidate HESS J1702-420, an **unidentified** TeV source with **no multi-wavelength counterpart**
- The new observations and analysis allowed the discovery of a **new source component** called HESS J1702-420A, previously hidden under the bulk emission traditionally associated with HESS J1702-420
- This new object has a power-law spectral slope of **Γ~1.53** and a spectrum that extends with no sign of curvature up to **100 TeV**, where the source is detected at 4.0σ confidence level
- in a hadronic emission scenario, the proton spectral cut-off of HESS J1702-420A is at **E_p > 0.5 PeV**, which implies that **the source harbors PeV protons**
- Nevertheless, a leptonic emission scenario for HESS J1702-420A could not be definitively ruled out
- XMM observations of HESS J1702-420A have been granted, to clarify its relationship with *Suzaku* src B
- Future deep observations with CTA, SWGO and KM3NeT will help constraining the spectrum near the cut-off region, probing the hadronic origin of the emission and determining whether either of the two detected components operates as a real cosmic ray PeVatron.

Backup

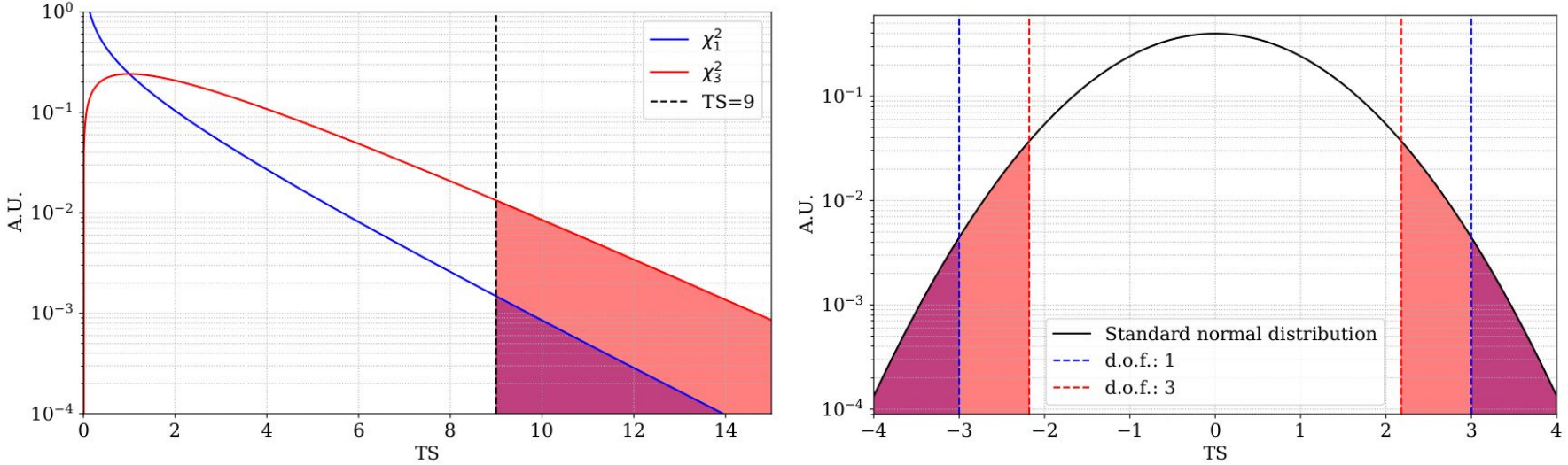
3D analysis with gammapy

- 3D → 2D (morphology) x 1D (spectrum)
- We performed a binned maximum likelihood analysis, similar to gtlike
- Gammapy allows to adjust a 3D source model to a data cube, in such a way that the cube of model-predicted counts mimics as closely as possible the measured data cube



3D analysis with gammapy

P-value of a χ^2 distribution with 1 or 3 d.o.f. → P-value of a standard normal Gaussian



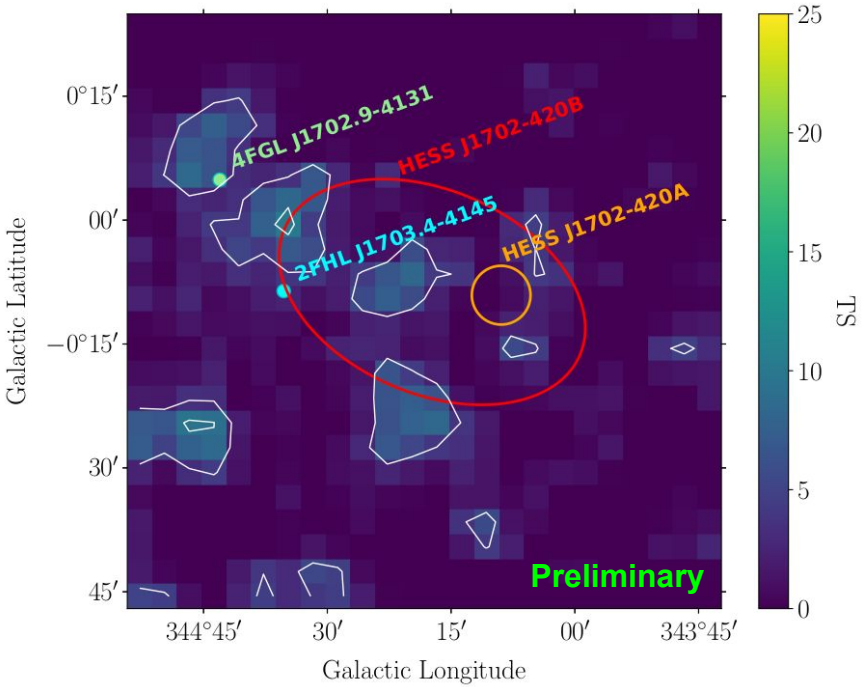
TS = 9 implies:

- significance=3σ for 1 d.o.f.
- significance=2.1σ for 3 d.o.f.

HE γ-ray upper limit with Fermi-LAT

- We analyzed ~12 yr of events with energies **> 10 GeV**, using Pass 8 data products and **fermipy**
- After modeling all sources (+ diffuse emission) in the region, we added an extended gaussian template identical to HESS J1702-420B
- This way, we estimated the significance for a possible excess associated with the TeV source
- In the absence of a clear detection (~4.3σ), we estimated the 99% c. l. **upper limit for the HE emission**:

$$\left(E^2 \frac{dN}{dE}\right)_{E=95\ \mathrm{GeV}} \leq 7.6 \times 10^{-9}\ \mathrm{GeV cm^{-2}\ s^{-1}}$$



HE γ-ray upper limit with Fermi-LAT

The data (photon event file and spacecraft file) were retrieved from the LAT data server through a query defined by the parameters in Table E.1. We adopted the event selection cuts described in Table E.2. For the analysis, we defined a square $10^{\circ} \times 10^{\circ}$ ROI, fully inscribed within the events selection circle. Events were binned spatially using $0.05^{\circ} \times 0.05^{\circ}$ spatial pixels, and spectrally using 8 bins per energy decade.

During the maximum likelihood fit, the spectral index and normalization of all sources within 3° from the ROI center and having a TS value higher than 25 were left free to vary. Additionally, the spectral normalization of all sources with TS > 30 within the whole $10^{\circ} \times 10^{\circ}$ was also adjusted. The Galactic diffuse emission model (`gll_iem_v07.fits`) was left free to vary, while the extra-Galactic diffuse model was considered fixed to the default one (`iso_P8R3_SOURCE_V2_v1.txt`).

Direction (Gal)	Radius	Time range (Gregorian)	Energy (GeV)
$(344.3^{\circ}, -0.2^{\circ})$	21.21°	2008-08-04 — 2020-06-26	1 — 1000

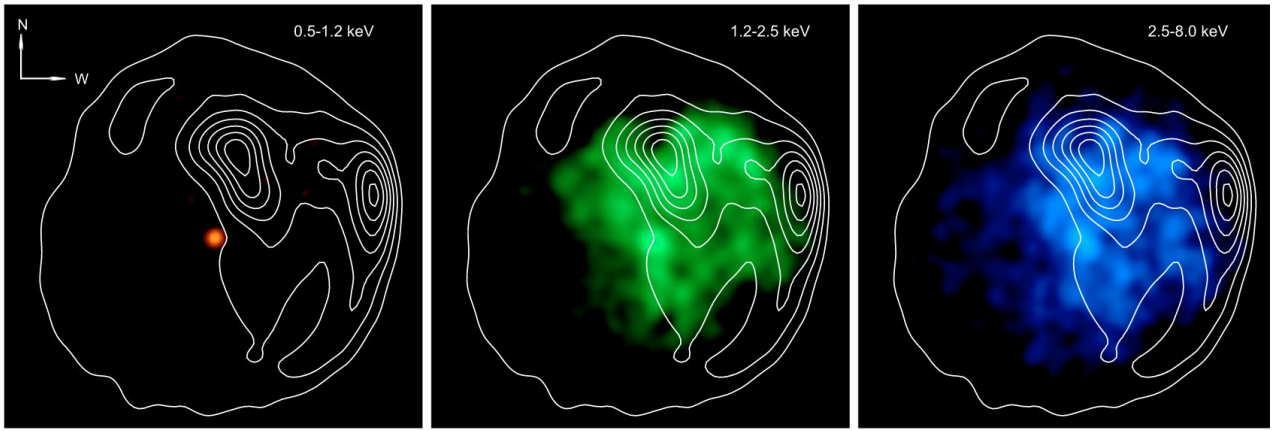
Table E.1: Query details for the *Fermi*-LAT data.

zmax	evclass	evtype	Selection filter
90	120	3	`(DATA_QUAL>0)&&(LAT_CONFIG==1)`

Table E.2: Events selection cuts for the *Fermi*-LAT analysis.

SNR G344.7-0.1

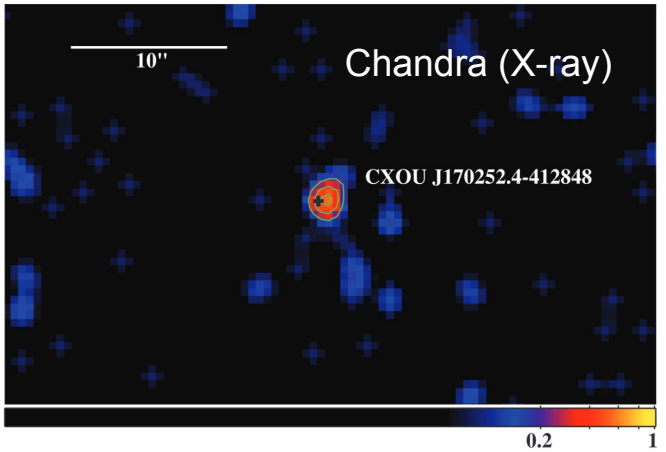
- Age: ~3 kyr
- Angular size: ~8 arcmin
- Distance from Earth: Unknown. X-ray absorbing column density ⇒ d > 8 kpc
- SN type: Debated (might be Ia or CC. No compact object supporting the CC hypothesis)
- References: Dubner et al. 1993; Whiteoak & Green 1996; Combi et al. 2010; Giacani et al. 2011; Yamaguchi et al. 2012; Eagle et al. 2020



Colors: **Chandra** (X-ray)
Contours: **MOST** (radio)

PSR J1702-4128

- Age: ~55 kyr
- Spin-down luminosity: $\dot{E} = 3.4 \times 10^{35}$ erg s^{-1}
- Distance from Earth: 5.2 kpc
- Physical separation from the peak of HESS J1702-420 (assuming the same distance): ~50 pc
- X-ray emission: inconspicuous (a faint, compact PWN was found by Chandra)
- References: Kramer et al. 2003; Chang et al. 2008

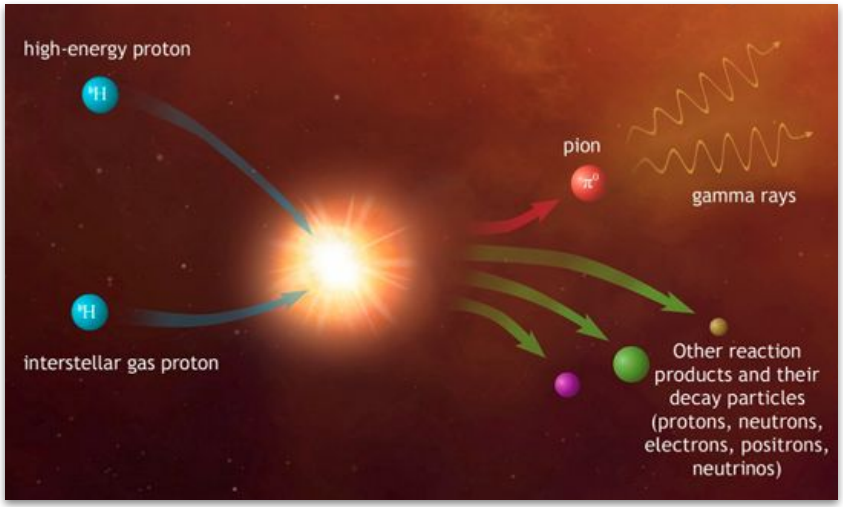


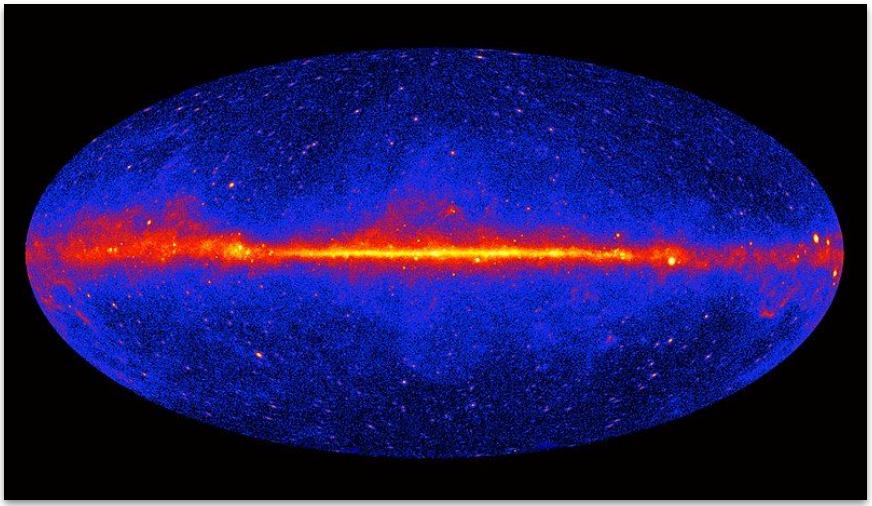
Analysis configuration: high-energy optimization

- Goal: Increase the collection area whilst keeping a correct PSF
- Solution: remove the Local Distance (=) cut strongly improves the reconstruction efficiency of high-energy gamma-rays
- Performances @ high energy (wrt standard config):
  - **Collection Area : ×≈2**
  - **Sensitivity : +(50-100) %**
  - **PSF(68%) : +25 %**
- Contact: *khelifi@in2p3.fr*

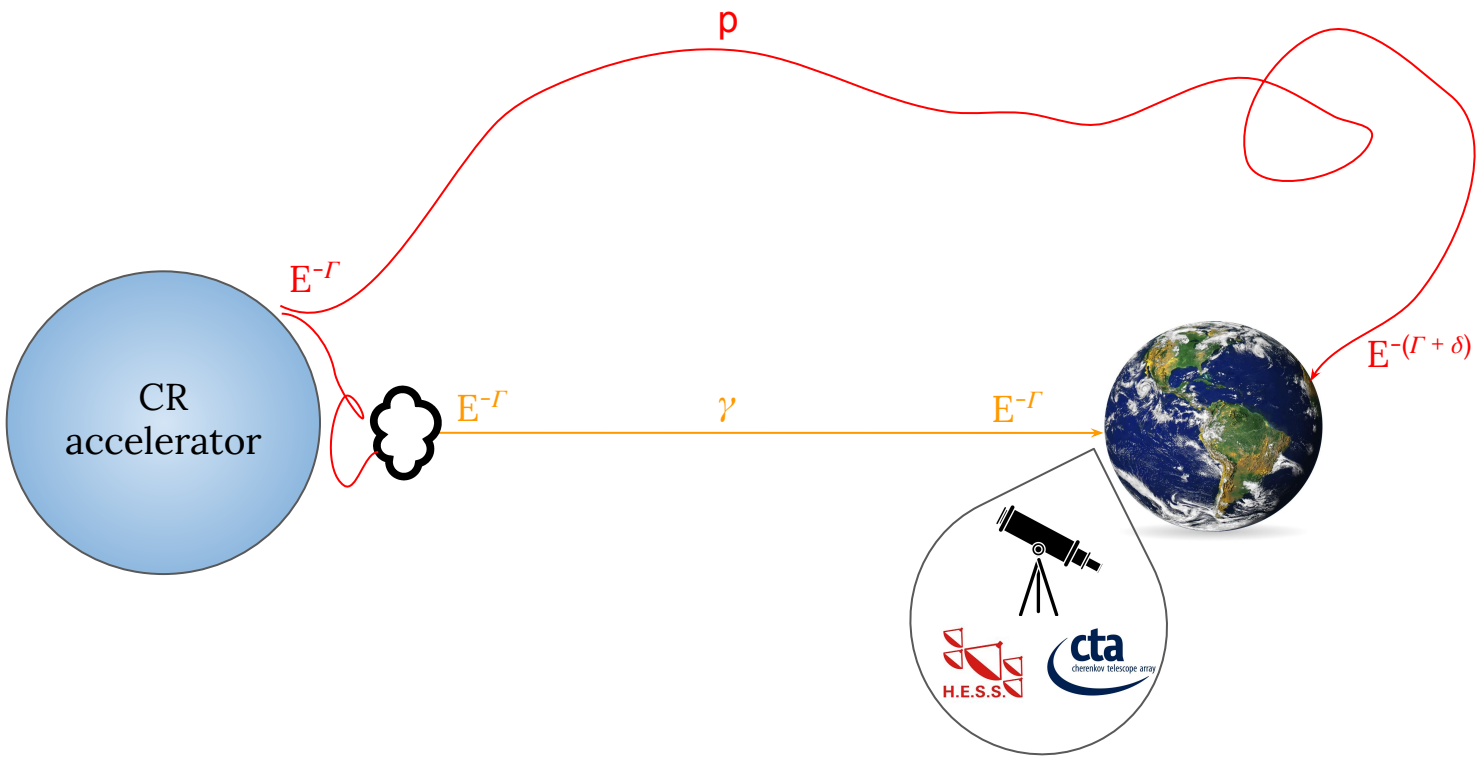
Gamma-rays from hadronic processes

$$p_{\mathrm{CR}}\, p_{\mathrm{target}} \longrightarrow \pi^0 + \ldots \longrightarrow \gamma\gamma$$

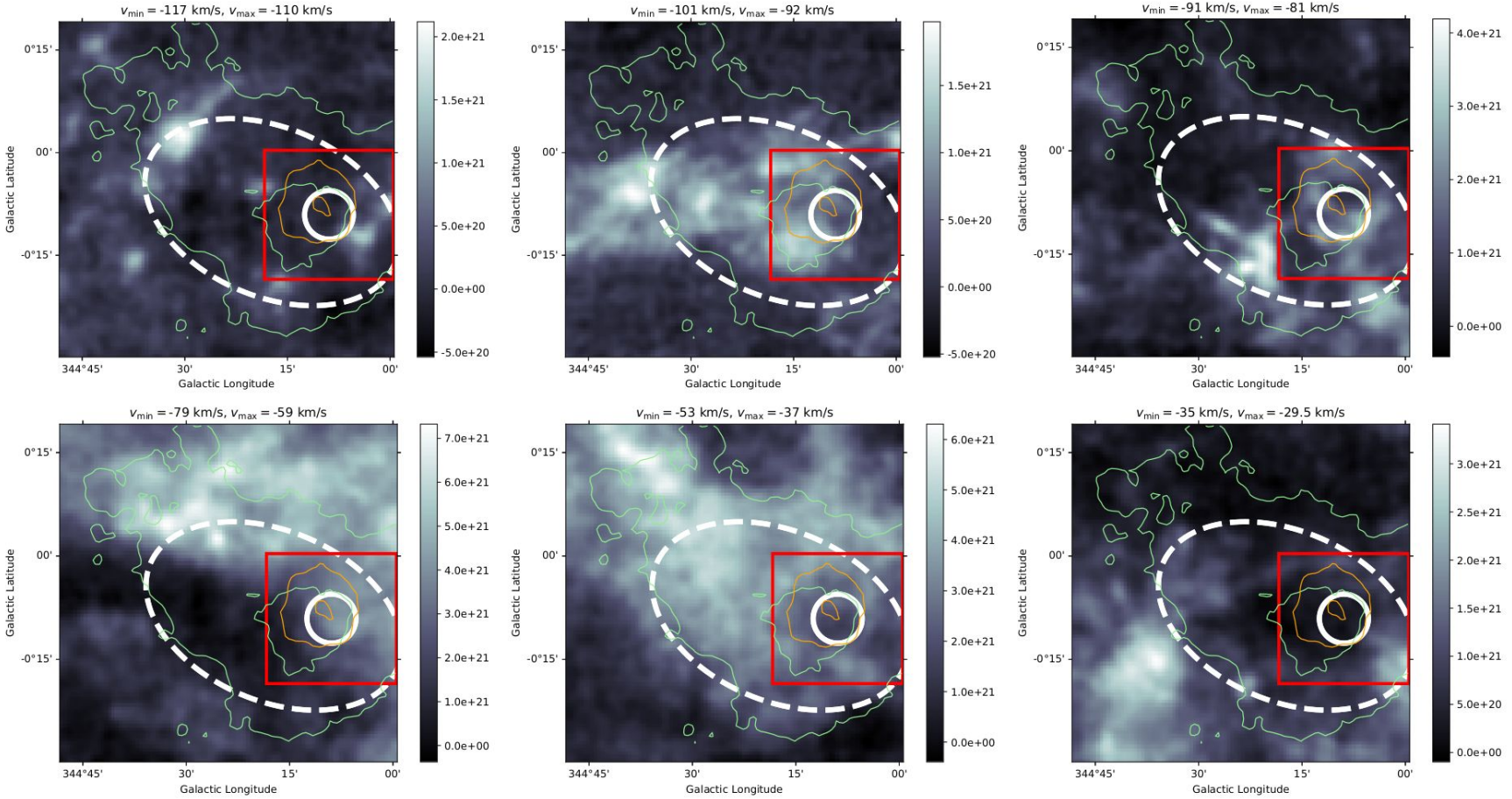




Gamma-rays from hadronic processes



Molecular hydrogen (H_2): Mopra data



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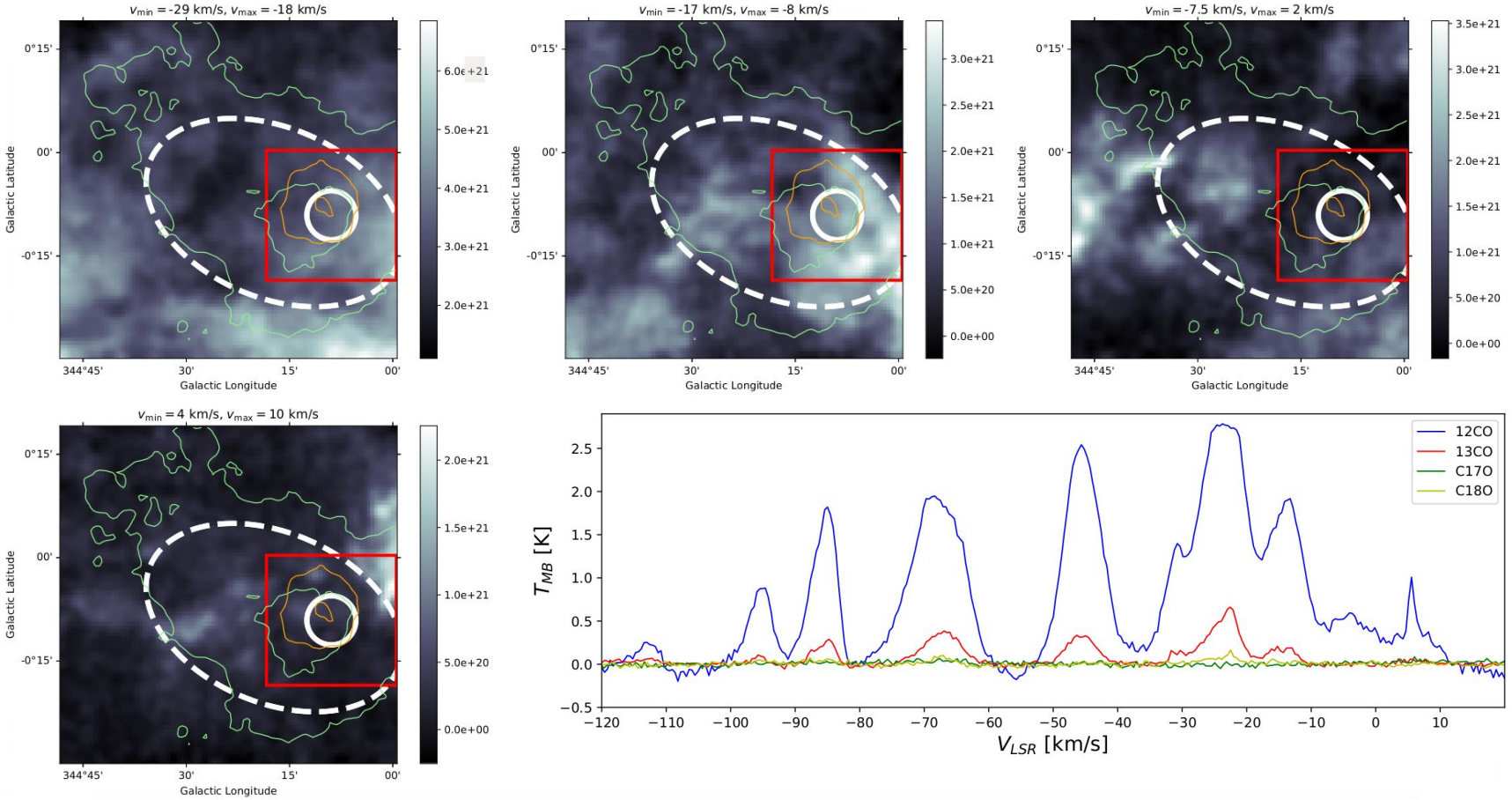

X-ray observations of HESS J1702-420 with *Suzaku*

- Estimated flux of src B (2-10 keV): $(1.9\pm0.7)\times10^{-14}$ erg s $^{-1}$ cm $^{-2}$ (**very low!**)

- Possible sources of **systematics**:
  - Leakage of src B outside the FoV
  - Edge effects at the FoV borders
  - Spectral (index=2.1) and N_H assumptions

- Reference: [Fujinaga et al. 2011]