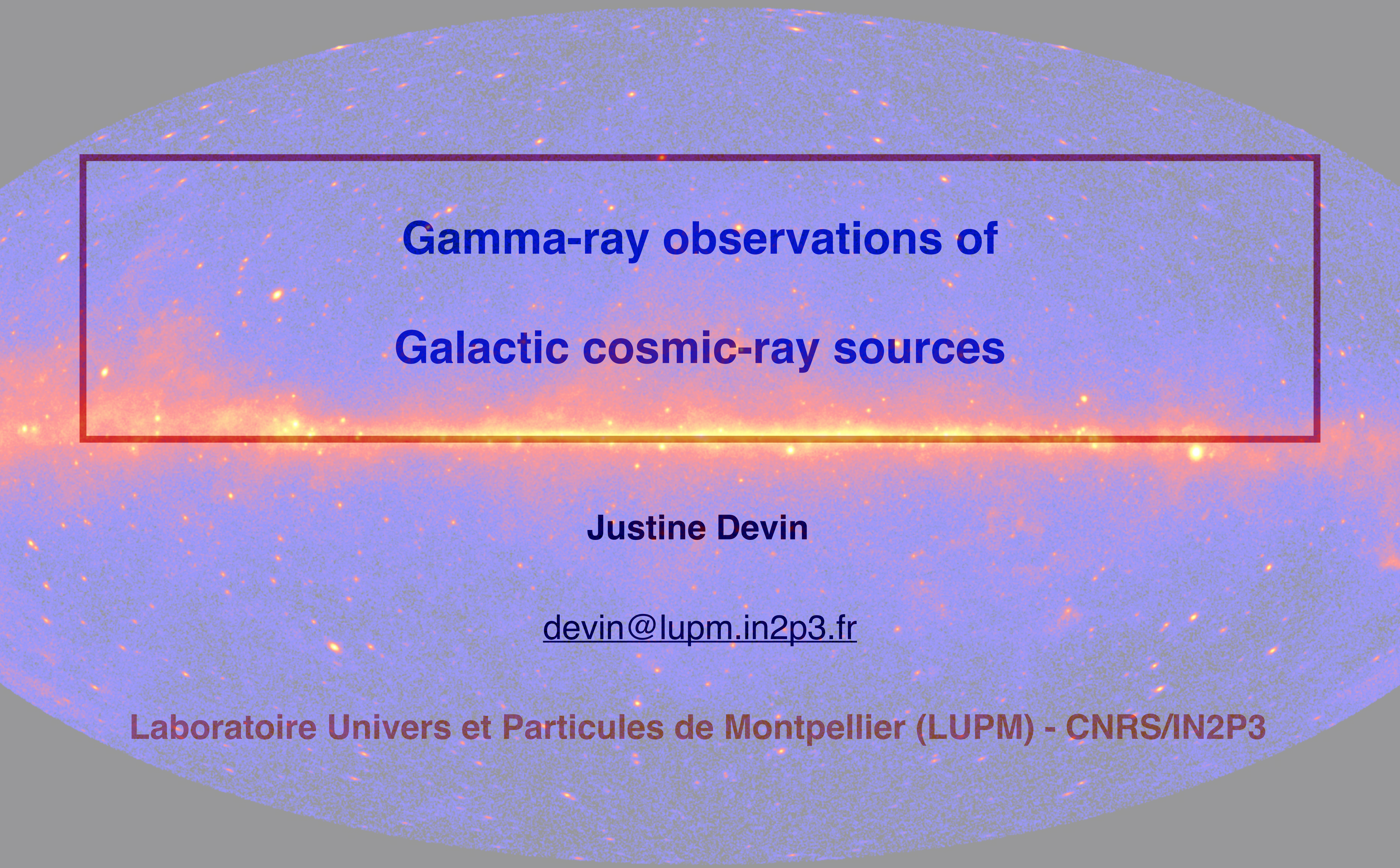

Gamma-ray observations of

Galactic cosmic-ray sources

Justine Devin

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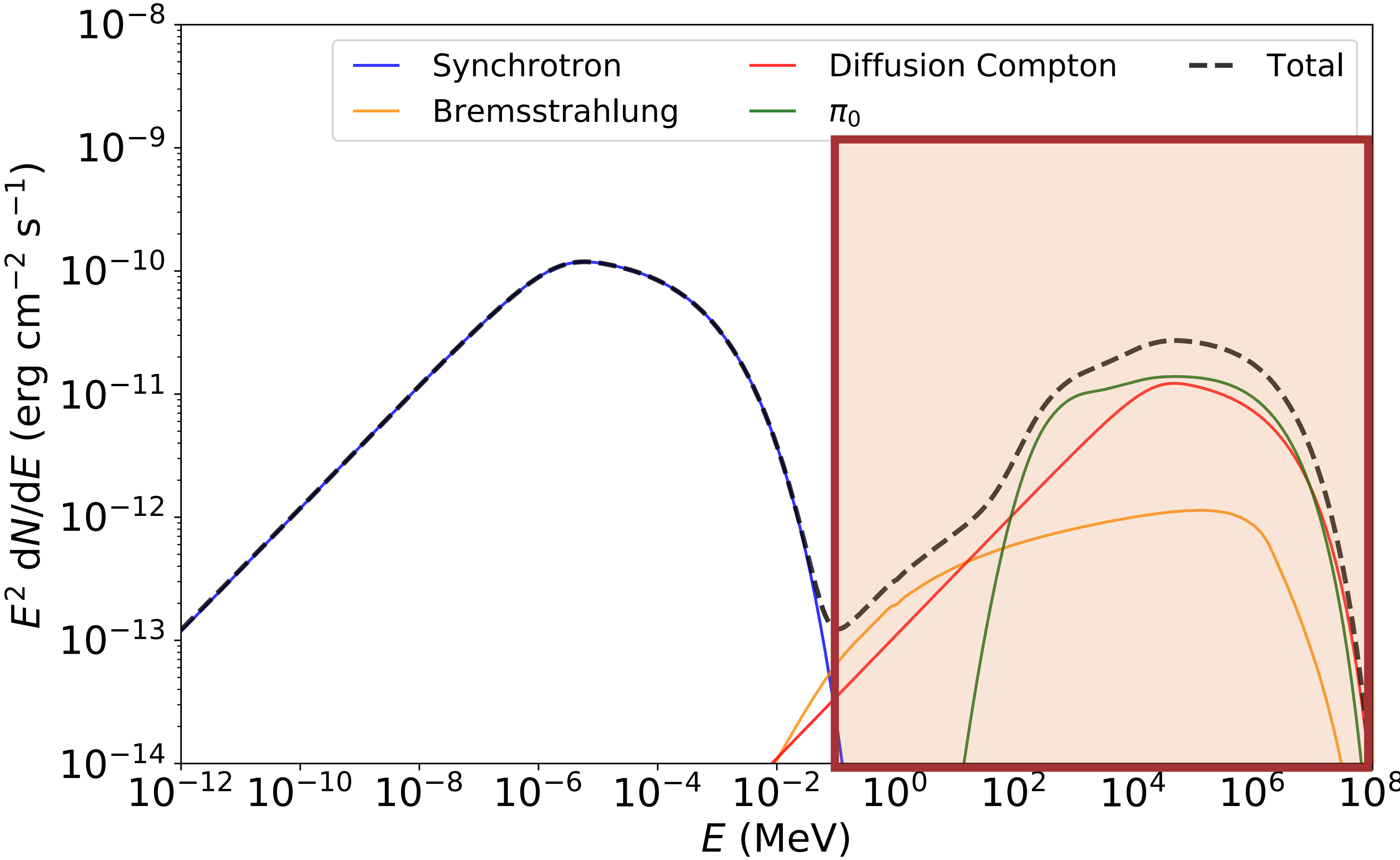
Laboratoire Univers et Particules de Montpellier (LUPM) - CNRS/IN2P3

— INTERCOS, March 2022 —

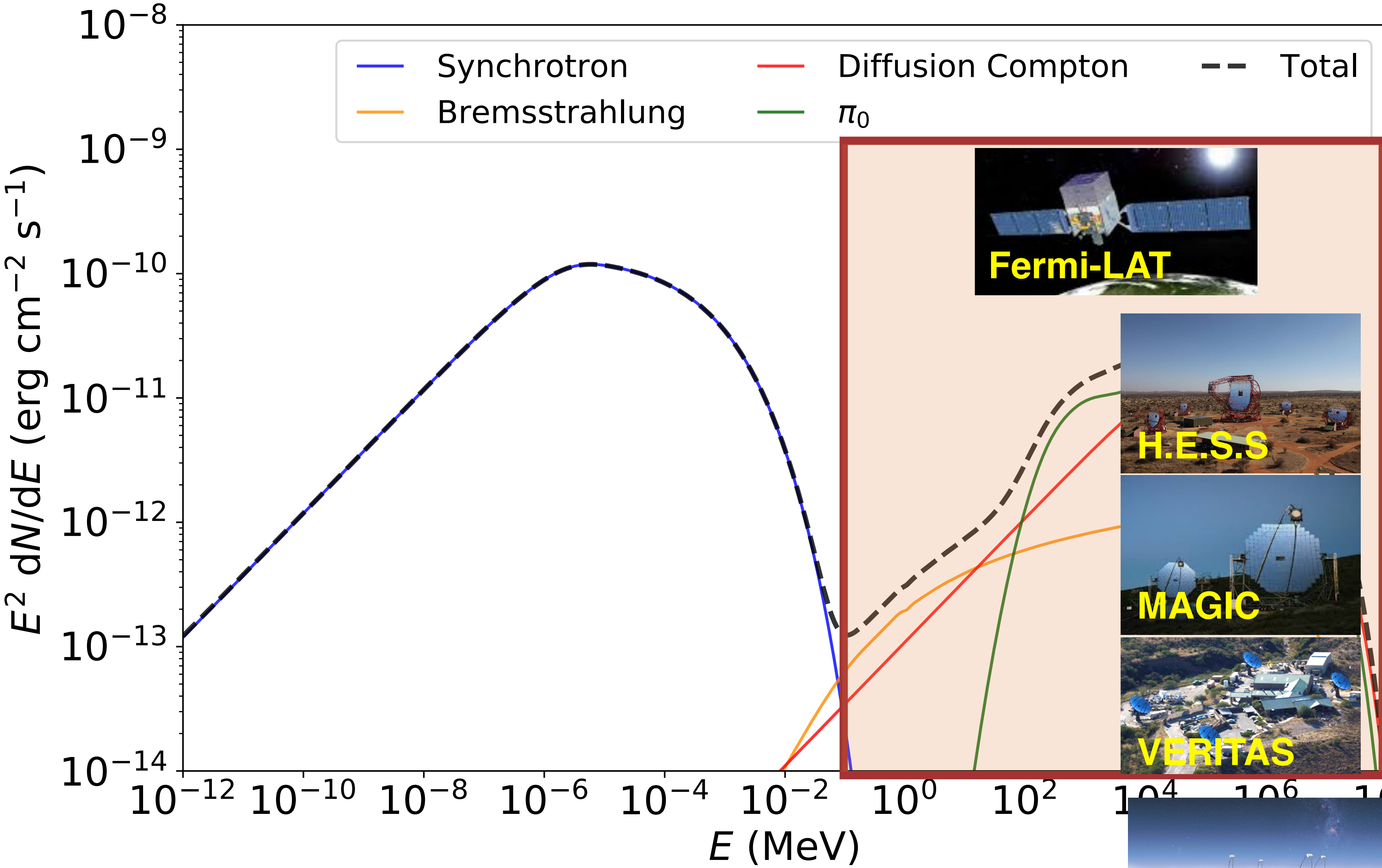
Gamma rays as a probe of cosmic-ray (CR) sources



- **High Energy (HE): Pion bump feature**
- **Very HE (VHE) / Ultra HE (UHE): E_{max}**

$$E_{\mathrm{max},\gamma} = f(E_{\mathrm{max,p}})$$

Gamma rays as a probe of cosmic-ray (CR) sources



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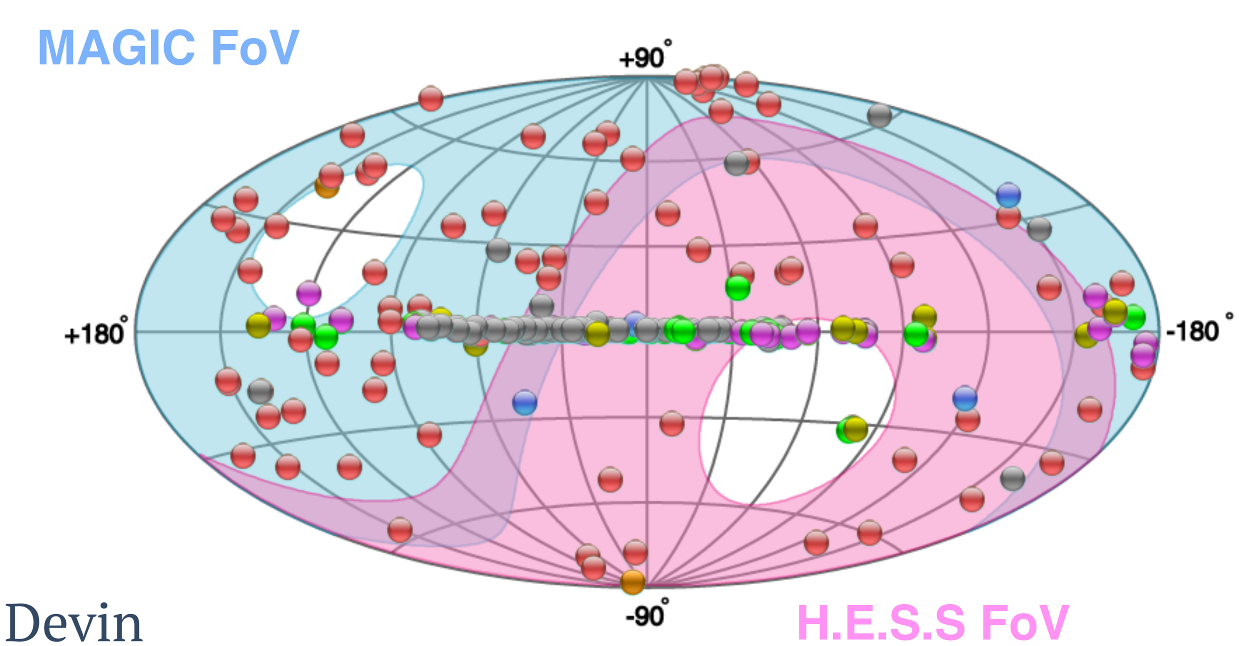
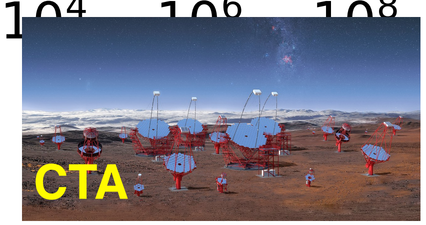




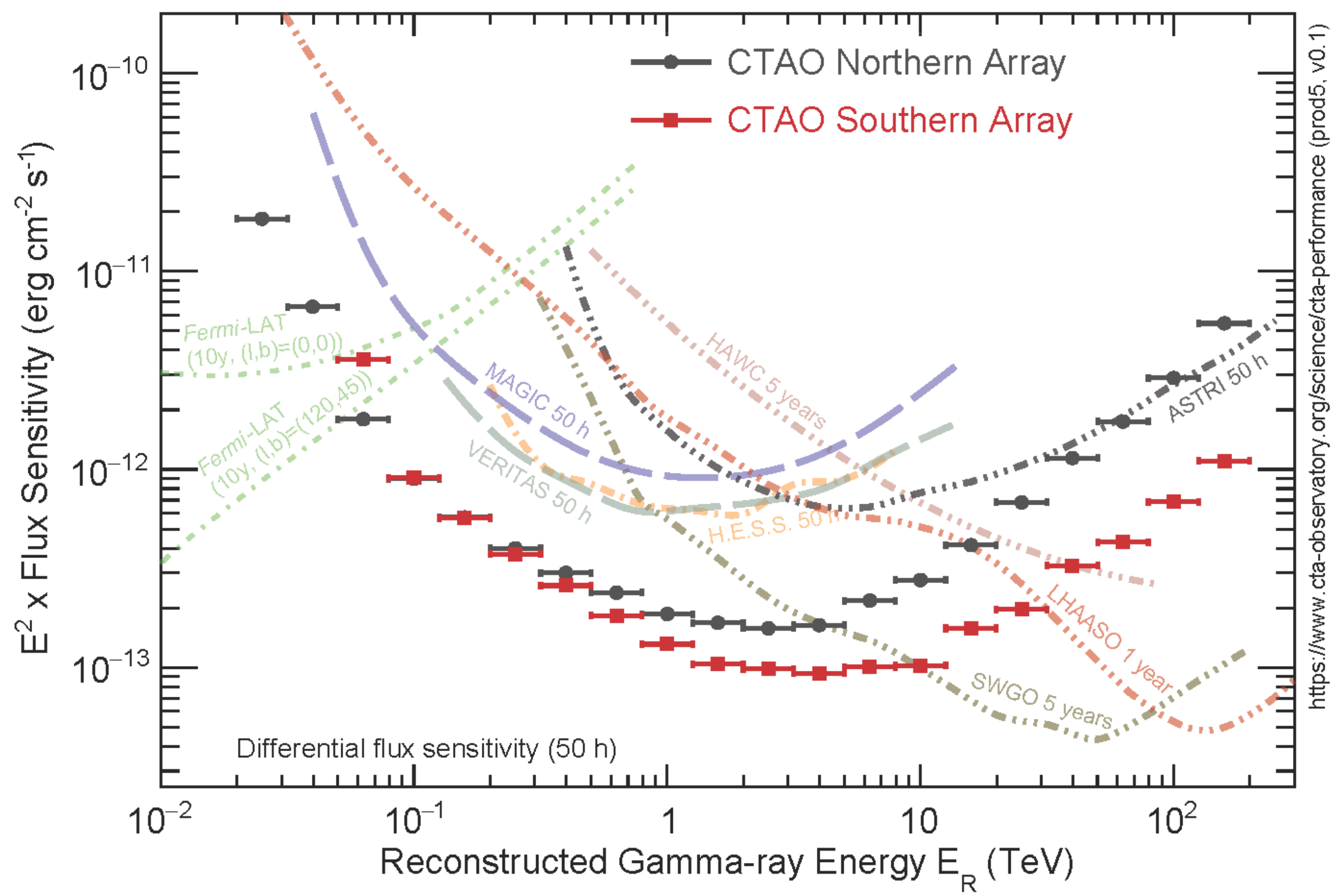
➡ under construction

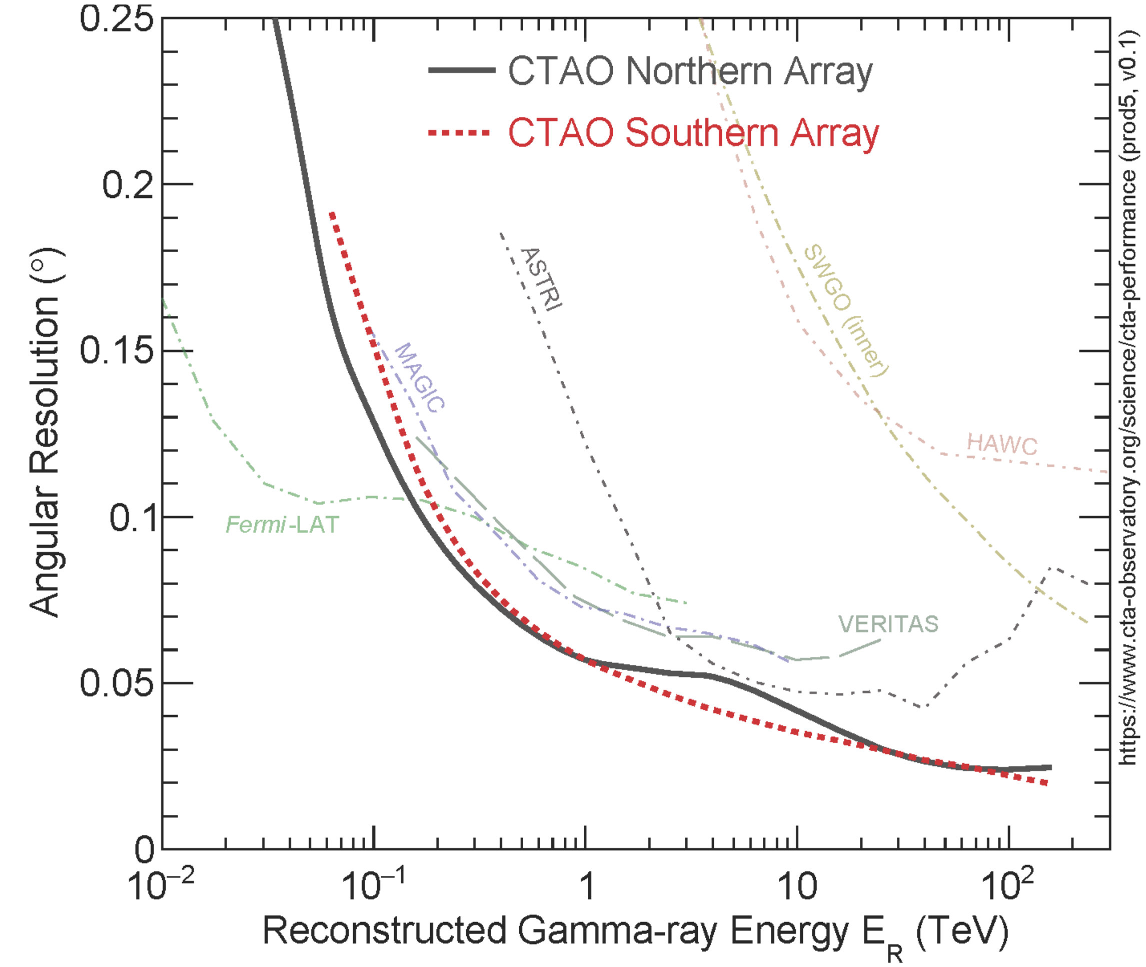
up to 100 TeV

above 100 TeV

➡ still under construction up to PeV energies

Performances of the instruments





- HAWC, LHAASO/KM2A, TibetASg: best sensitivity above ~ 30 TeV
  ➡ **suitable to detect the sources of UHE photons (above ~100 TeV)**

- Angular resolution:

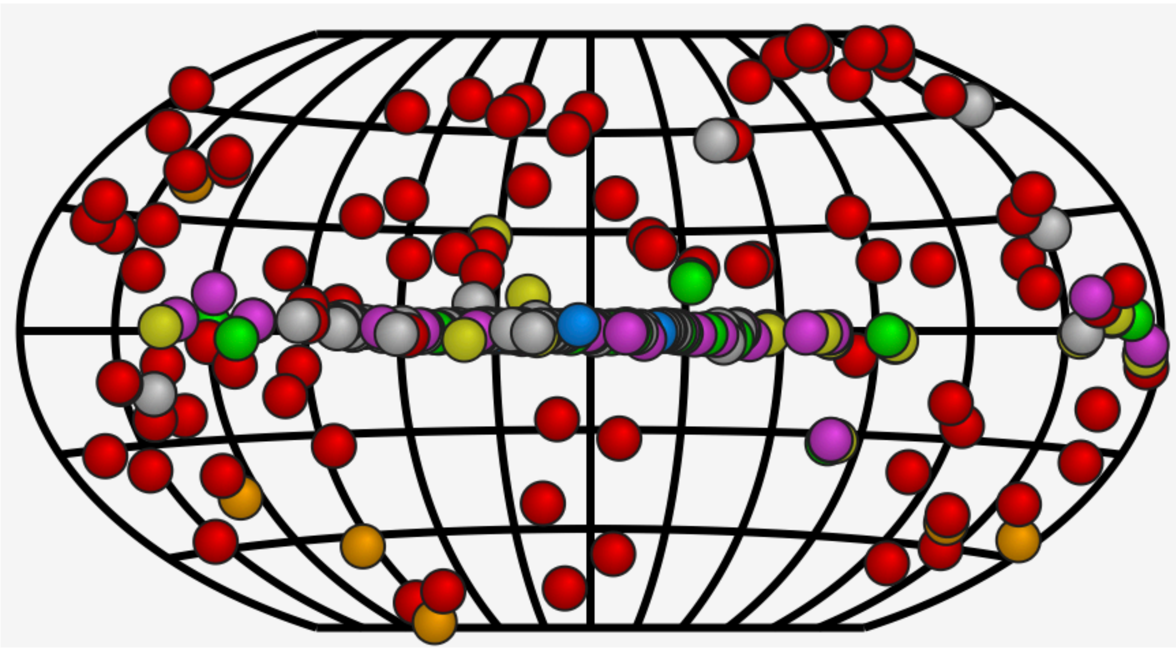
CTA ~ 0.04° (10 TeV)

HAWC ~ 0.15° (10 TeV), LHAASO/KM2A ~ 0.5–0.8° (20 TeV), TibetASg ~ 0.5° (10 TeV)

➡ **CTA will allow to better constrain the nature of these sources**

The VHE / UHE Galactic sky

TeV Catalog: http://tevcat2.uchicago.edu



250 sources listed in total

~ 150 Galactic sources

- 78 HESS Gal. Plane Survey sources
- 9 HAWC sources > 56 TeV
- 12 LHAASO sources > 100 TeV
- 12 Tibet ASg sources

Several types of Galactic gamma-ray sources:

➡ Supernova remnants (SNRs), pulsar wind nebulae (PWNe), pulsars, binaries, star forming regions (SFRs), superbubbles

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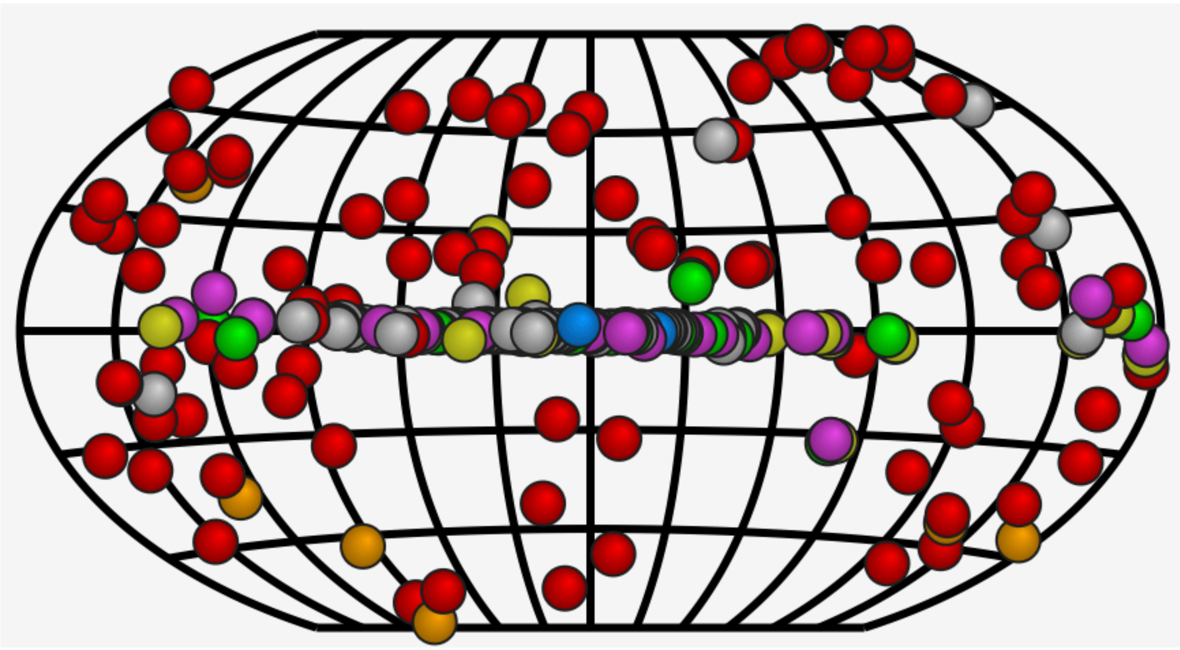

250 sources listed in total

~ 150 Galactic sources

- 78 HESS Gal. Plane Survey sources **[47]**
- 9 HAWC sources > 56 TeV **[8]**
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- 12 Tibet ASg sources **[11]**

Several types of Galactic gamma-ray sources:

➡ Supernova remnants (SNRs), pulsar wind nebulae (PWNe), pulsars, binaries, star forming regions (SFRs), superbubbles

➡ **+ Unidentified sources**

Which are the main Galactic cosmic-ray sources?

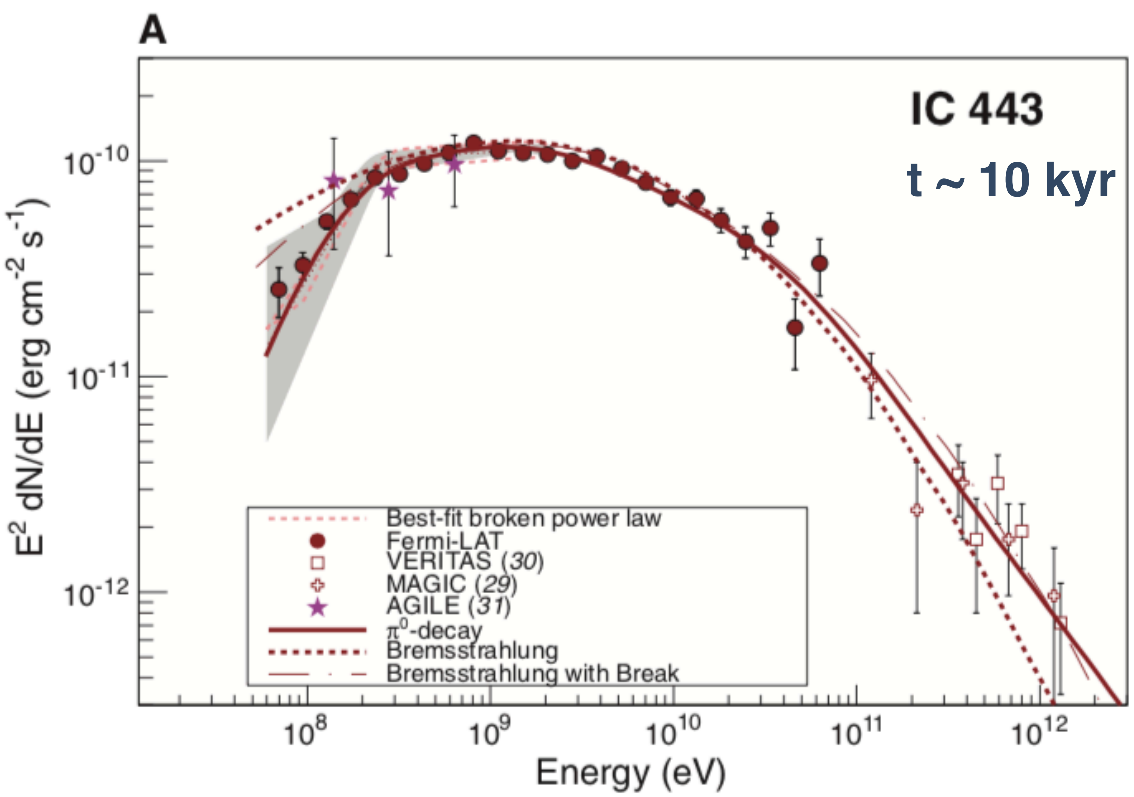
➡ Search for a low-energy break and Emax,p > PeV

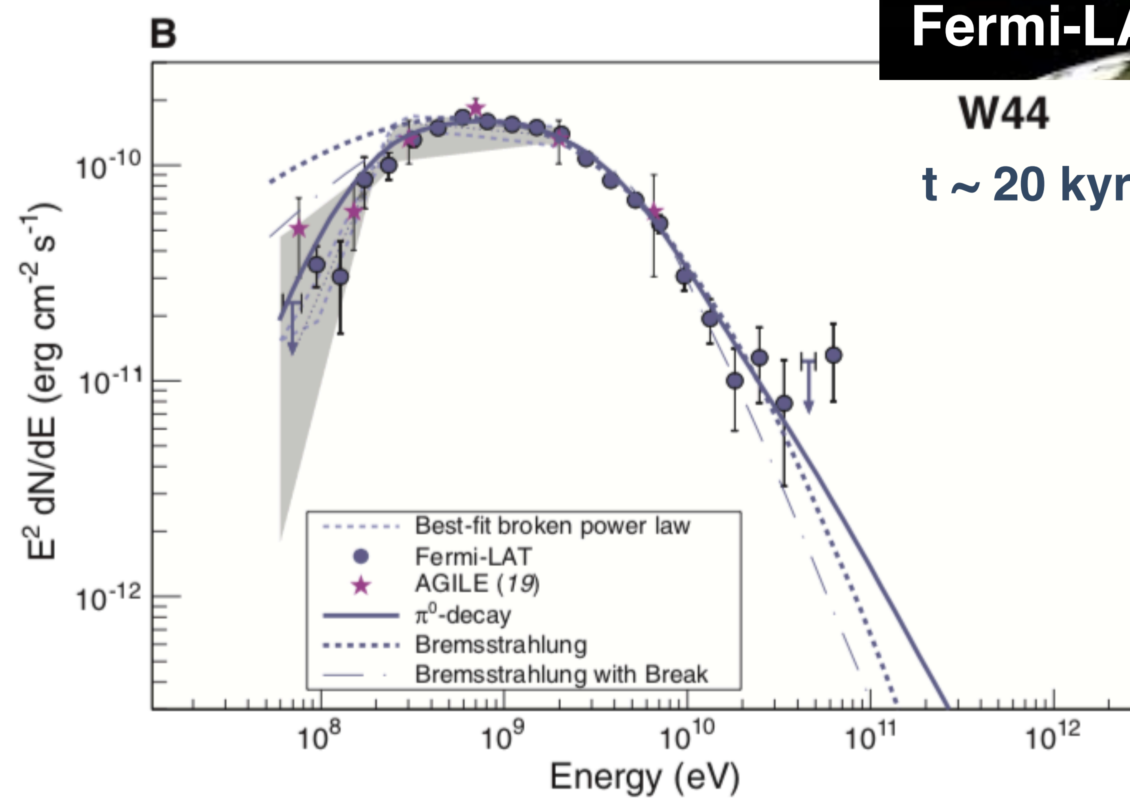
The SNR paradigm as Galactic cosmic-ray sources

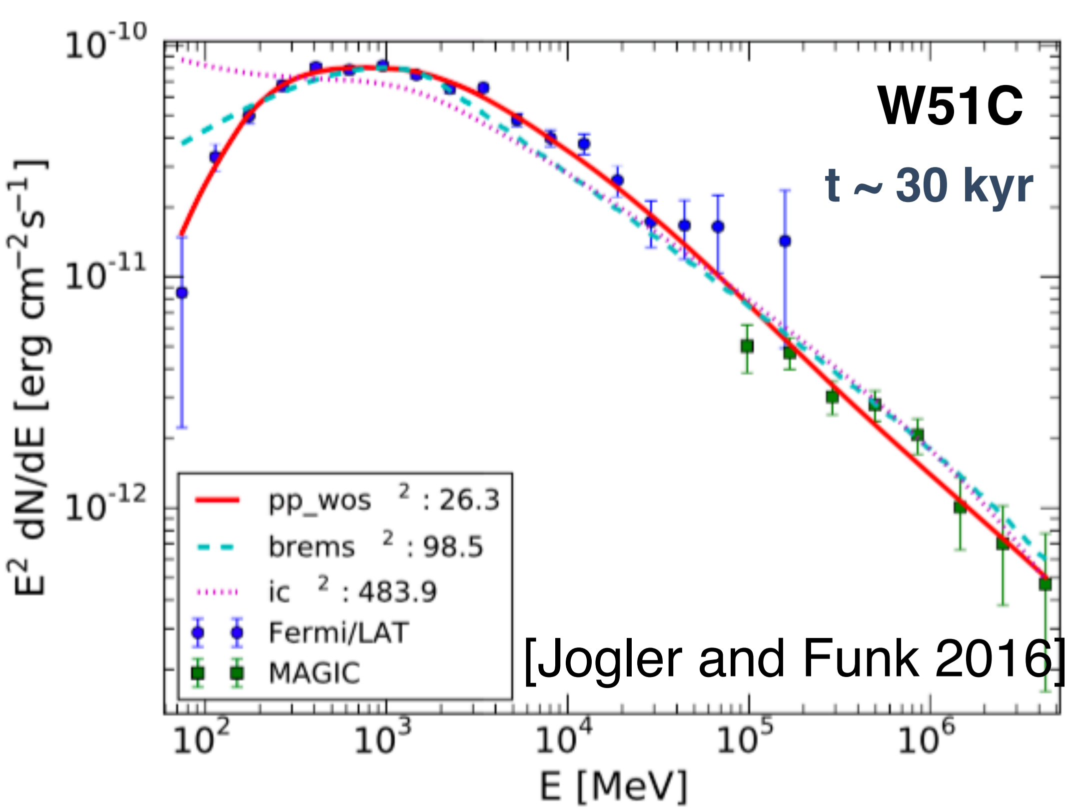
Proton acceleration in SNRs

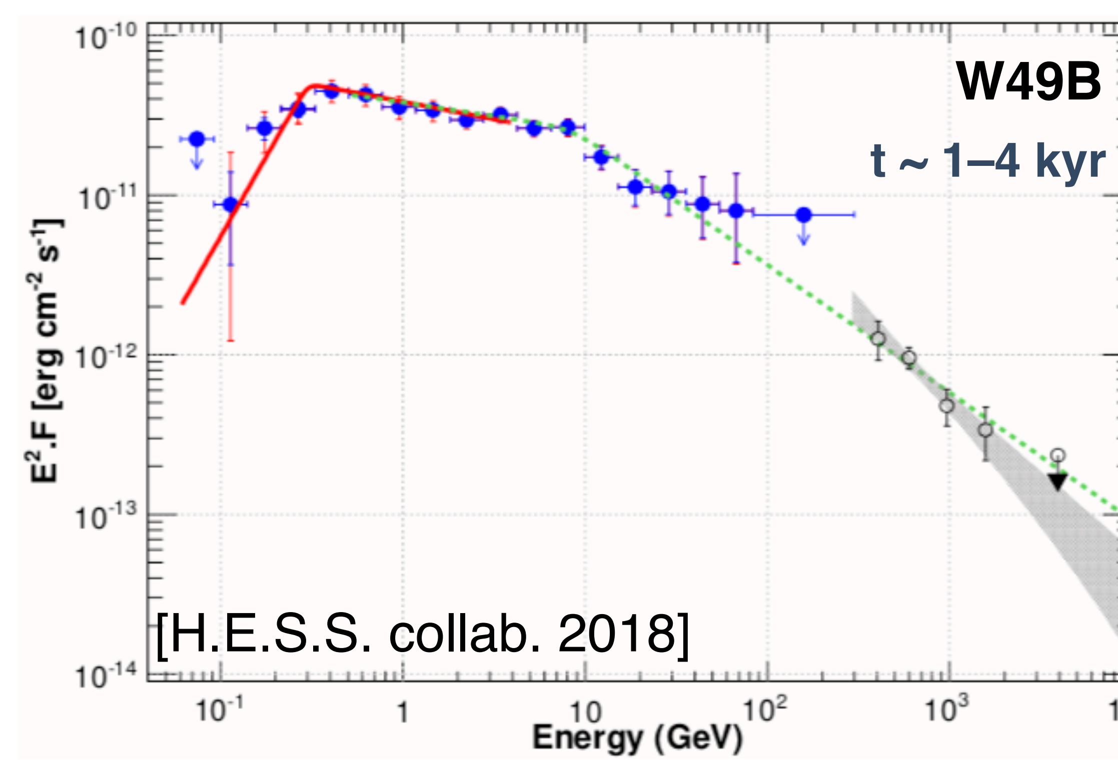
First evidences:

[Ackermann et al. 2013]





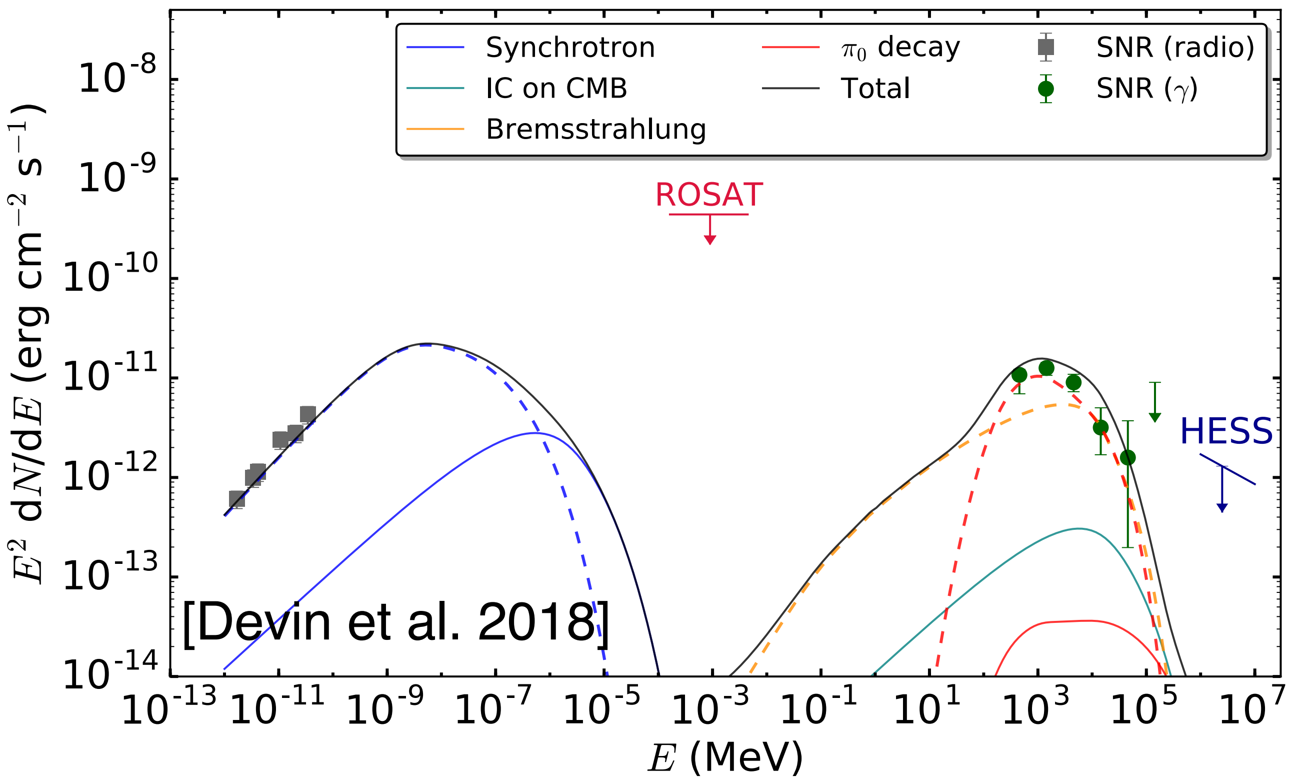




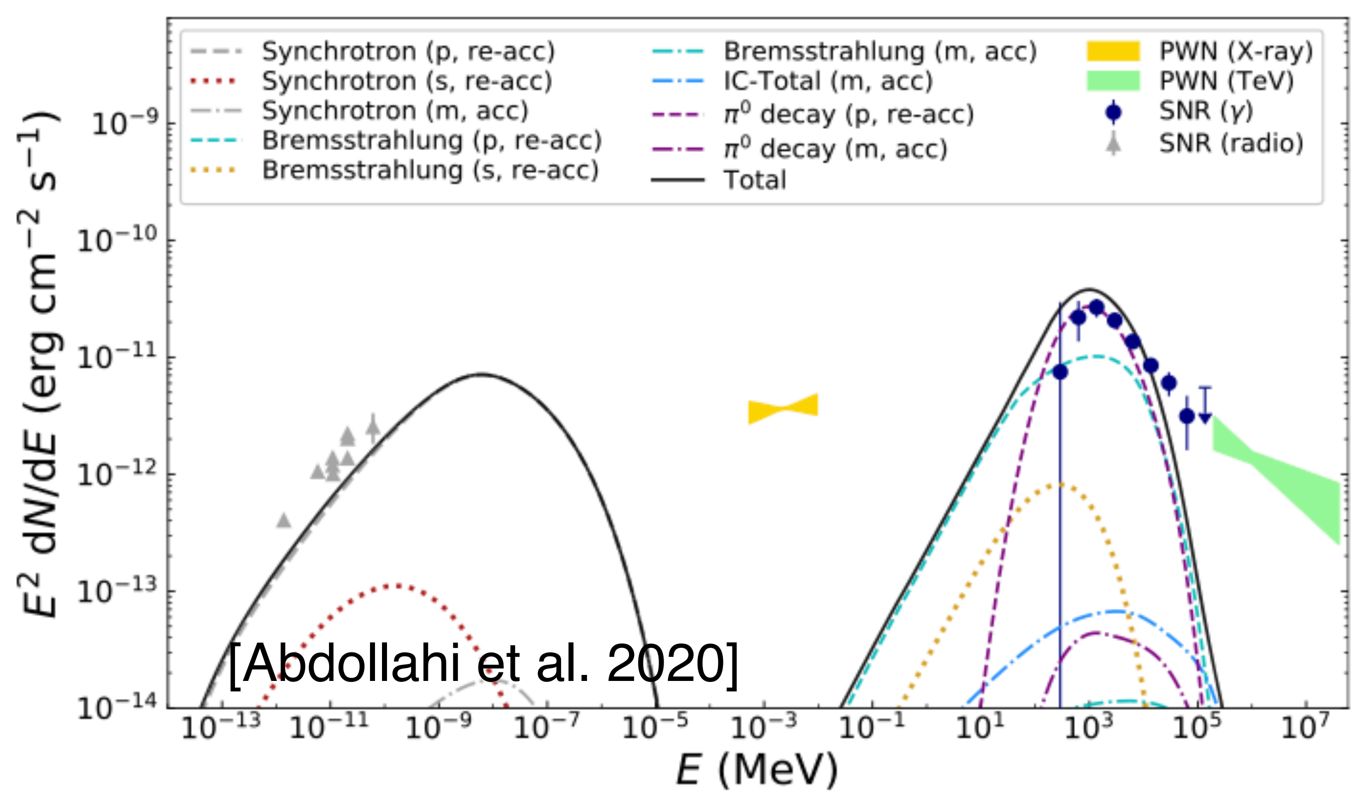
Proton acceleration in SNRs

Hadronic model also preferred for other SNRs:

G326.3–1.8



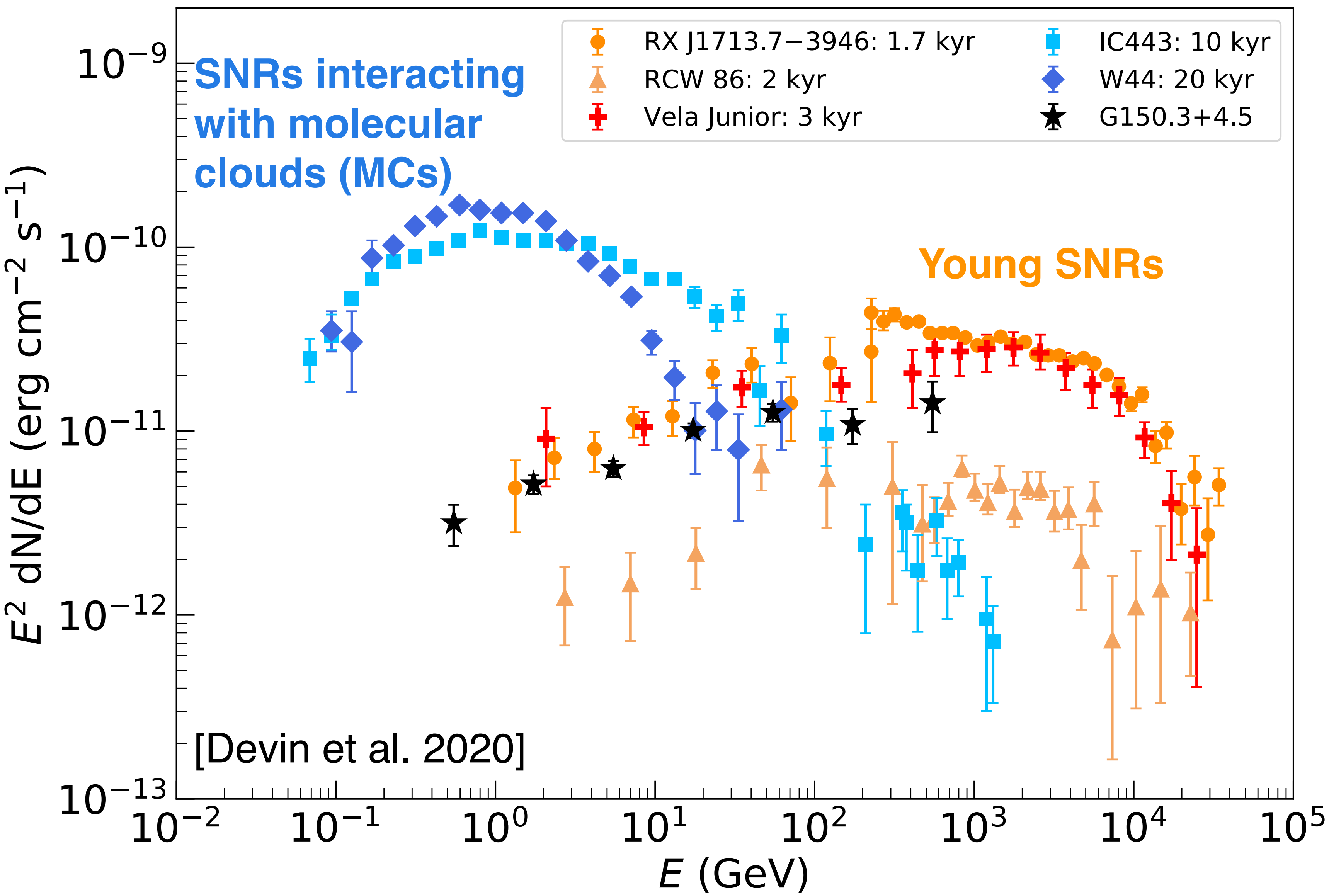
CTB 37A

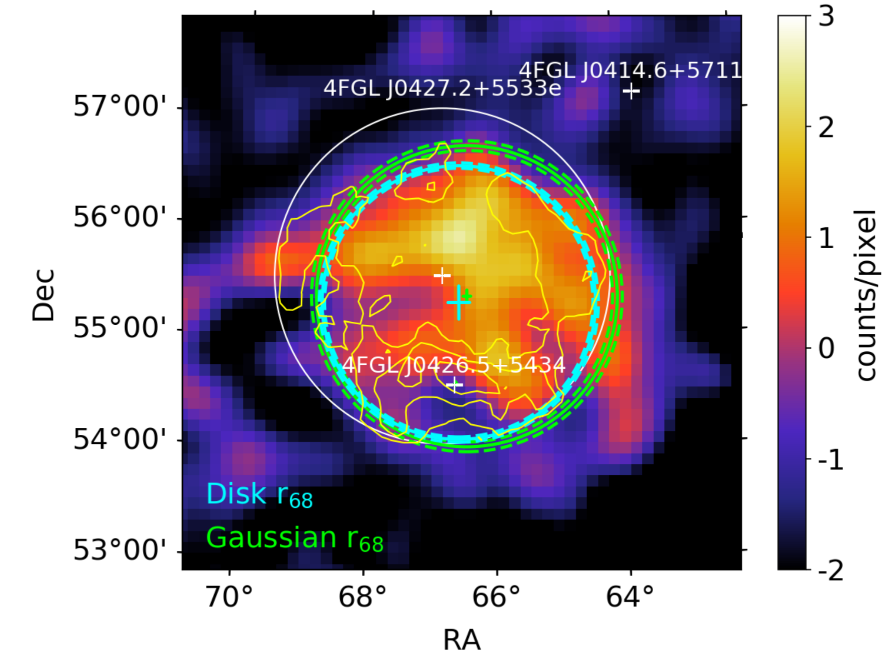


+ Cygnus Loop [Tutone et al. 2021], W28 [Abdo et al. 2010], …

SNRs in which proton acceleration was confirmed are relatively old (t > 5–10 kyr) with $E_{max,p}$ < hundred (or few hundreds) of GeV

VHE emission from dynamically young SNRs



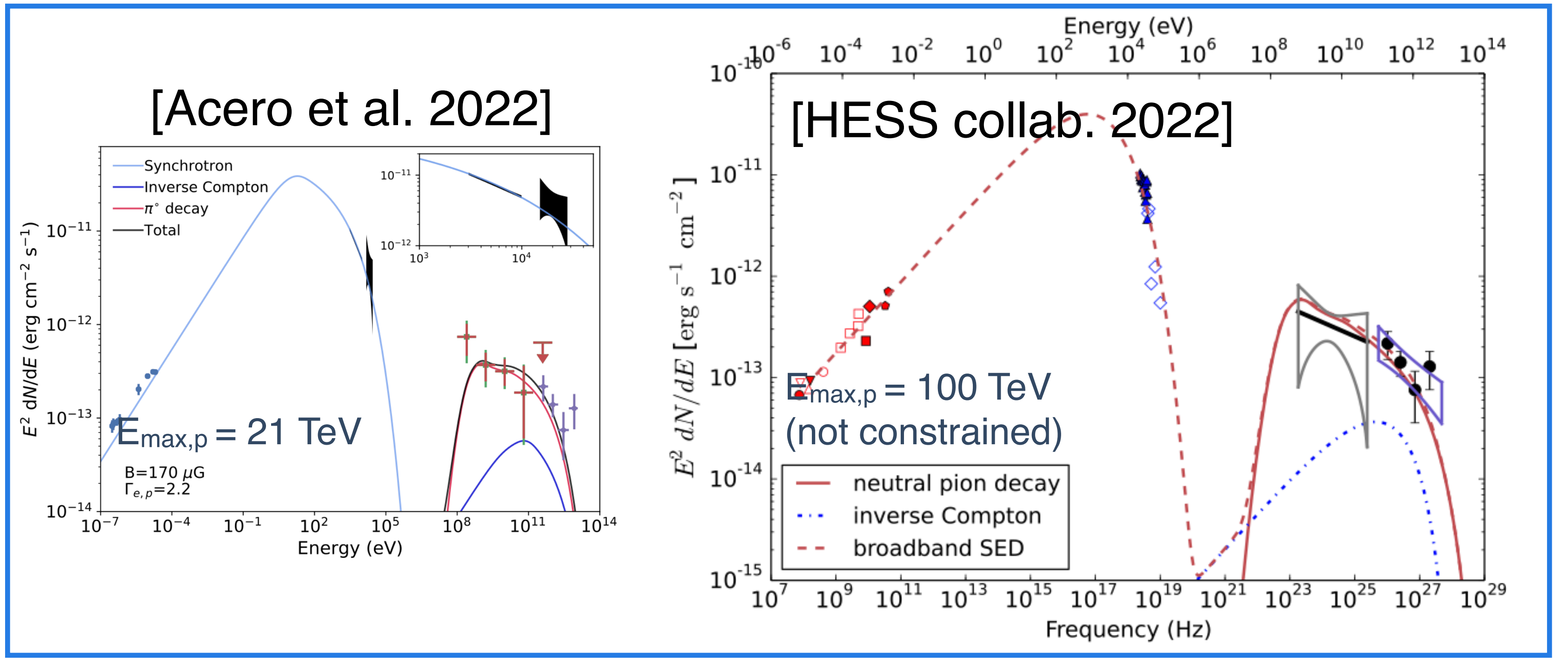


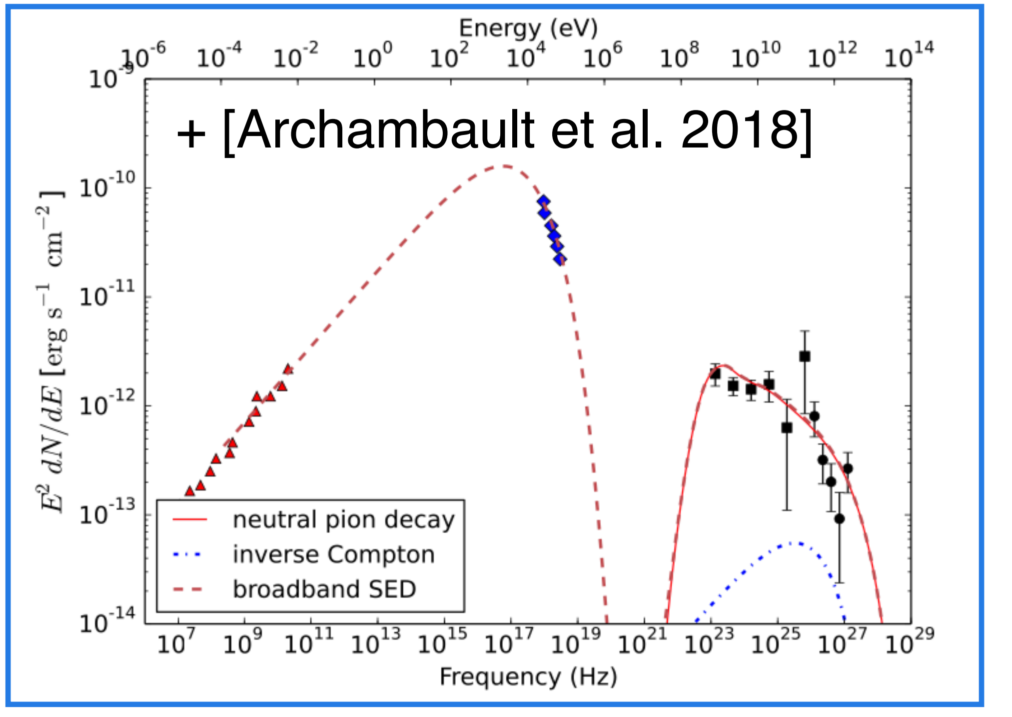
+ [Ackermann et al. 2013, HESS collab. 2018a, 2018b, Ajello et al. 2016]

Brightest SNRs at TeV energies also have a spectral a cutoff ($E_{max,e,p}$ < 100 TeV)

VHE emission from historical SNRs

- **Kepler (~ 400 yrs) and Tycho (450 yrs)**





➡ Emission likely hadronic (power law also works)

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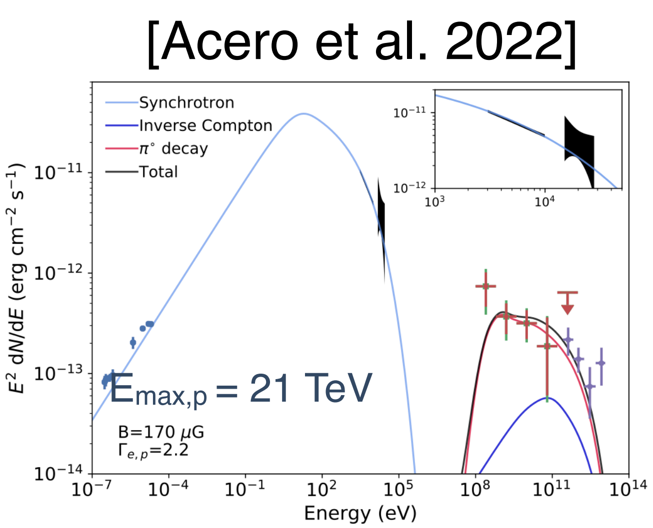
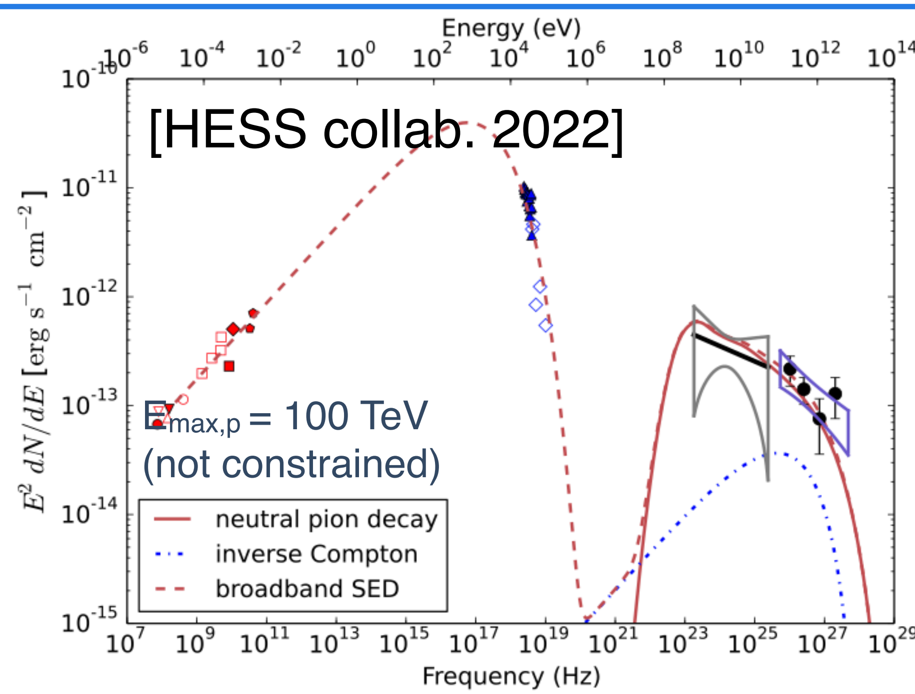
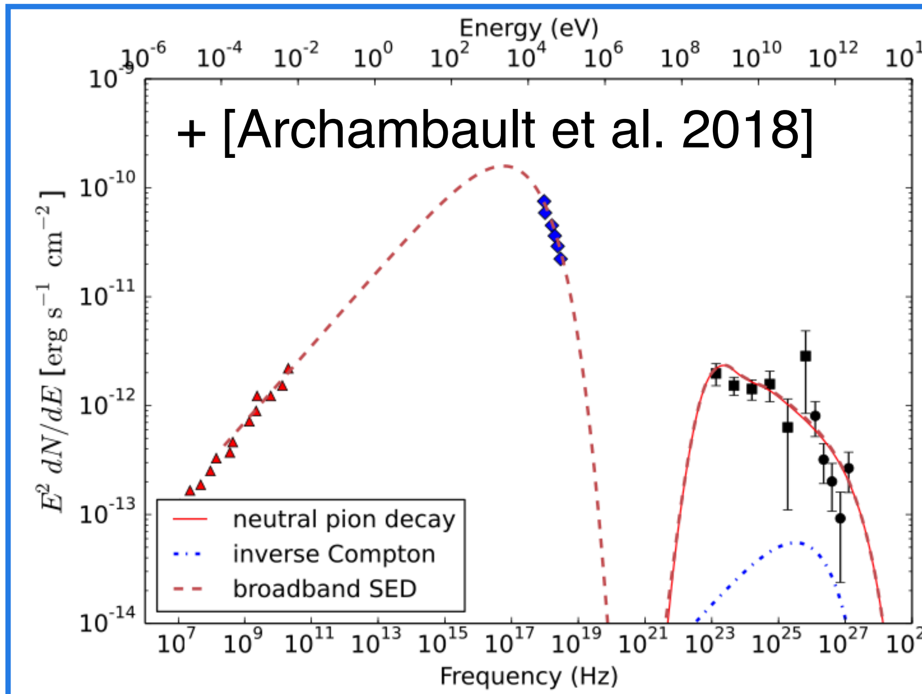


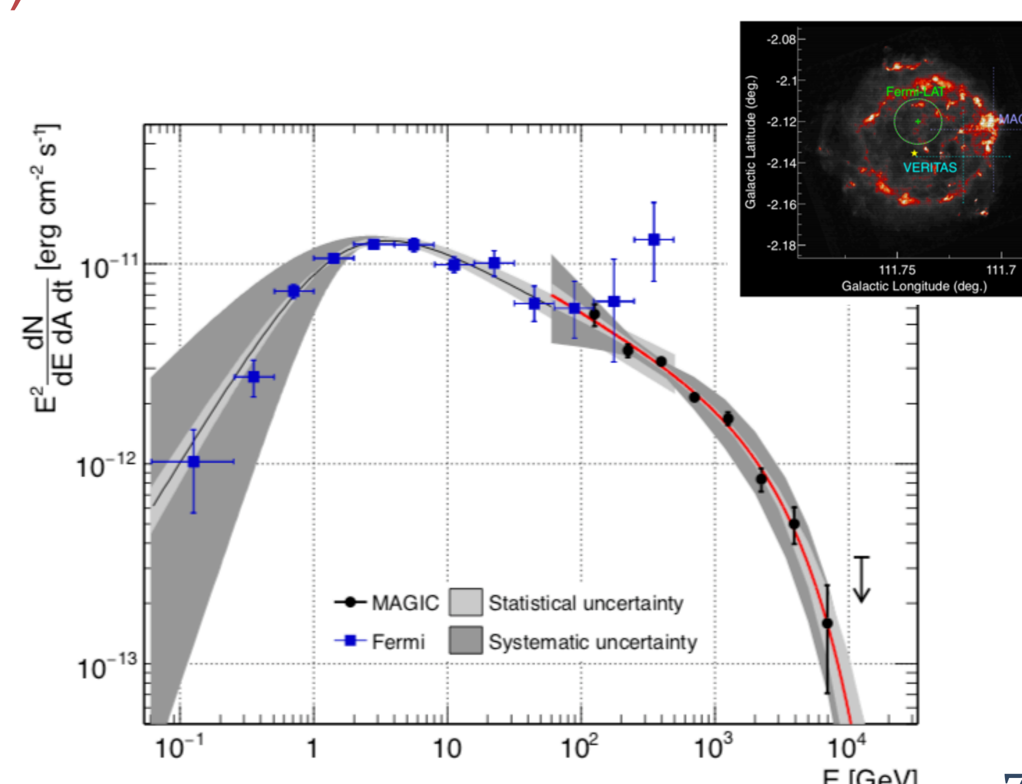




➡ Emission likely hadronic (power law also works)

- **Cassiopeia A (~ 340 yrs)**

➡ Pion bump detected but $E_{max,p}$ ~ 12 TeV



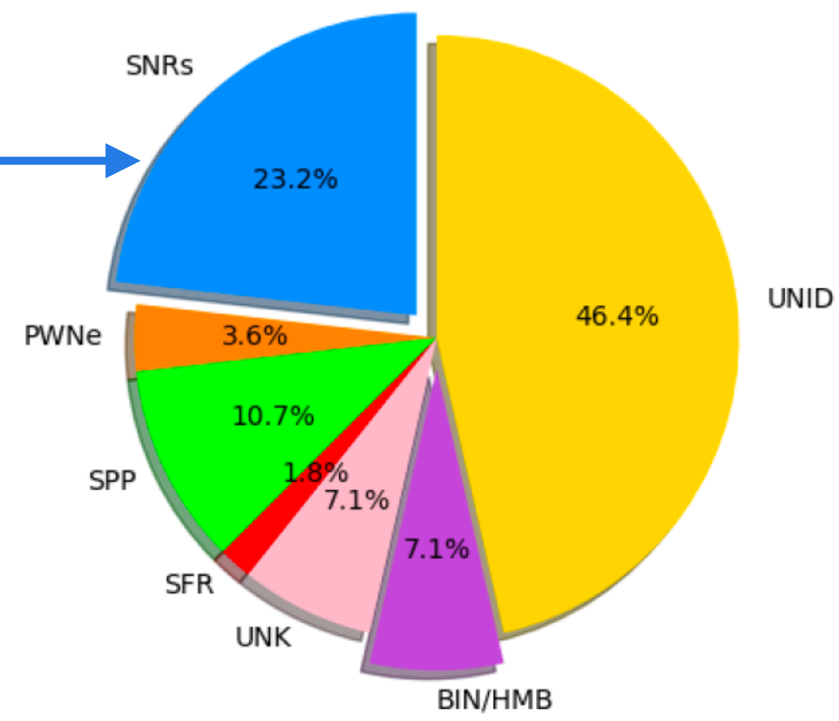
[MAGIC collab. 2017, Yuan et al. 2013]

Which Galactic sources can be proton accelerators?

[Lemoine-Goumard & Ballet, ICRC 2021]

Automatic search for the pion bump feature in the Fermi-LAT cataloged sources
➡ 56 sources show a significant low-energy break in their spectrum

10 firm identifications
+ 3 SNR associations



➡ **SNRs are the dominant class of identified sources with a low-energy break**

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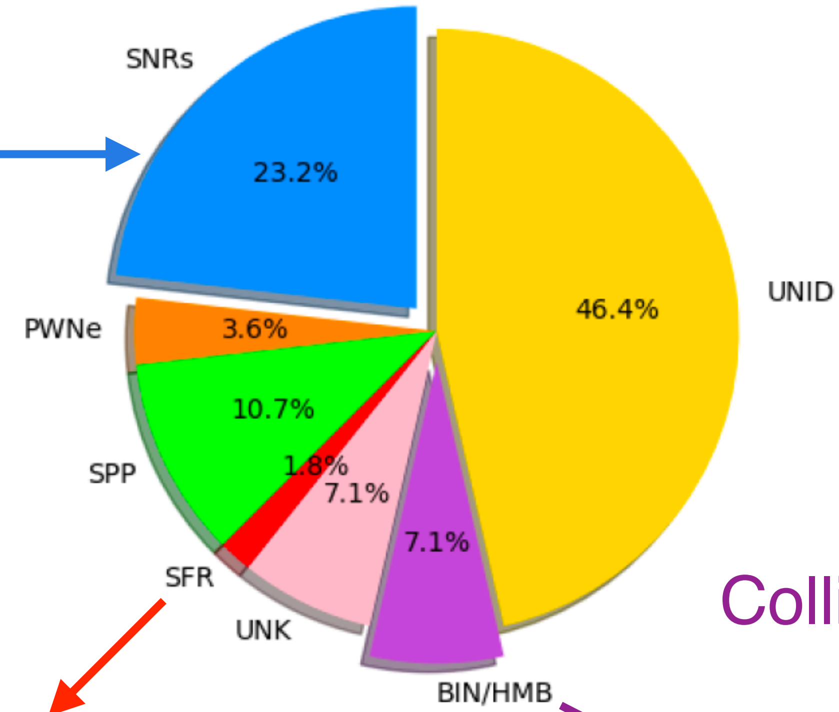

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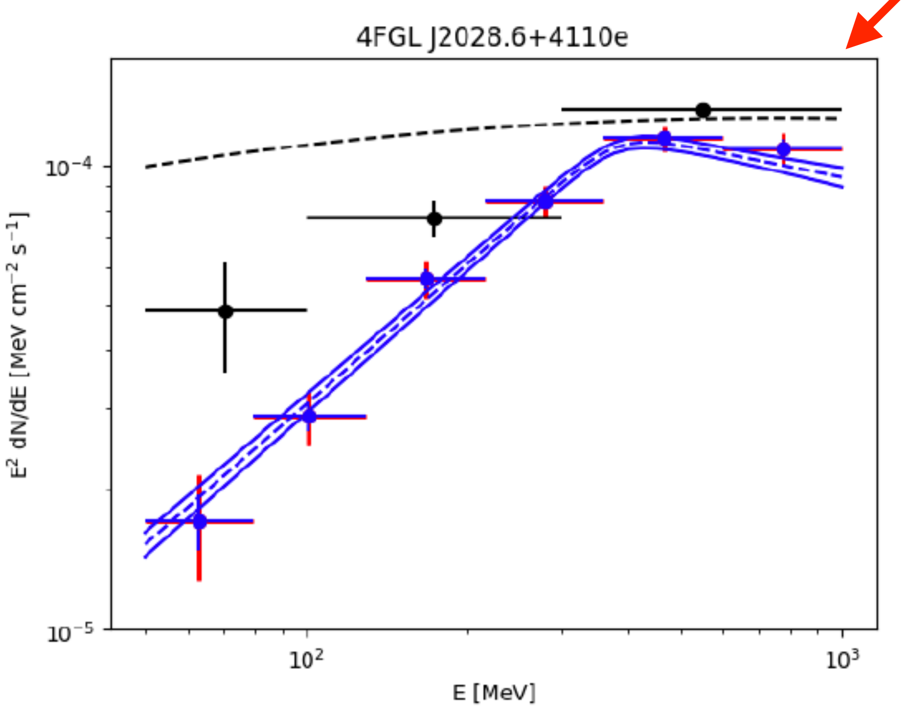
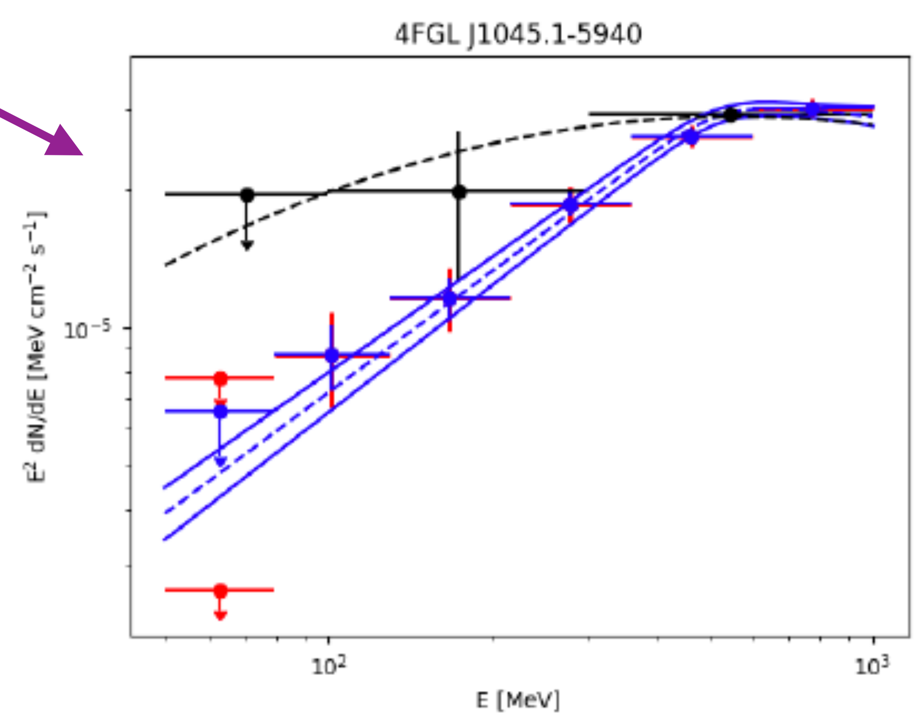
Associations:

Cygnus Cocoon



Colliding wind binary Eta Carinae



UNK: Blazar Candidate of Uncertain type at b < 10°, possibility Galactic sources

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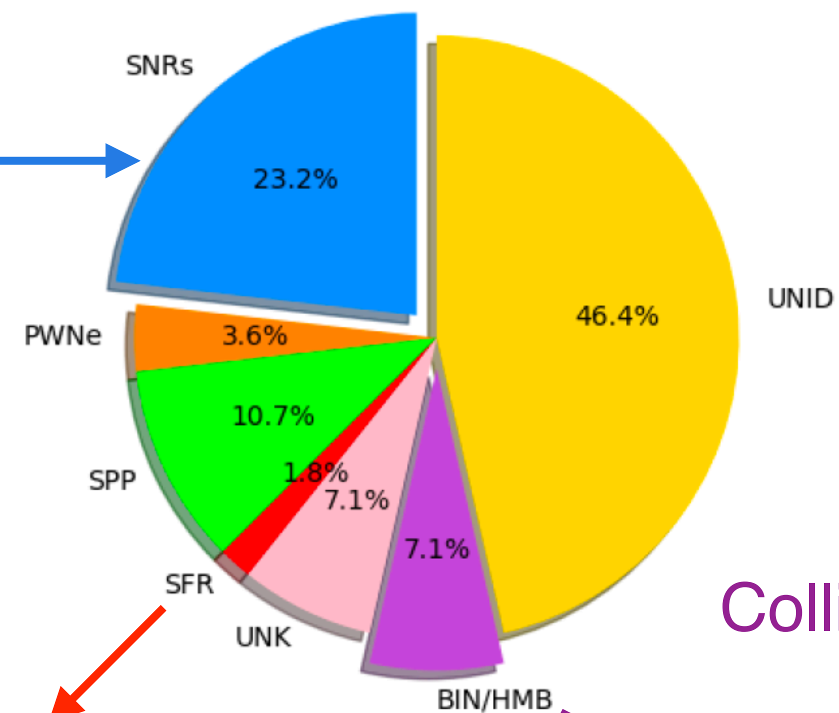

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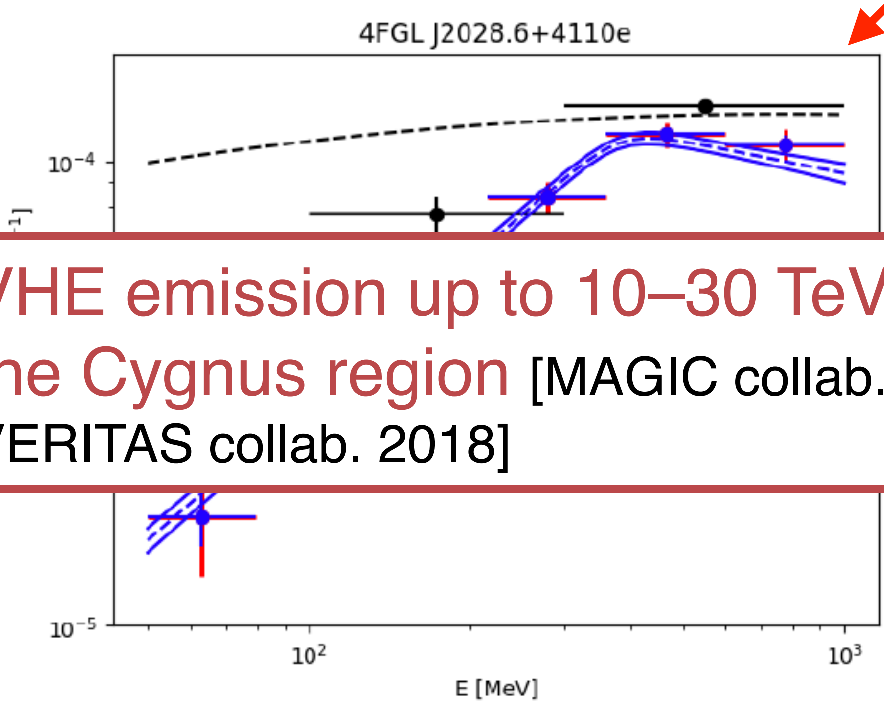
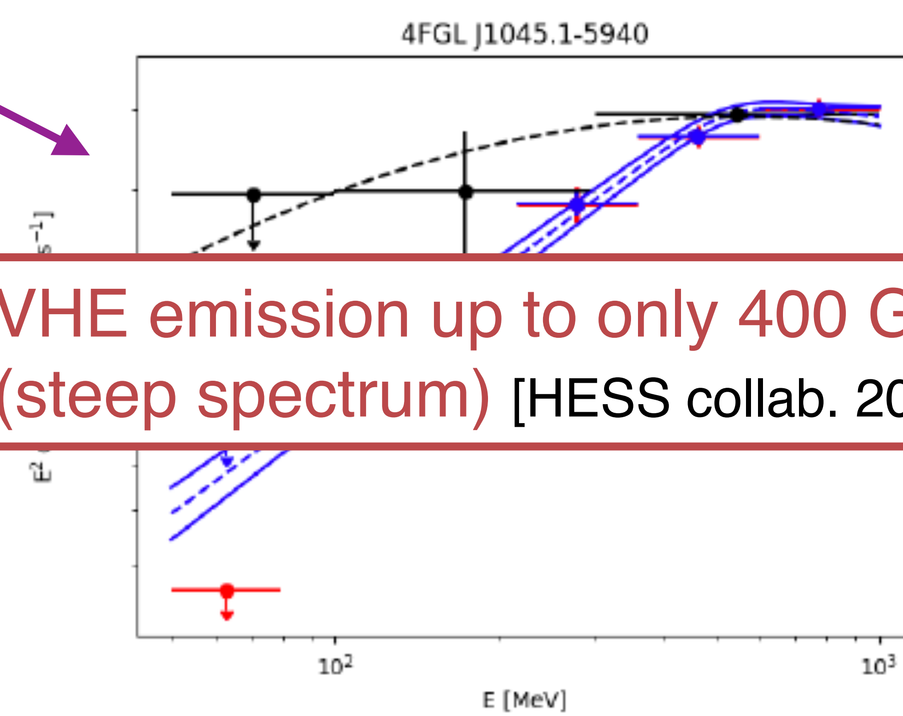


VHE emission up to 10–30 TeV within the Cygnus region [MAGIC collab. 2008, VERITAS collab. 2018]

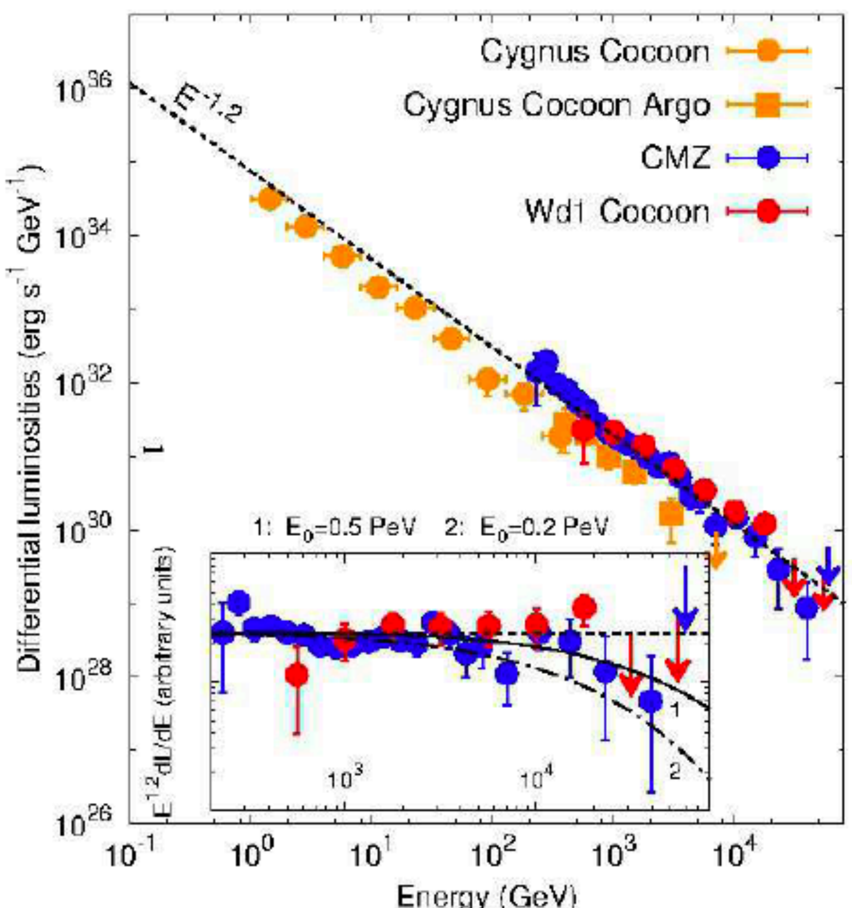


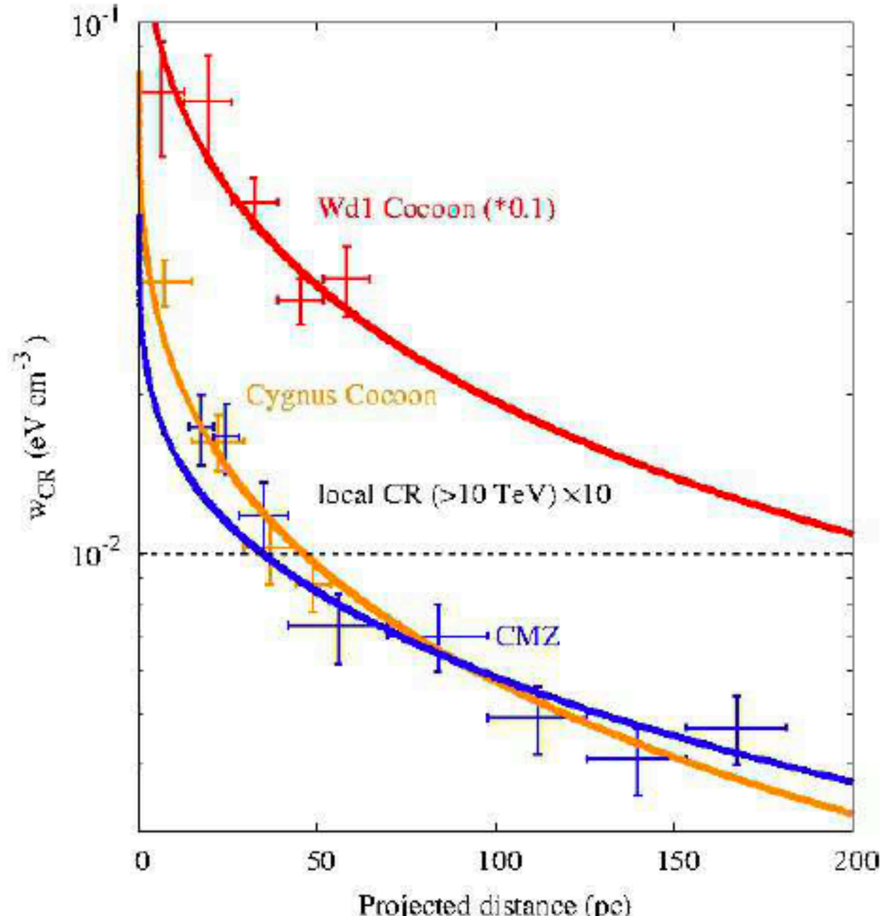
VHE emission up to only 400 GeV (steep spectrum) [HESS collab. 2020]

UNK: Blazar Candidate of Uncertain type at b < 10°, possibility Galactic sources

VHE emission from Star Forming Regions (SFRs)

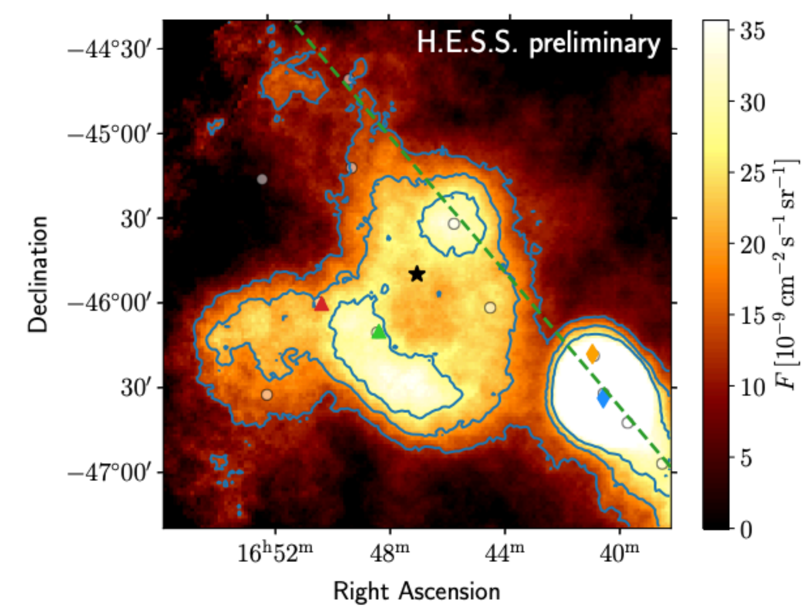
VHE emission with a 1/r profile (diffusion of continuously injected CRs):





[Aharonian et al. 2019]

[+ 3D analysis with HESS data in Morhmann et al., ICRC2021]



Westerlund 1: Lack of energy-dependent morphology; CRs can be produced by past SN (up to 150 SNe) activity or in interactive winds of massive stars (or a combination of both)

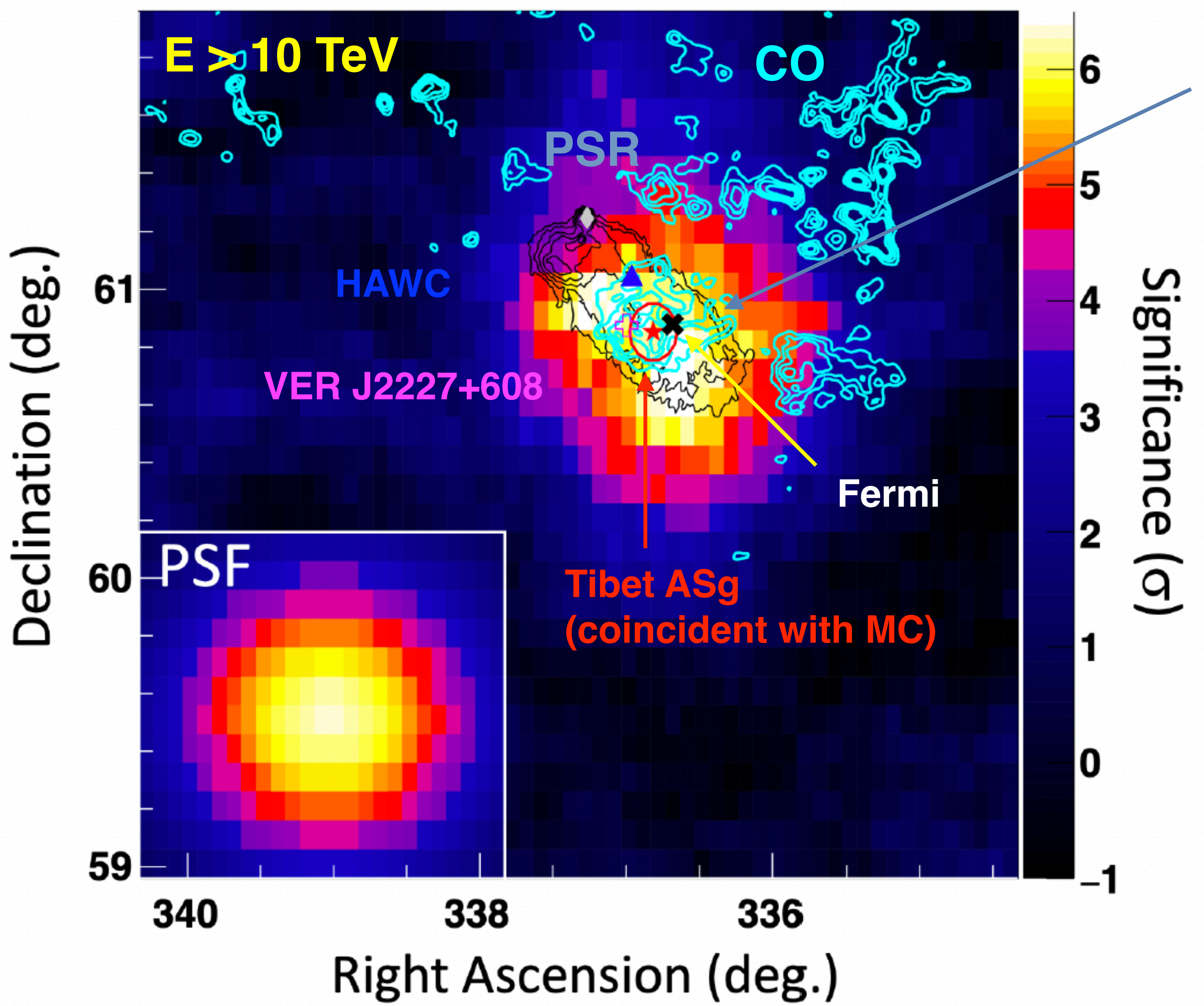
/!\ Background/foreground (even unknown) sources cannot be completely ruled out for sources with large angular extent as stellar clusters (Wd1 ~ 1°, Cygnus ~ 2°)

Going at ultra-high energies:

HAWC, Tibet ASgamma, LHAASO

Detection of UHE emission towards G106.3+2.7

VER J2227+608/Tibet ASg (~0.4° offset from the PSR) consistent with MGRO source (overlapping PSR) and HAWC (MC/PWN)

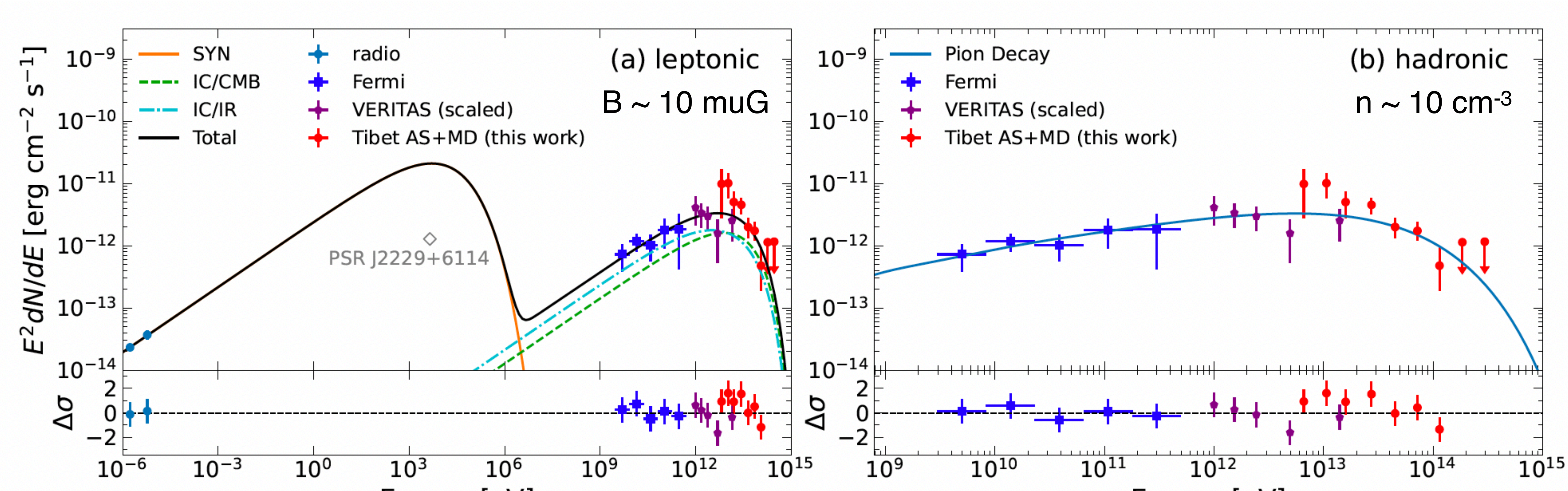


- **PSR J2229+6114:**
  Edot = 2.2 x 10^{37} erg s^{-1}
  Characteristic age ~ 10 kyr

- **SNR G106.3+2.7:**
  t_{age} = 10 kyr (old but derived assuming an association with the pulsar)

[Tibet ASg collab. 2021]

Detection of UHE emission towards G106.3+2.7



[Tibet ASg collab. 2021]

Particle spectrum:

$\alpha = 2.30^{+0.08}_{-0.07}$ $E_{\rm cut} = 190^{+127}_{-66}$ TeV

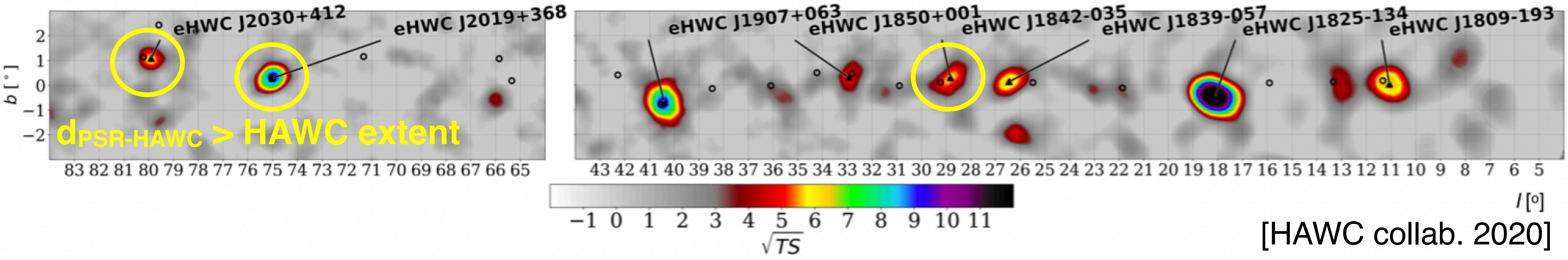
$\alpha = 1.79^{+0.08}_{-0.09}$ $E_{\rm cut} = 499^{+382}_{-180}$ TeV

Both hadronic and leptonic models work:

➡ Need X-ray observations to constrain the synchrotron spectrum
➡ CTA (with a better PSF) will help understand the origin of the emission (**SNR/PWN**); PWN scenario still very plausible

Highest-energy HAWC sources

- **E > 56 TeV:** 8 extended sources + the Crab PWN
  (6 of them are associated to an energetic pulsar)



[HAWC collab. 2020]

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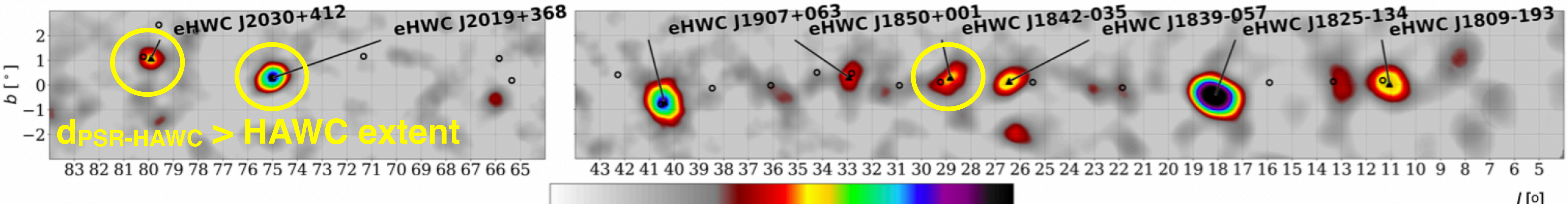
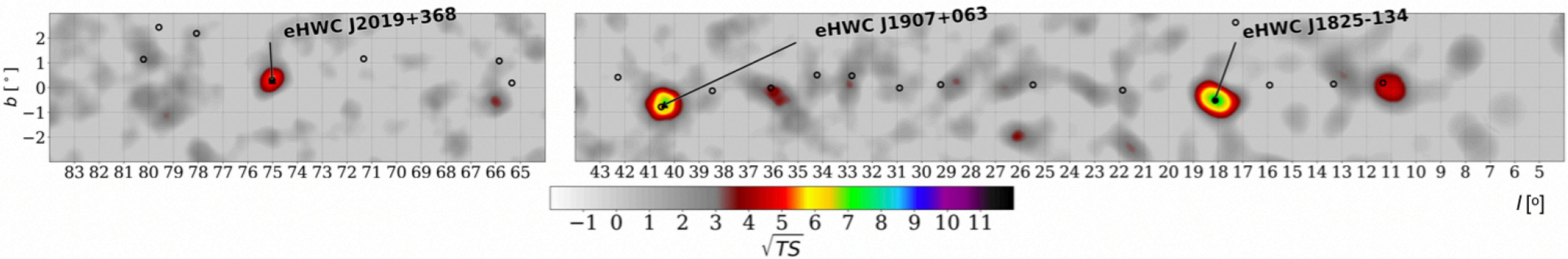
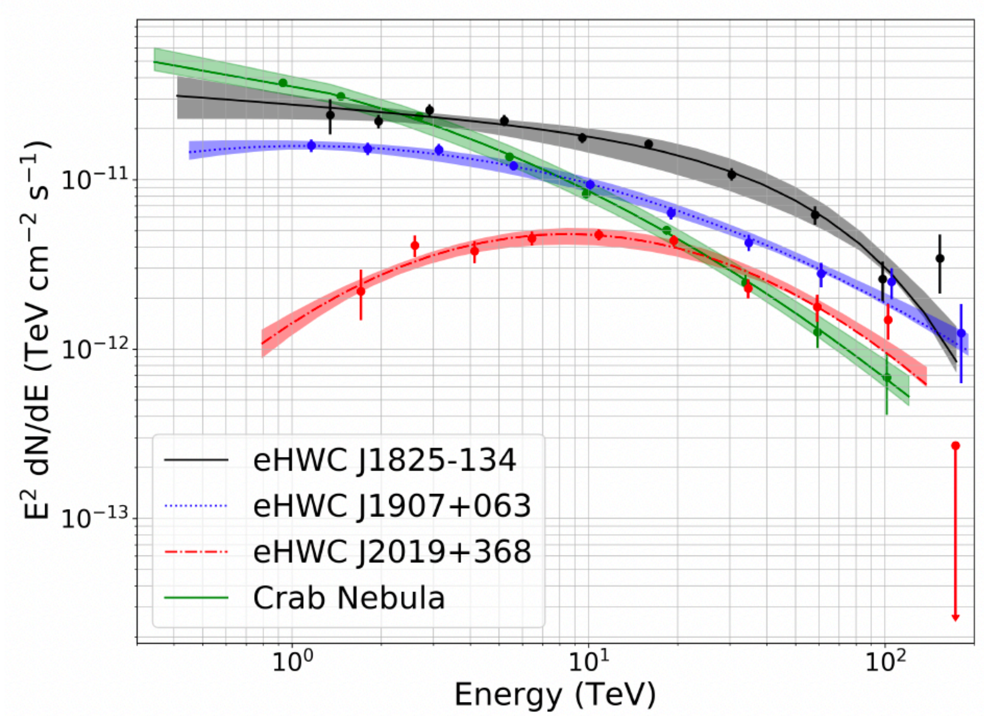


- **E > 100 TeV:**

[HAWC collab. 2020]





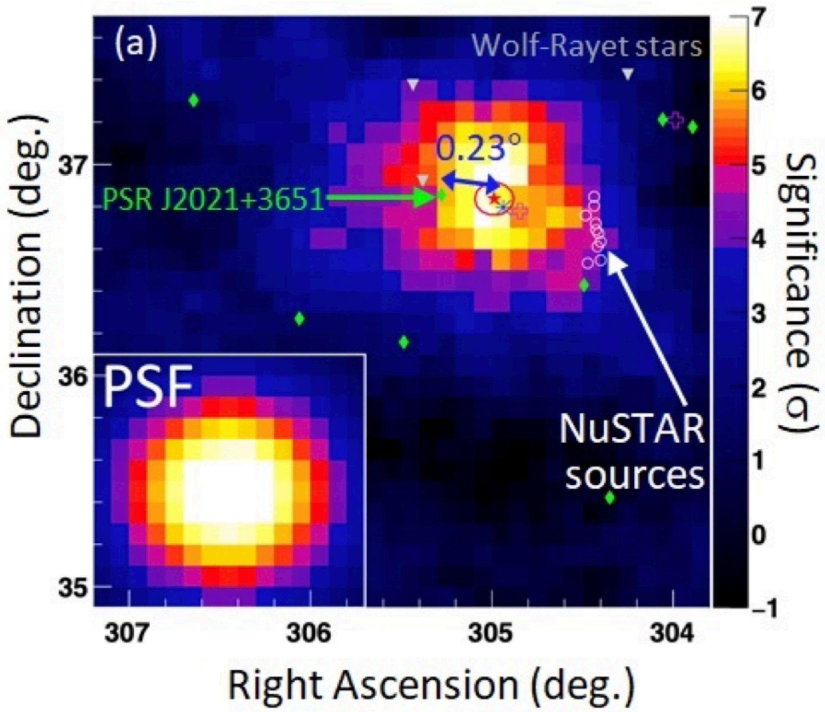
For the 3 sources: cut-off or curvature before 100 TeV (Klein-Nishina effect?)

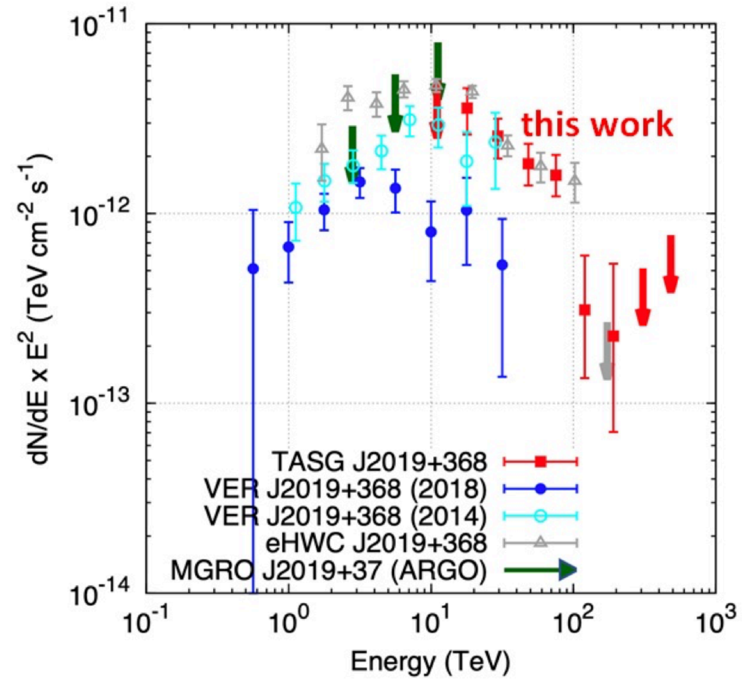
Future X-ray observations will help understand the origin (leptonic or hadronic) of the emission

UHE emissions towards the Cygnus region (HAWC, TibetASg)

[Katayose et al., TibetASg collab. ICRC 2021]

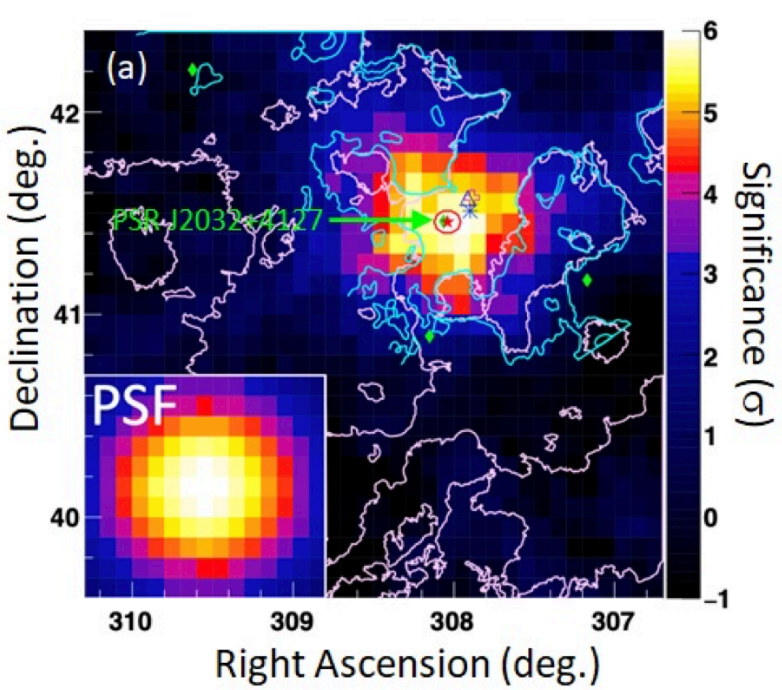
- TASG J2019+368 (**eHWC J2019+368**) — Cygnus OB1

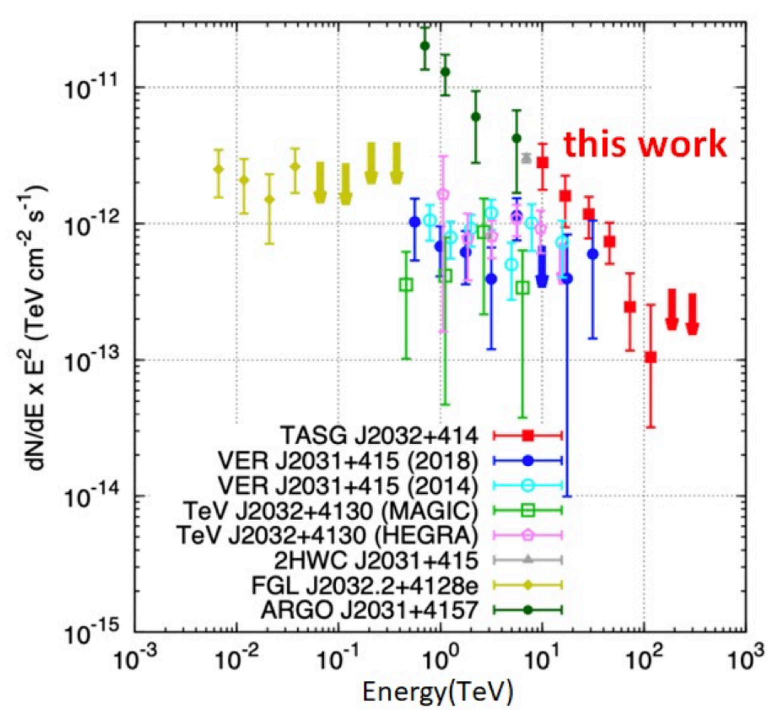




Spatially coincident with the PWN G75.2+0.1

- TASG J2032+414 (**2HWC J2031+415**) — Cygnus OB2

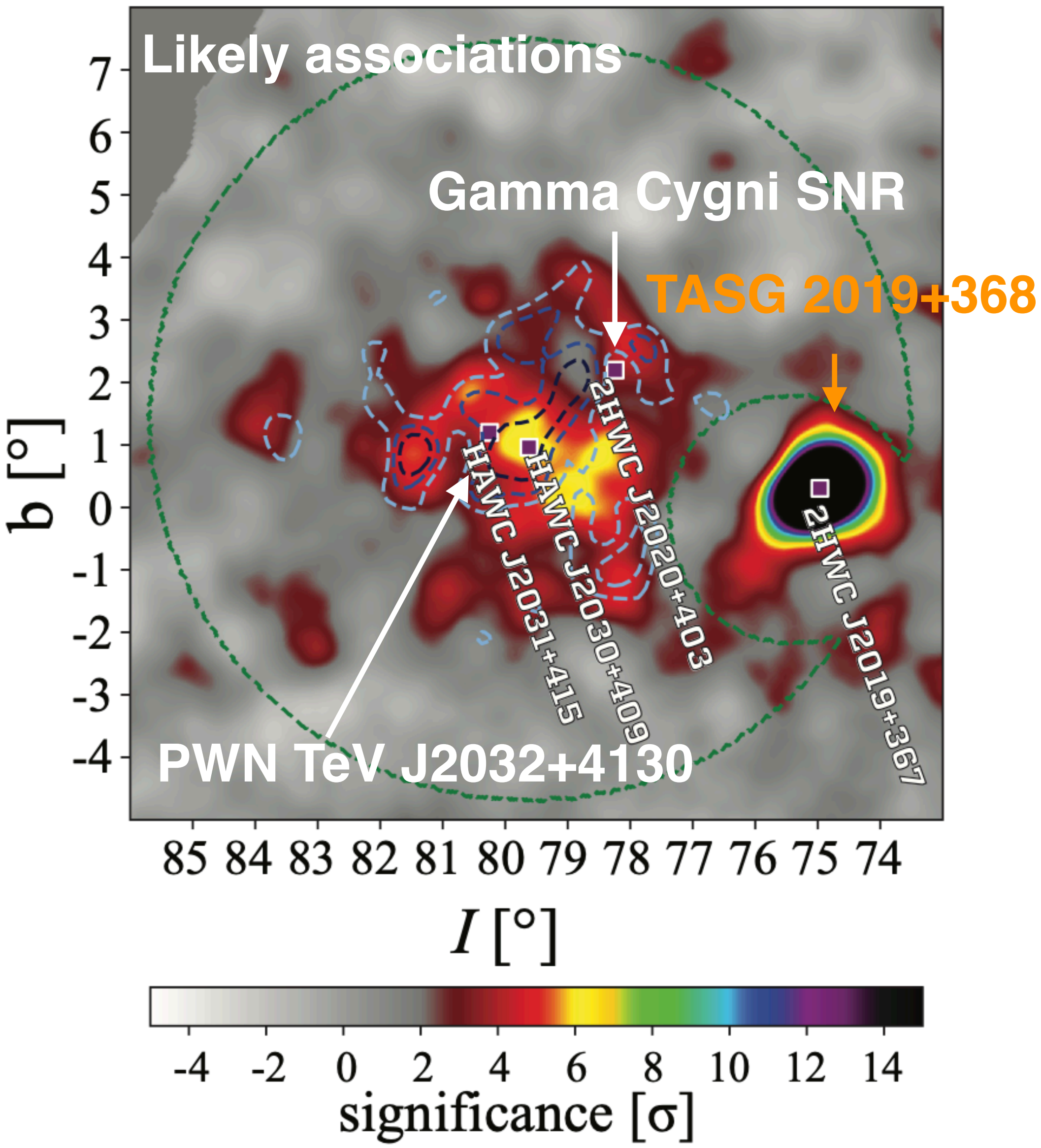




Likely associated with the PWN TeV J2032+4130

UHE emission from the Cygnus Cocoon (HAWC)

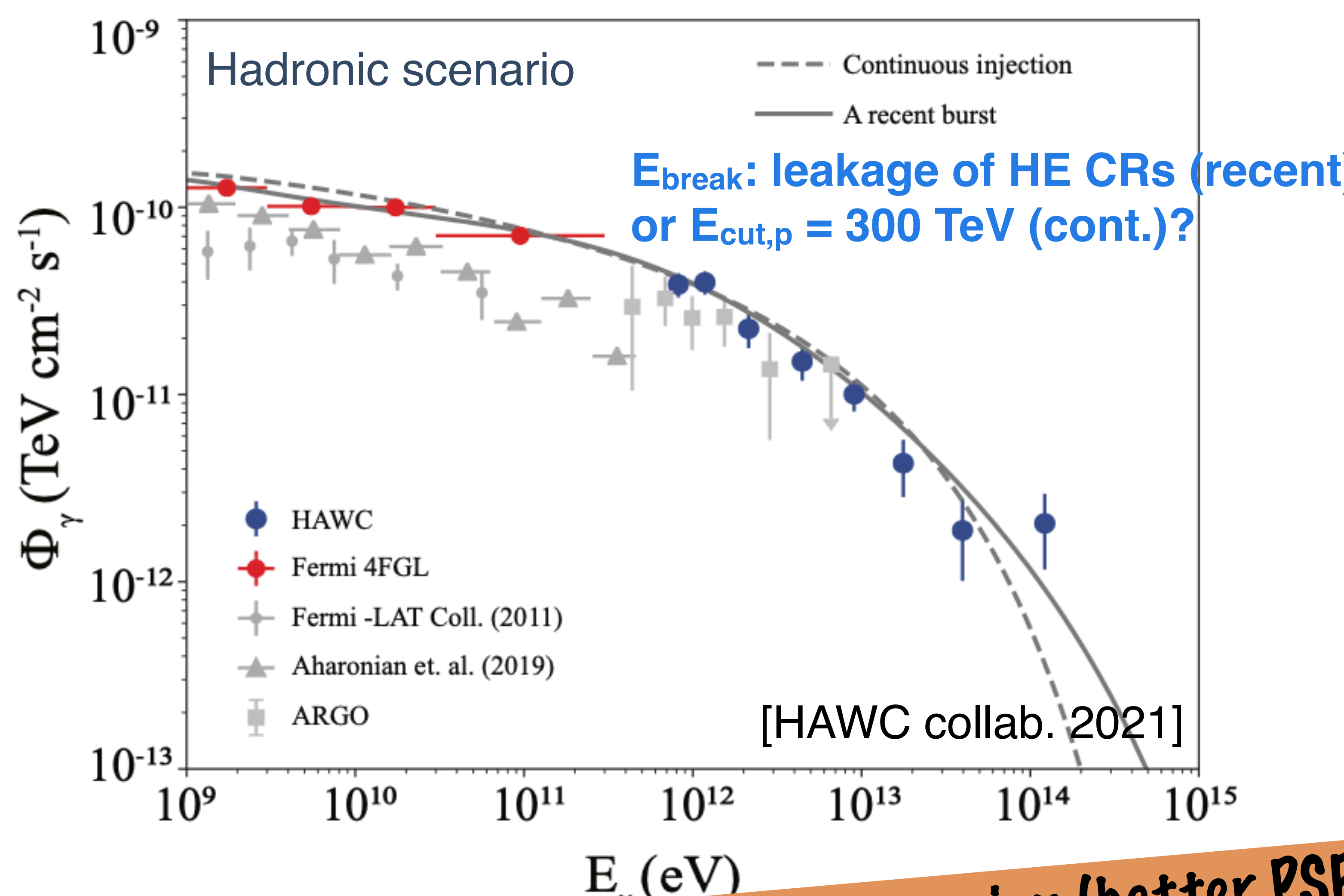
Cygnus cocoon: Superbubble surrounding a region of OB2 massive star formation



/!\ Background/foreground sources cannot be ruled out

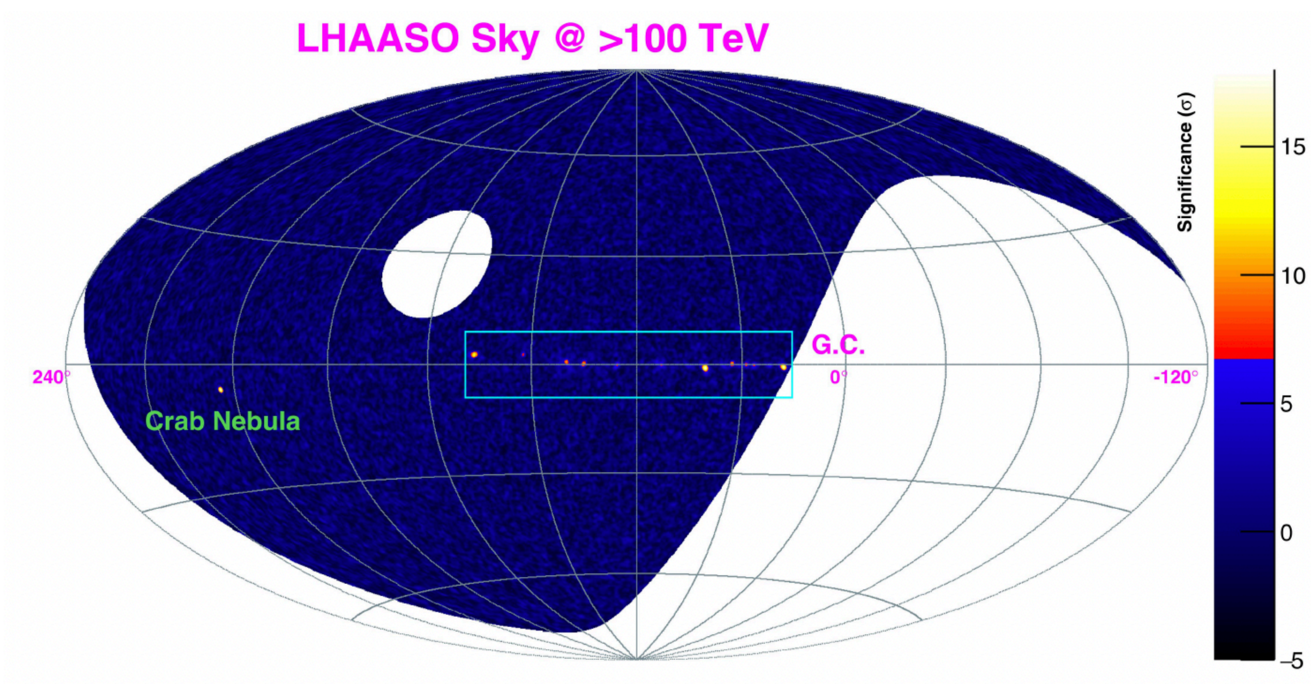
HAWC J2030+409: counterpart of the GeV Cygnus Cocoon

Leptonic scenario unlikely (radio and X-ray data)
+ Pion bump detected toward this region
[Lemoine-Goumard & Ballet, ICRC 2021]



CTA will help resolve the emission region (better PSF)

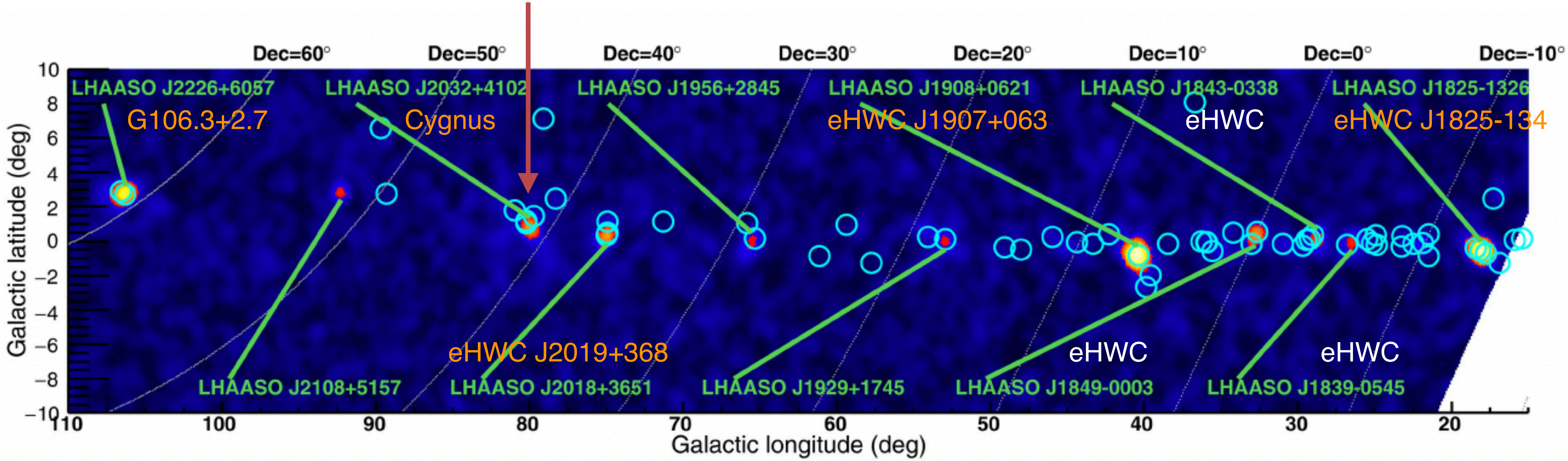
Gamma-ray emissions > 100 TeV detected by LHAASO



12 Galactic sources (Crab PWN + 11 UNID)

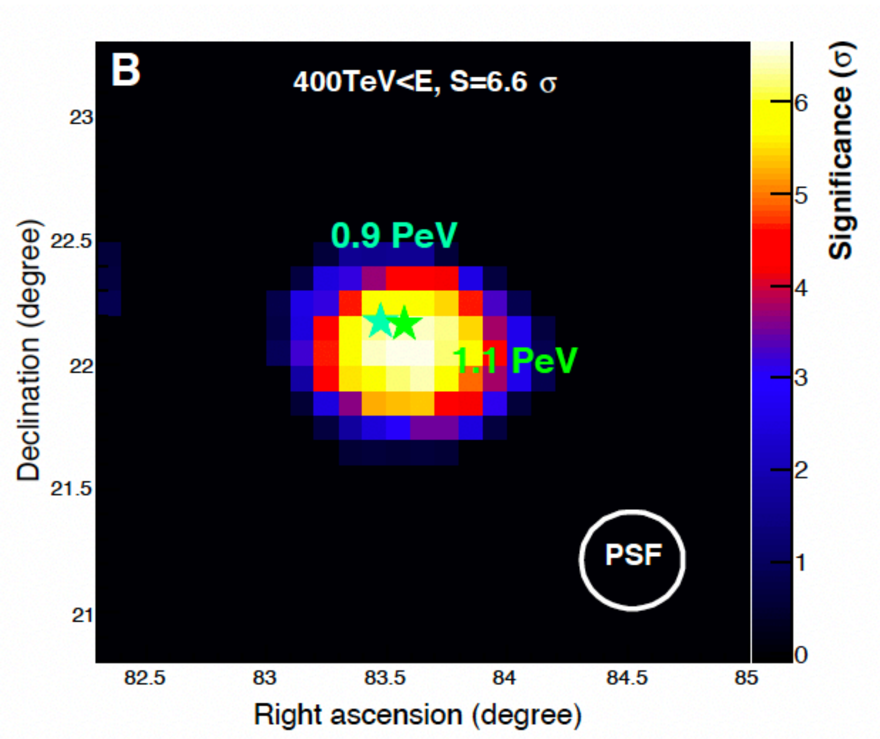
[LHAASO collab. 2021]

E_{max} = 1.4 PeV ! (Cygnus region)

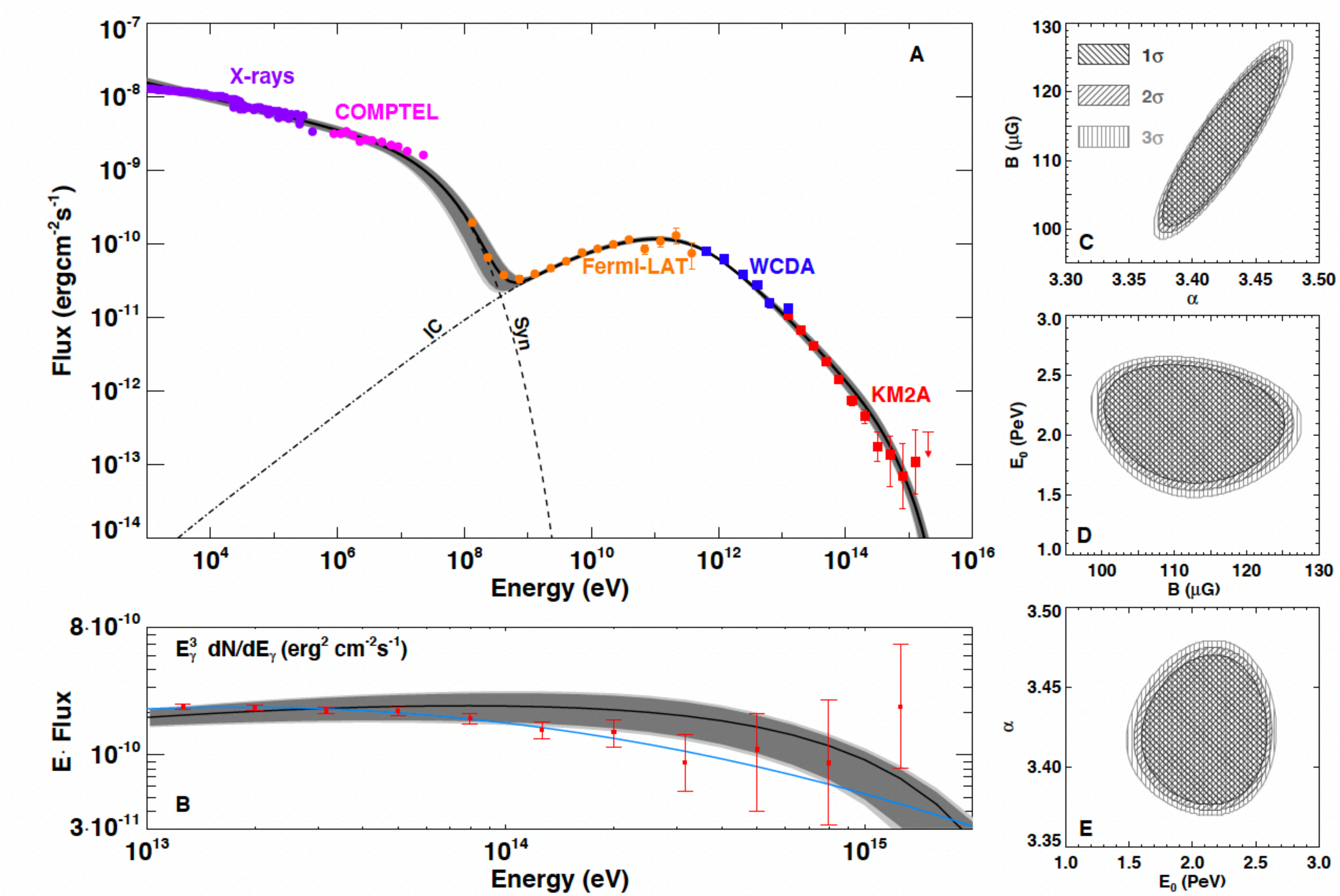


The Crab PWN as a likely PeV electron accelerator

Photon of 1.1 PeV !



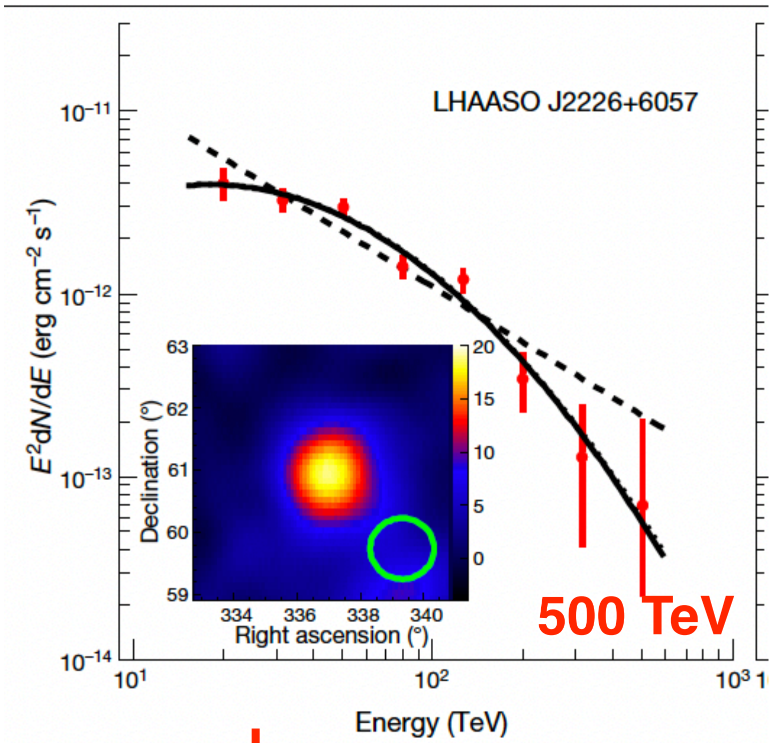
[LHAASO collab. 2021]



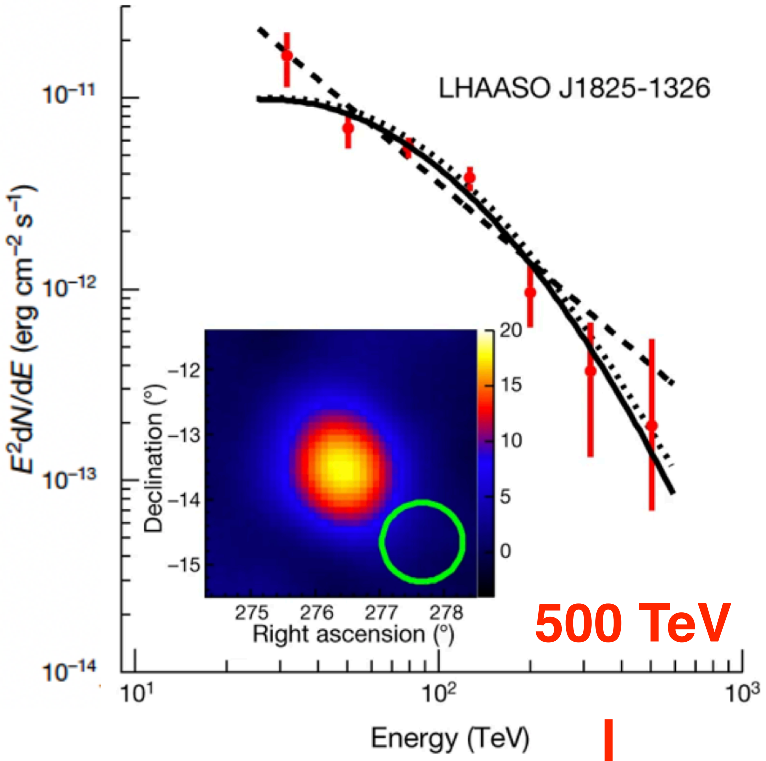
➡ **Likely leptonic: $E_{max,e}$ = 2.15 PeV**, alpha = 3.42, B = 112 muG

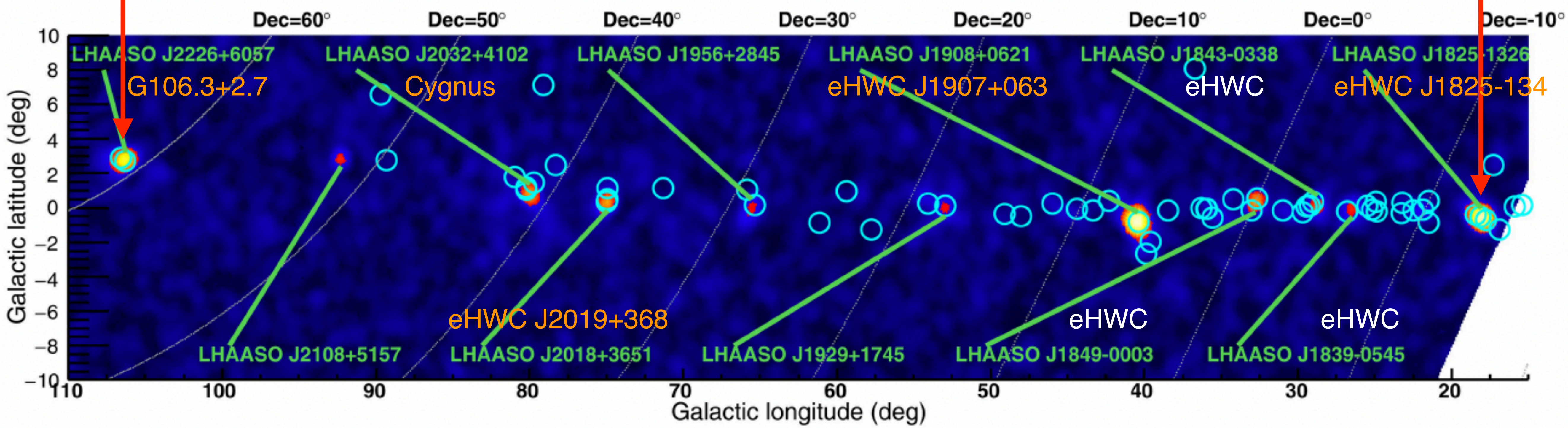
- Steepening of the spectrum between 60 TeV and 500 TeV?
- Hardening of the spectrum at 1 PeV? Would need a second e- or proton population but not enough significant

Spectra at higher energy with LHAASO



[LHAASO collab., ICRC 2021]





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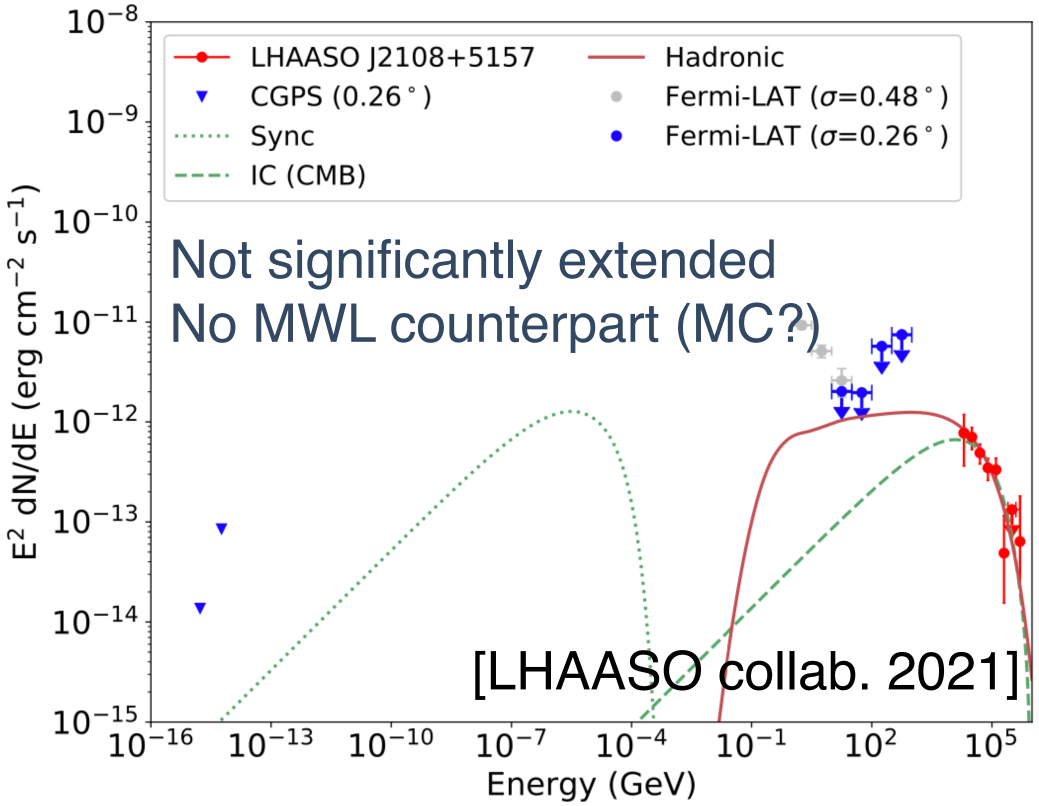
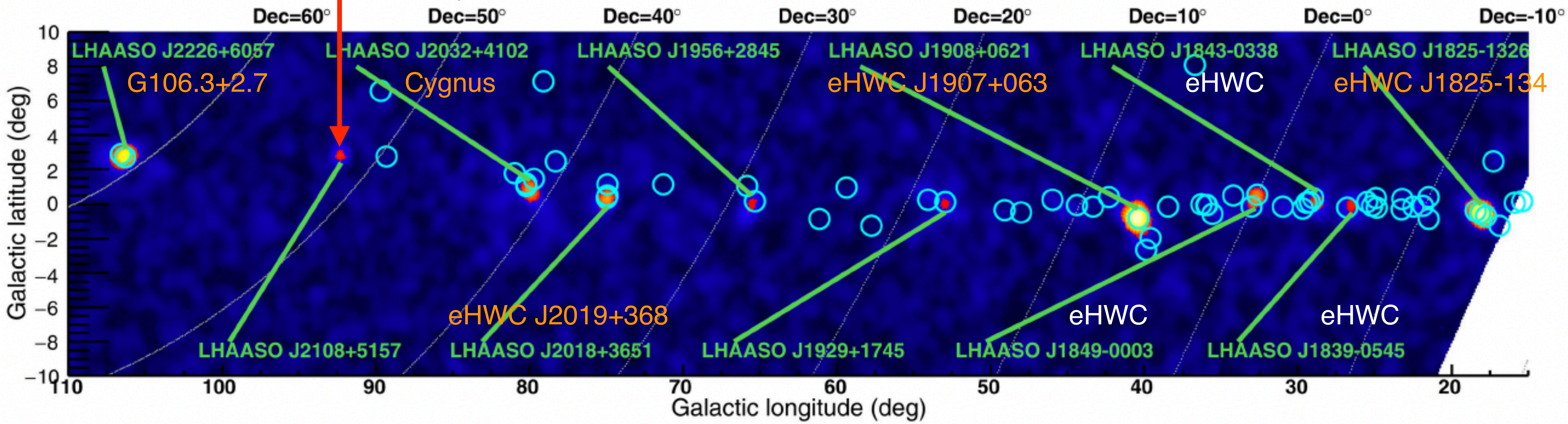
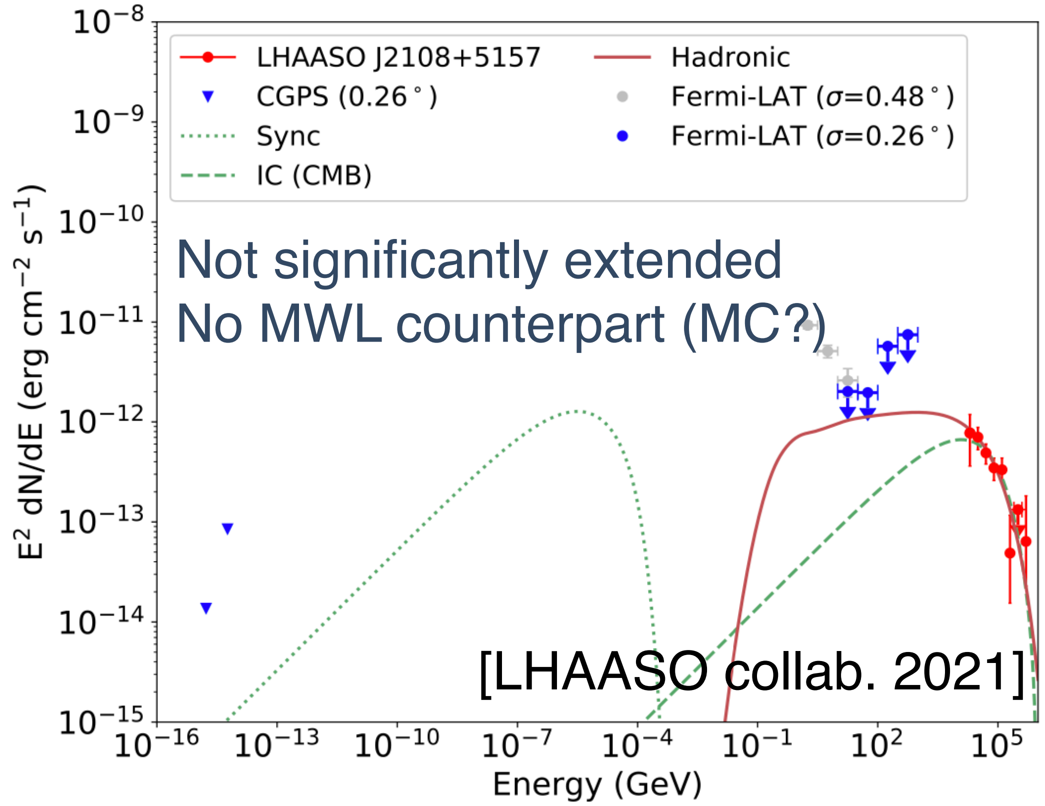


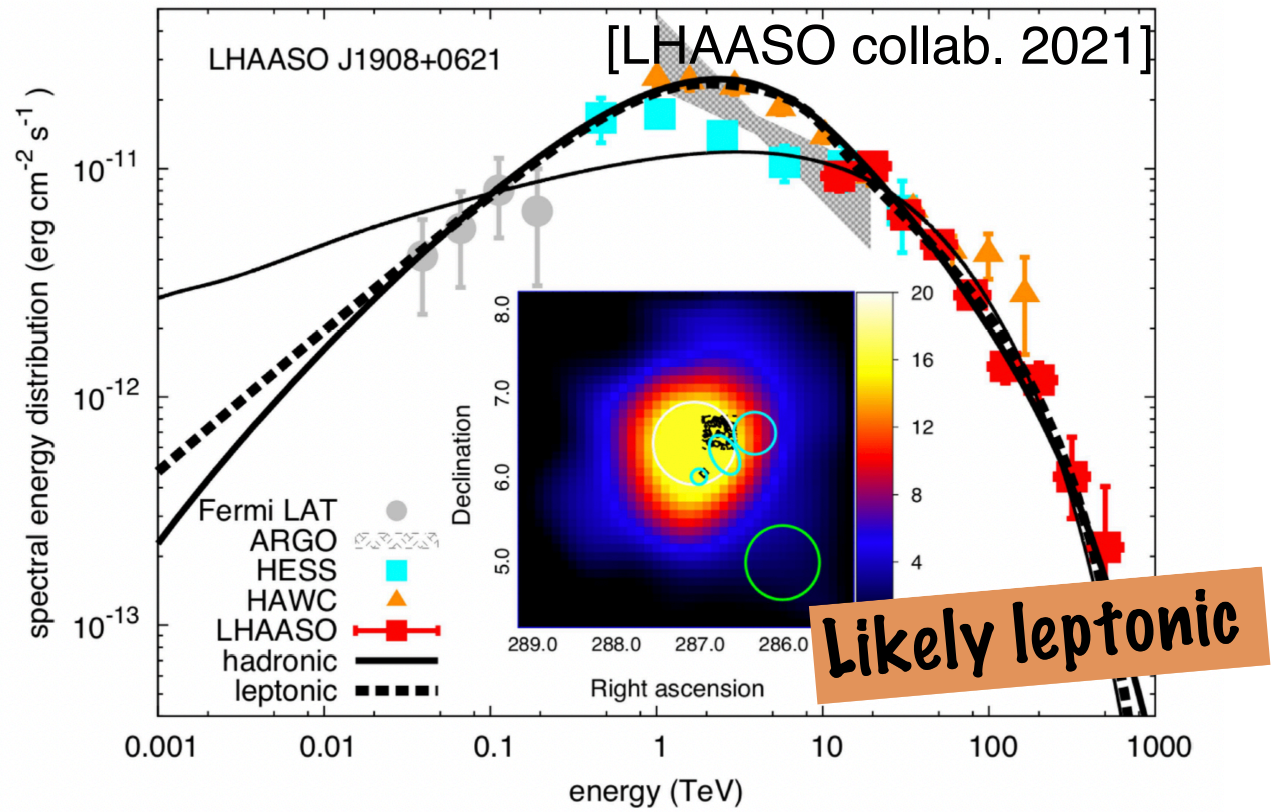
$E_{max,e}$ = 200 TeV (PLEC)

$E_{max,p}$ = 600 TeV (PLEC)



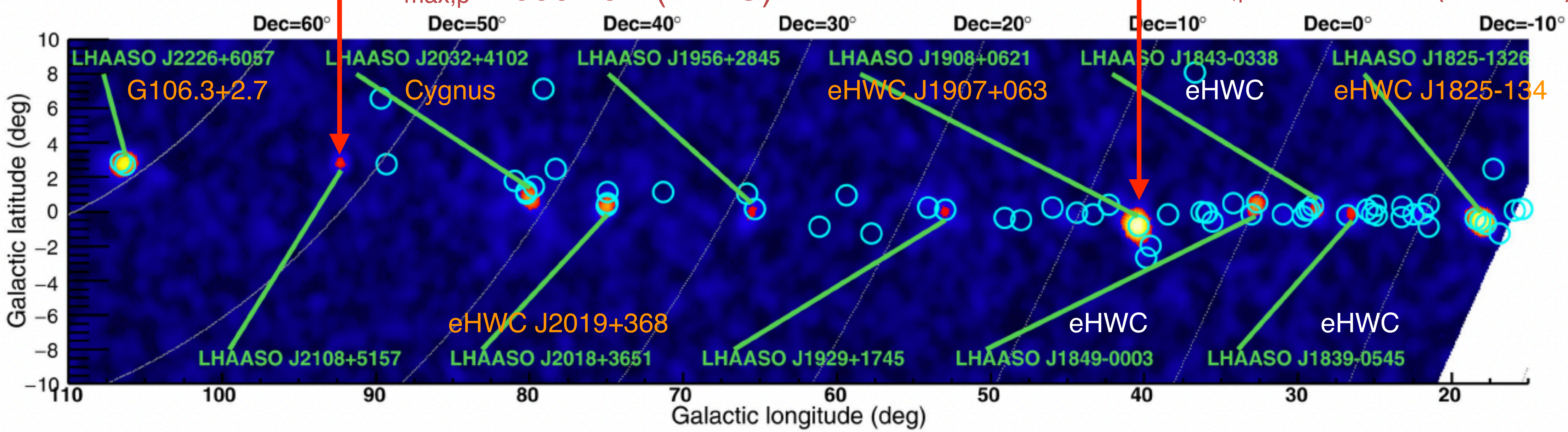
Spectra at higher energy with LHAASO





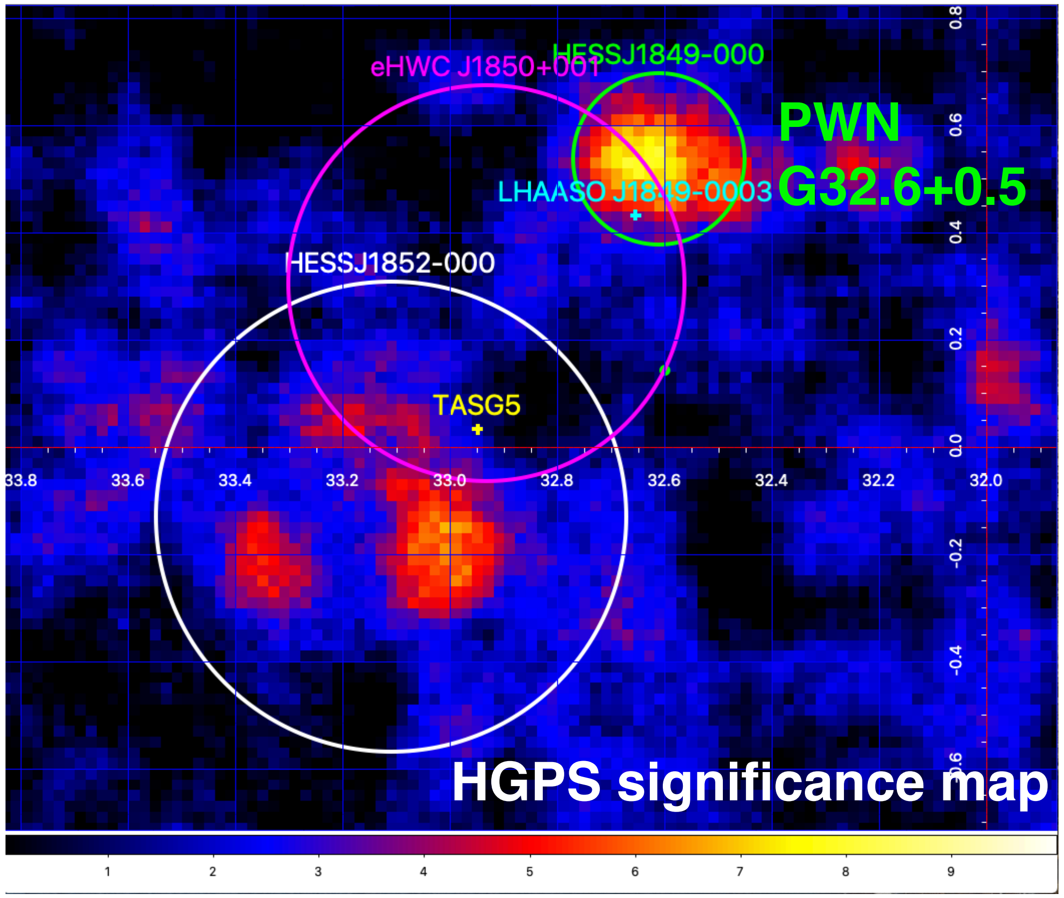
$E_{max,e}$ = 200 TeV (PLEC)
$E_{max,p}$ = 600 TeV (PLEC)

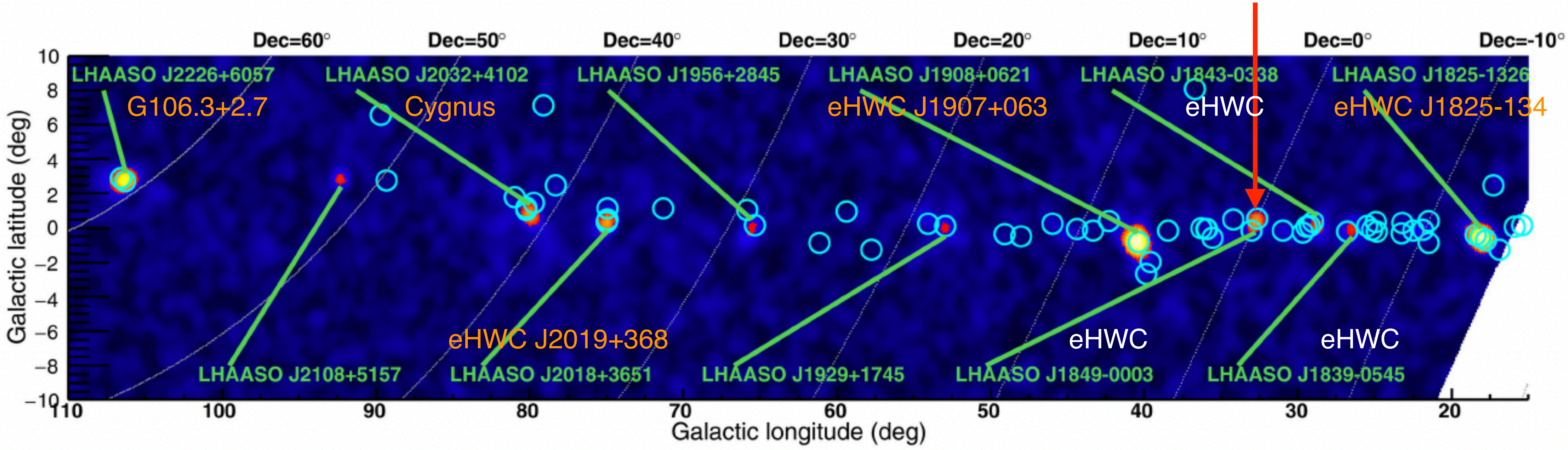
$E_{max,e}$ = 800 TeV (PLEC)
$E_{max,p}$ = 1.3 PeV (BPLEC)



In the vicinity of LHAASO J1849–0003

- **LHAASO J1849—0003** is associated with **HESS J1849–000** (VHE counterpart of the known X-ray PWN G32.6+0.5 [Terrier et al. 2008])





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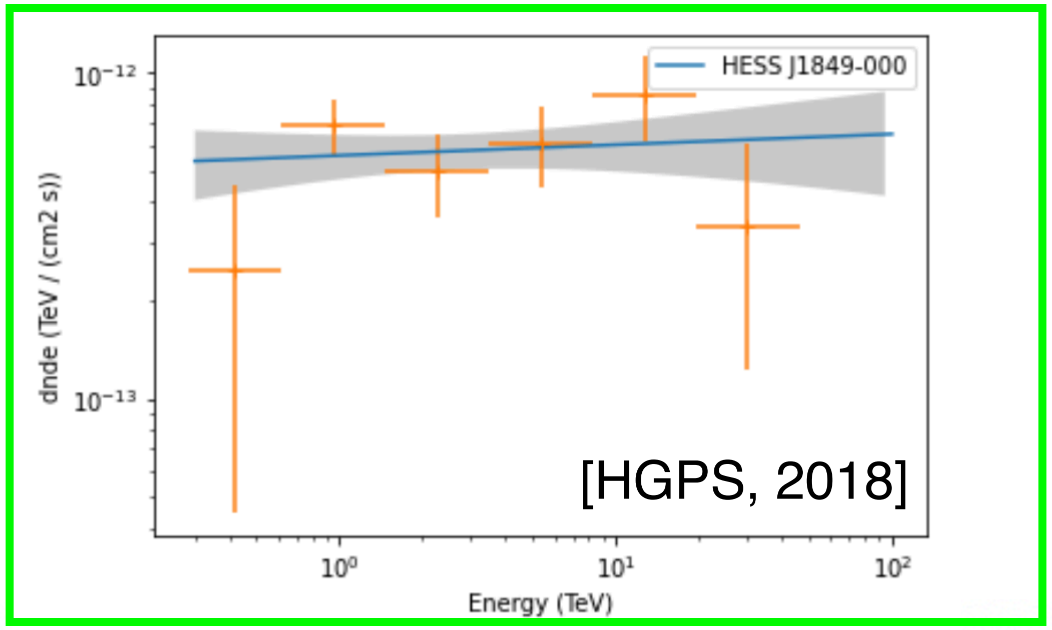
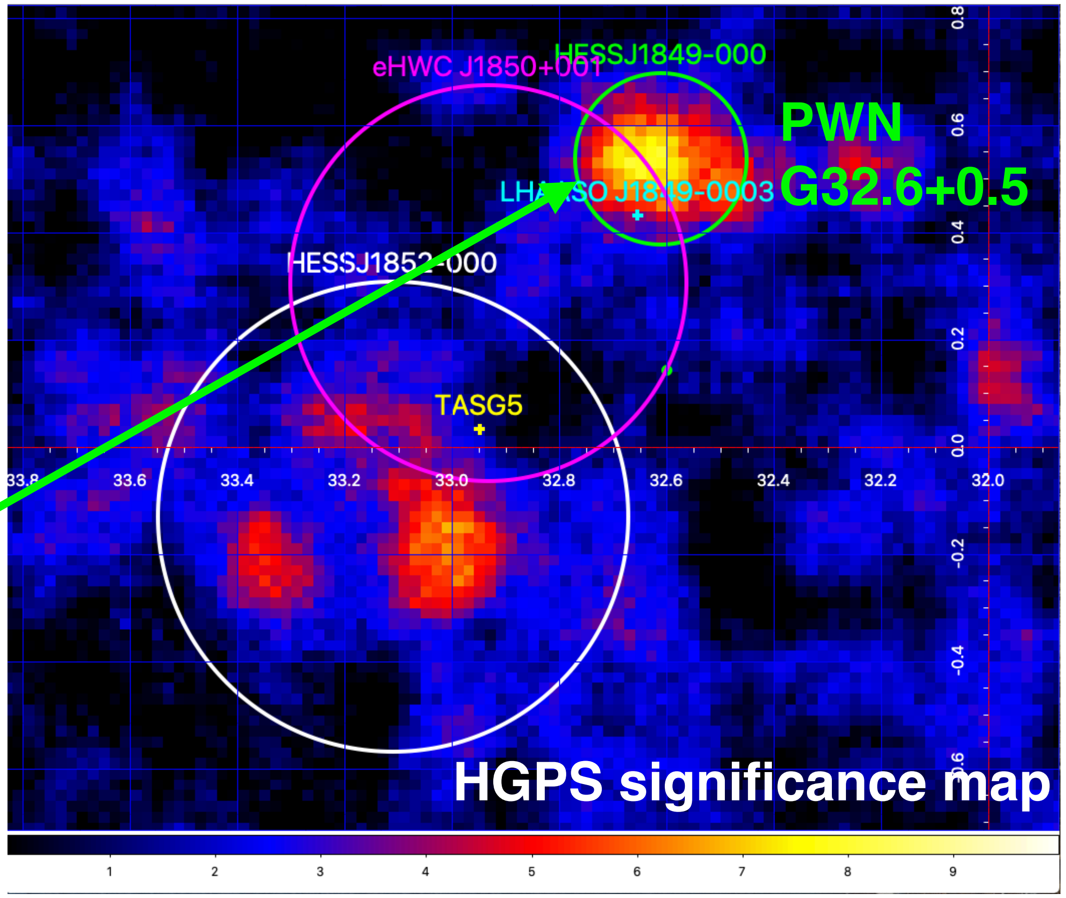
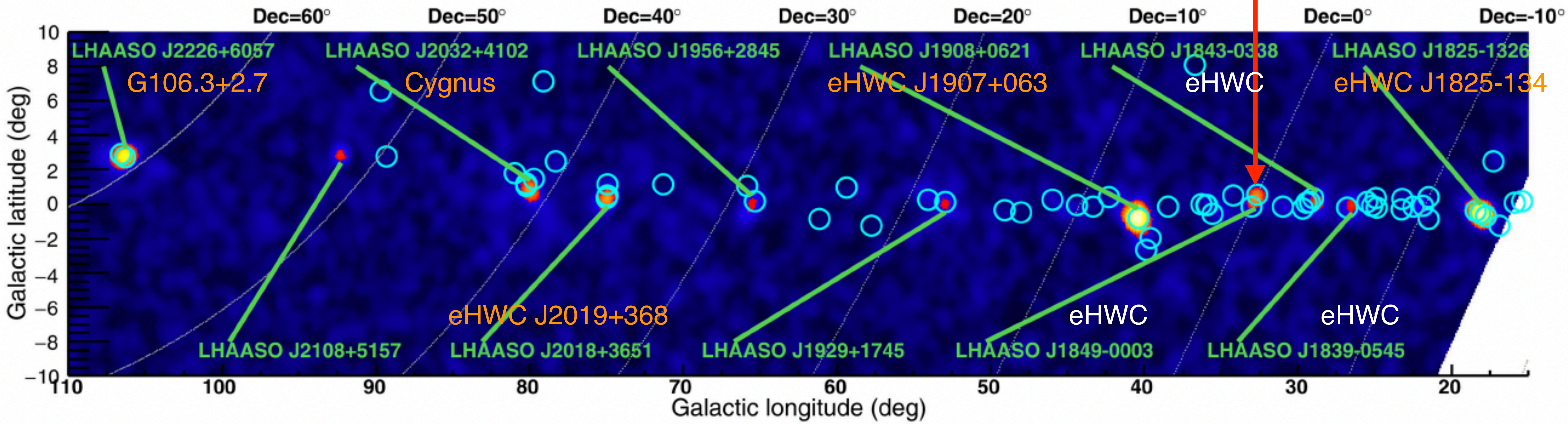
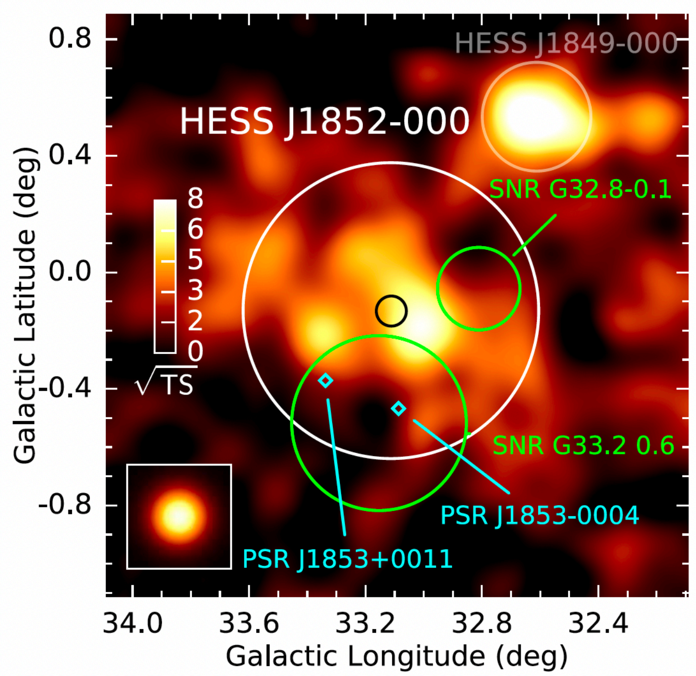


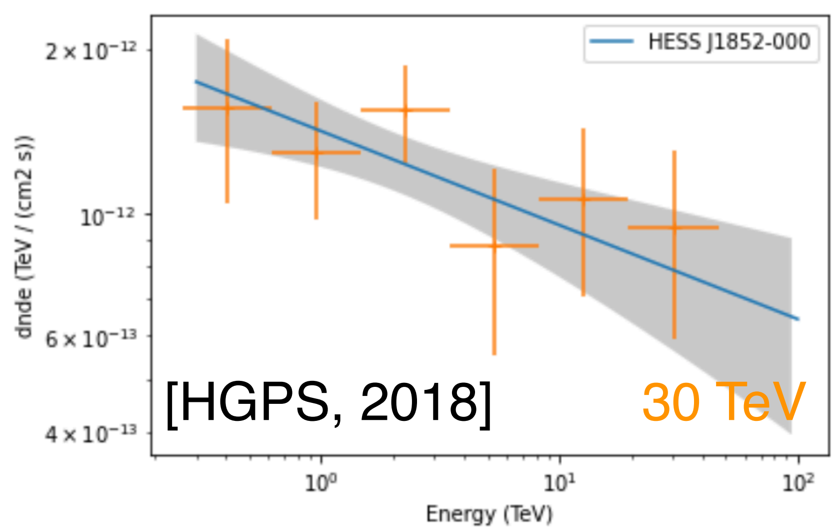


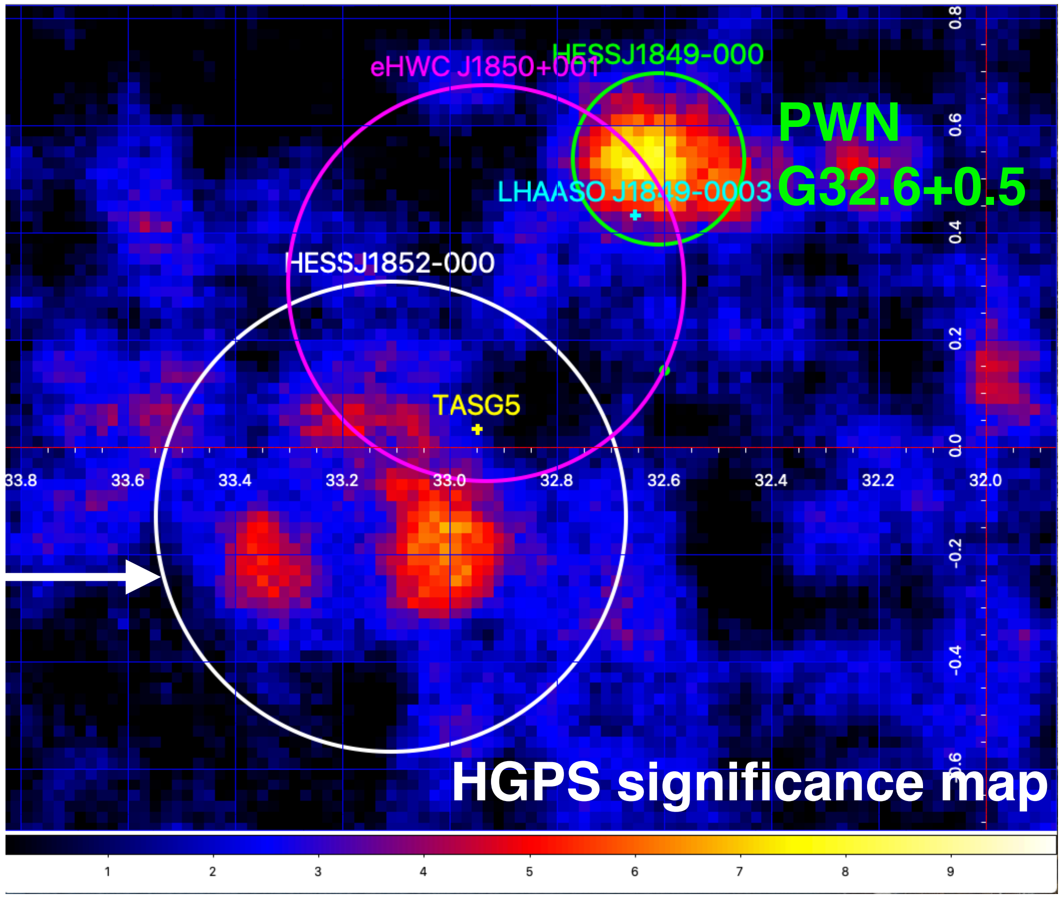


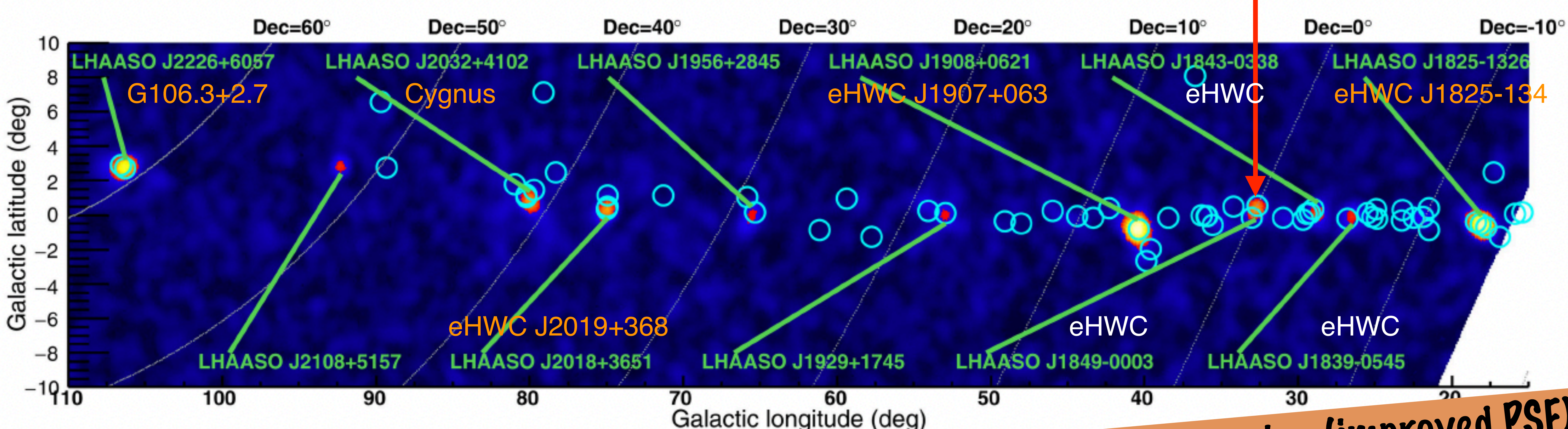
In the vicinity of LHAASO J1849–0003

- eHWC J1850+061 and one Tibet ASg source overlap with **HESS J1852–000** (UNID)









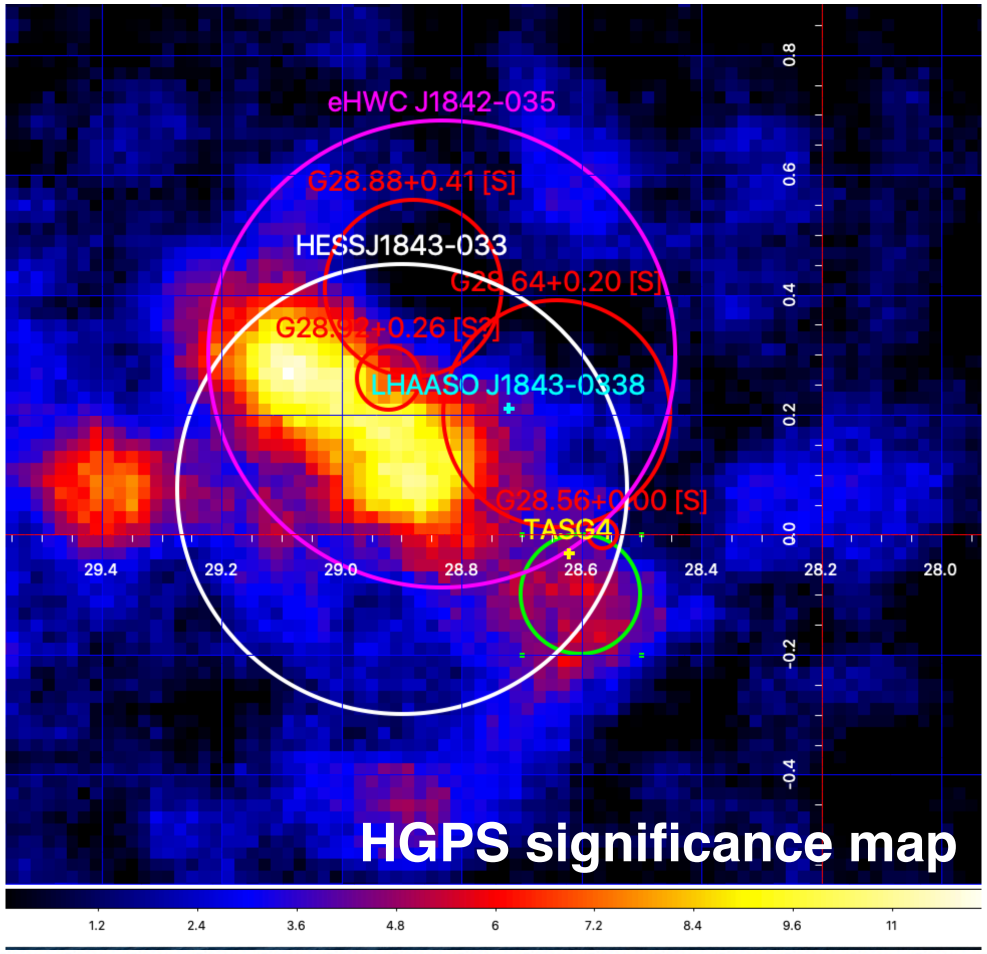
CTA will help resolve the emission region (improved PSF)

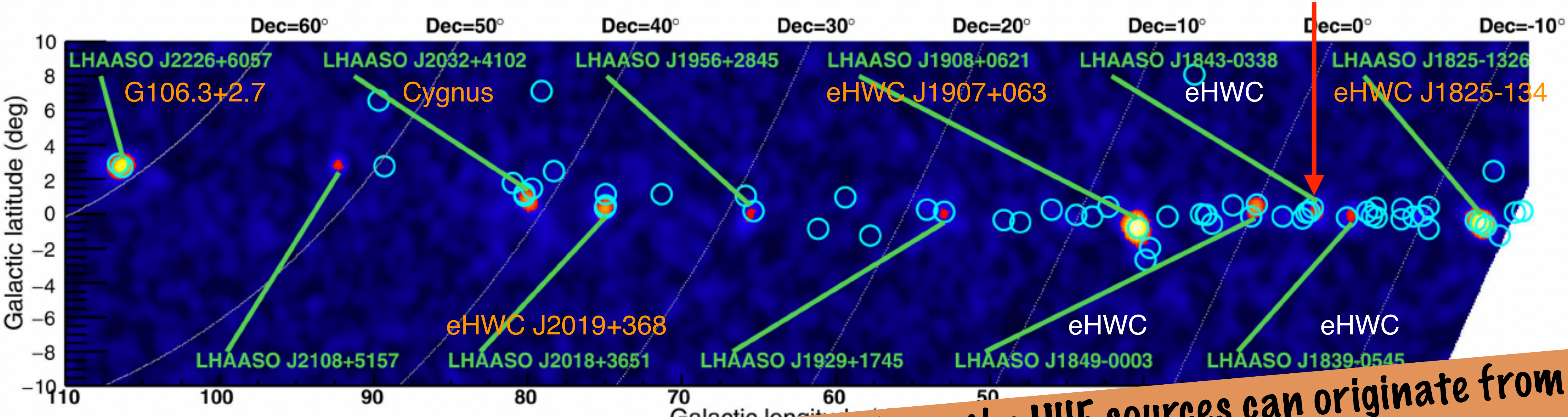
LHAASO J1843—0338

- **LHAASO J1843—0338**, **eHWC J1842—035** and **TibetASg source** overlap with:

- **HESS J1843–033** (UNID)
- **SNR candidates** [Anderson et al. 2017]
- the X-ray synchrotron emitting **SNR G28.6–0.1**

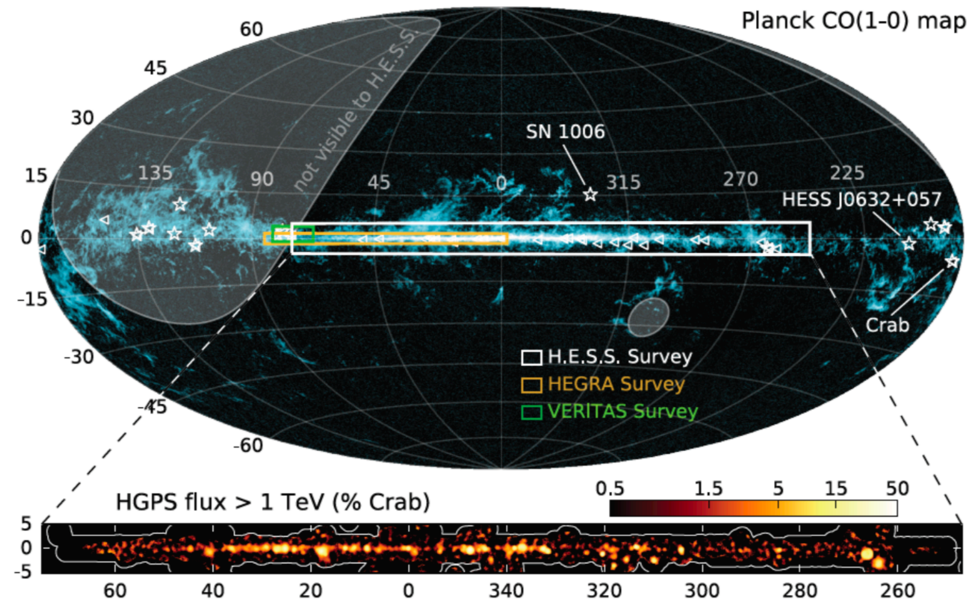
- **eHWC J1842—035** is one of the 3 sources for which $d_{PSR\text{-}HAWC}$ > HAWC extent





Gamma rays from the UHE sources can originate from PWNe (or halos), SFRs and potentially SNRs

Other PeVatron candidates

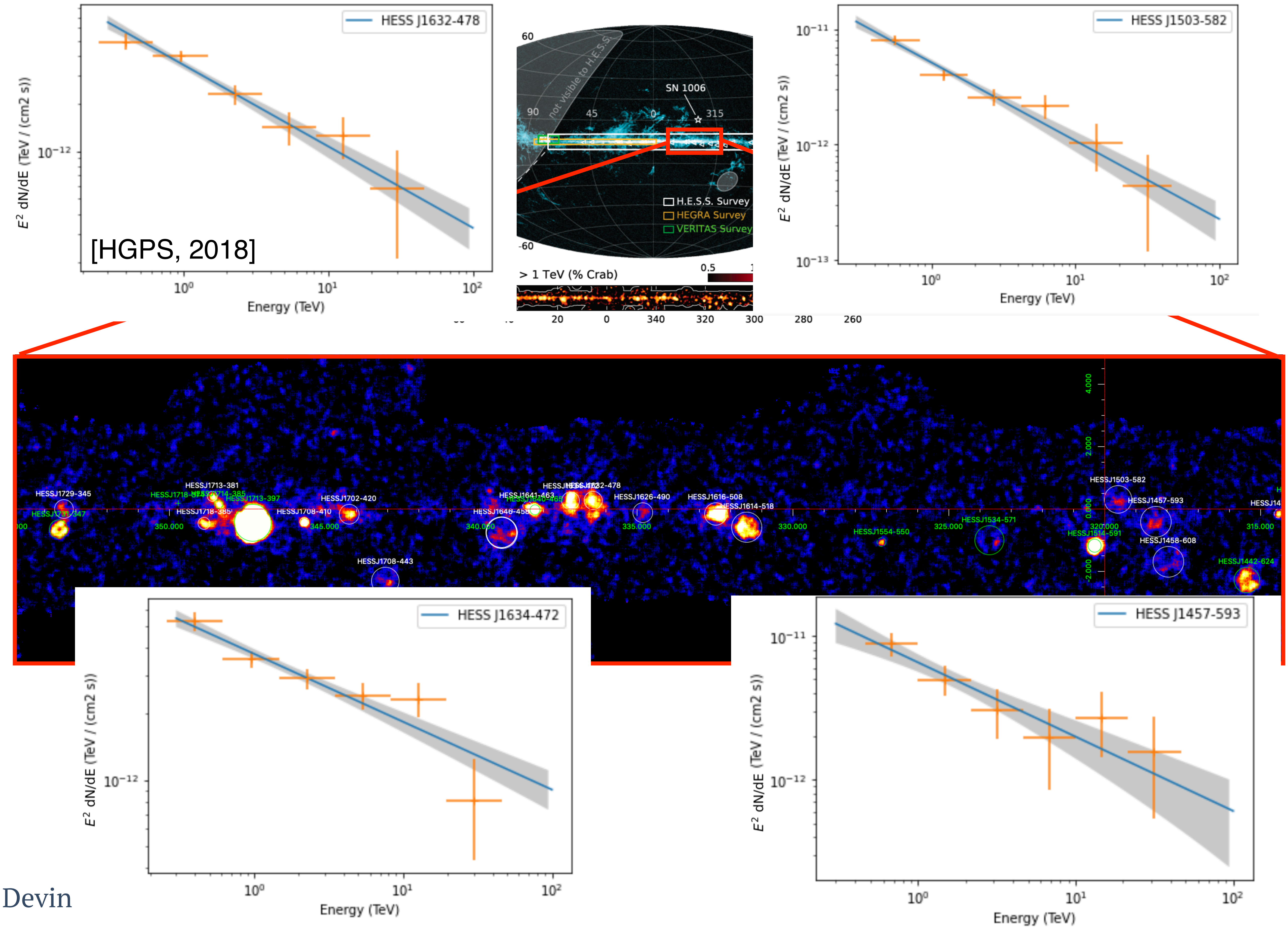


[HESS collab. 2018]

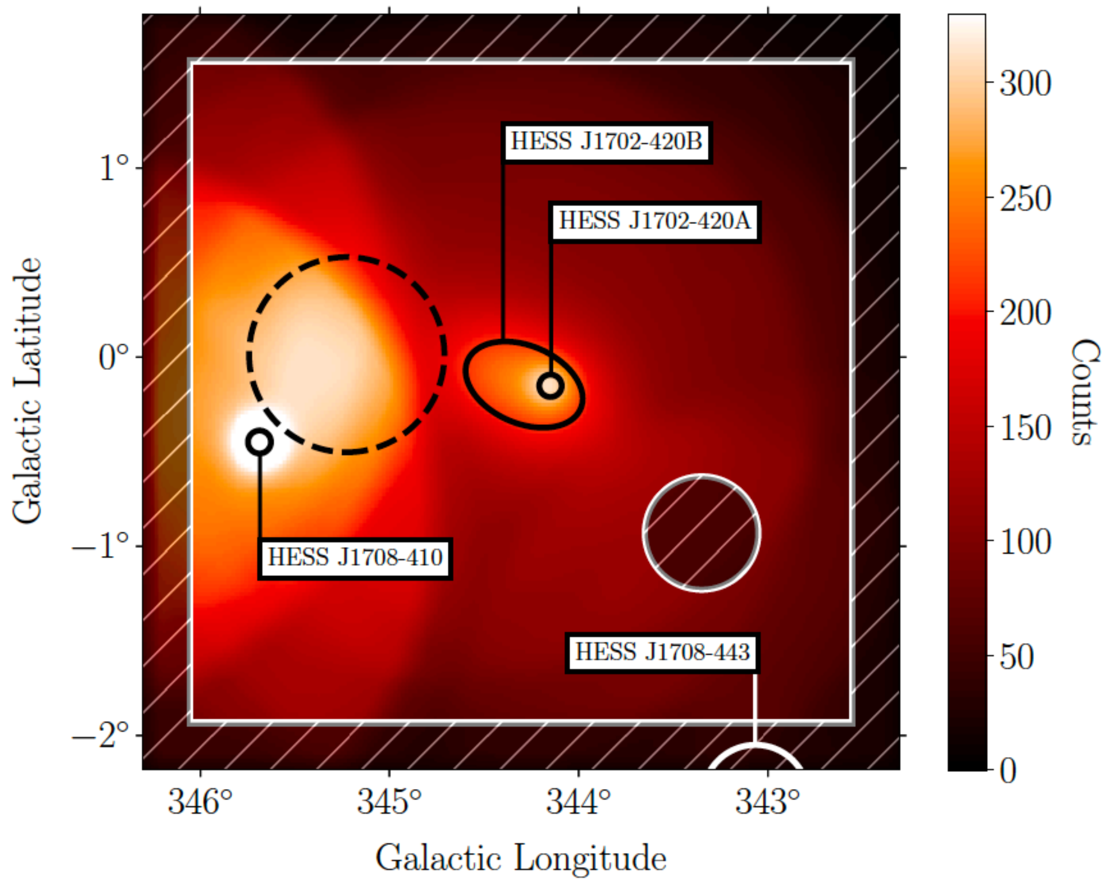
Hard sources in the HGPS:

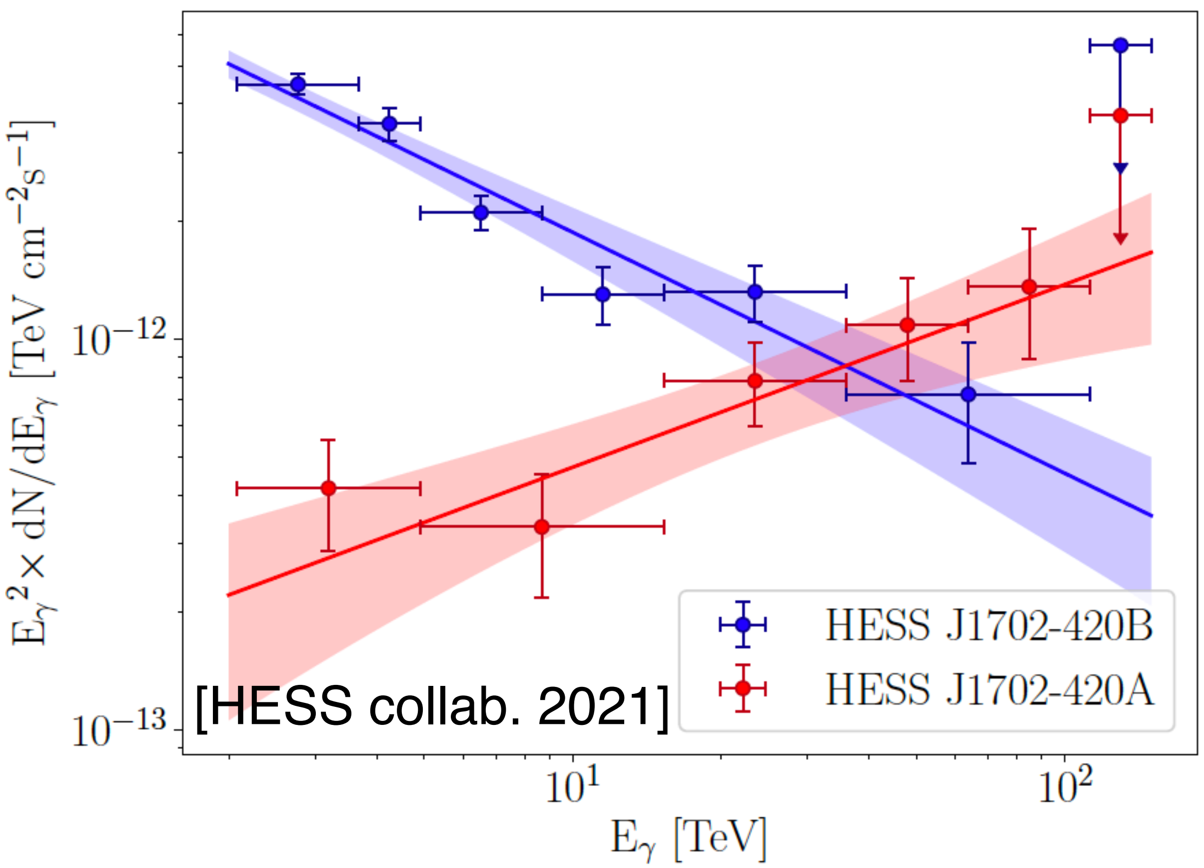
~ 17/47 UNID with flux points > 10 TeV and no cutoff detected

Other PeVatron candidates



Other PeVatron candidates — HESS J1702—420





First spectro-morphological analysis (3D) at VHE with Gammapy
➡ allows to separate components with different spectral shape

No evident MWL counterparts for HESS J1702—420A and HESS J1702–420B

For HESS J1702—420A: $E_{max,e} > 64$ TeV (PLEC)
$E_{max,p} > 0.55$ PeV (PLEC)

➡ One of the most solid PeVatron candidates detected so far in HESS data

Conclusions and potential future outcomes

- **Evidences for proton acceleration in SNRs but E_{max} << PeV** even for the youngest SNRs. Are these objects already too evolved?

  ➡ **CTA might detect gamma-ray emission from extragalactic core-collapse supernovae** to probe the maximum energy reached by particles in the first stage of evolution (< 1 yr) [CTA consortium paper in prep.]

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- **Star forming regions (like Cygnus Cocoon) could act as proton PeVatrons** (mulitple past supernovae or collective winds from stars)

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  ➡ **emission from SNRs? PWNe? SFRs? (main sources of UHE emission?)**

- The improved sensitivity of CTA will significantly increase the sample of known SNRs and PWNe in the Milky Way, providing a better understanding of these sources
  ➡ **detection of escaping CRs from dynamically young SNRs?**

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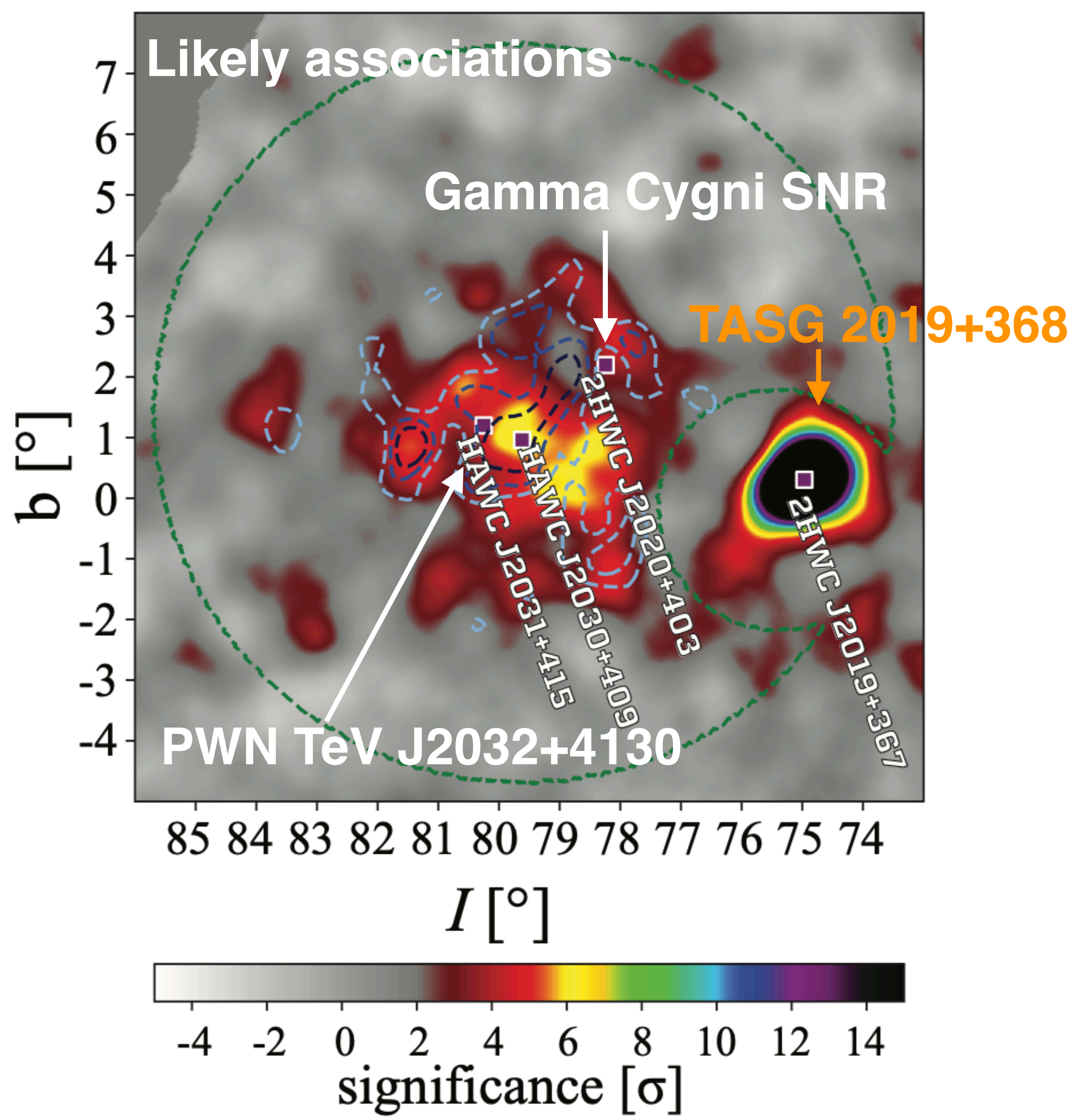
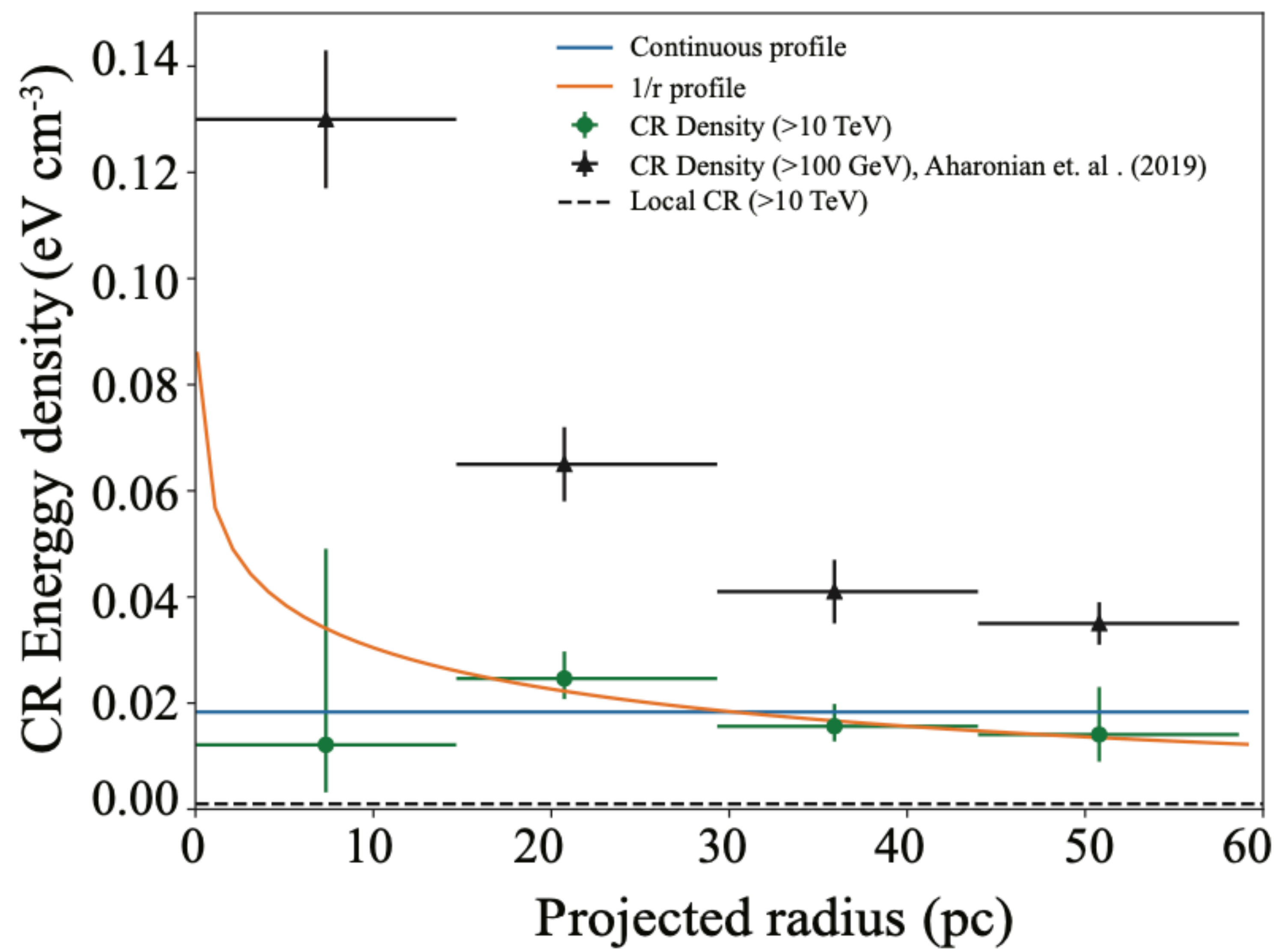
- Multiwavelength observations (radio, X-ray) of the PeVatron candidates will help identify them and contrain the origin of the emission (leptonic/hadronic), as neutrino detections

BACKUP SLIDES

UHE emission from the Cygnus Cocoon

[HAWC collab. 2021]



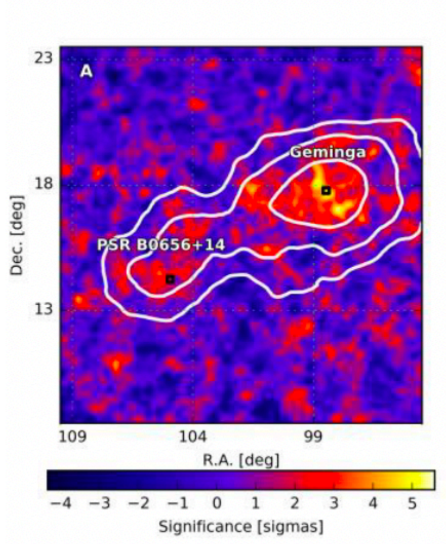


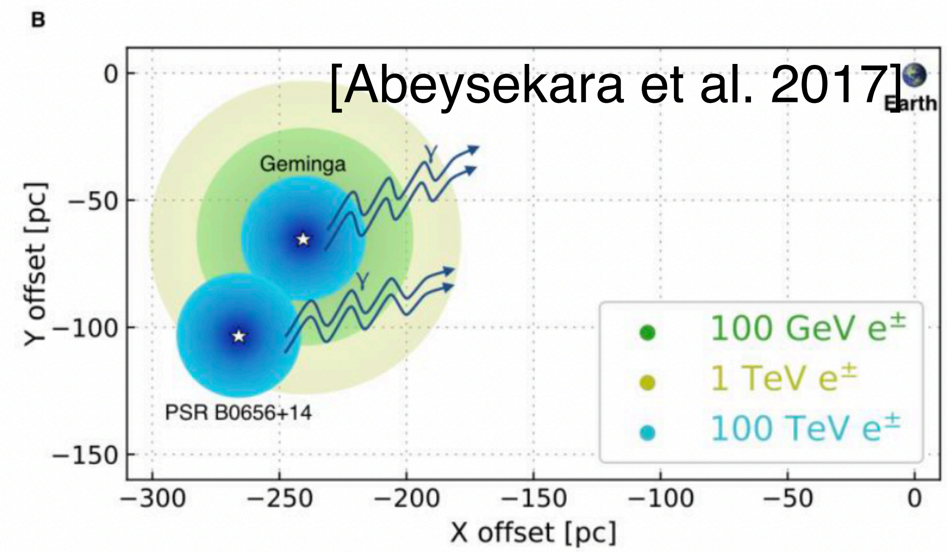
- **Enhanced CR density** (nearby accelerator, not due to CR sea)
- 1/r profile: continuous injection vs constant profile: burst-like event (like a supernova event) ==> **Both profiles agree with data**
- 1/r profile less stiking for TeV CRs because of their shorter escape time

VHE emission from PWN halos

PWN halos: gamma rays produced by Inverse Compton scattering of e-/e+ that were accelerated by a pulsar/PWN and diffuse in the interstellar medium

TeV PWN halos around Geminga and Monogem first detected by HAWC:

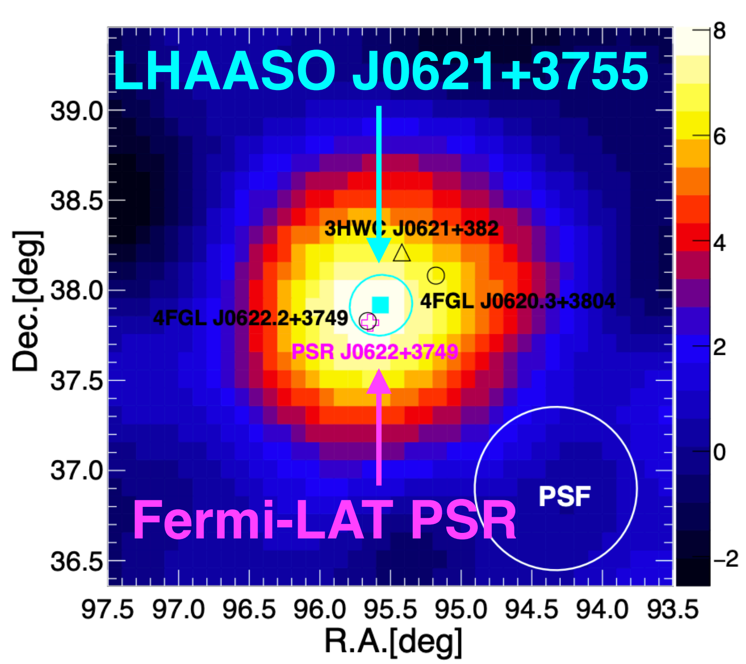


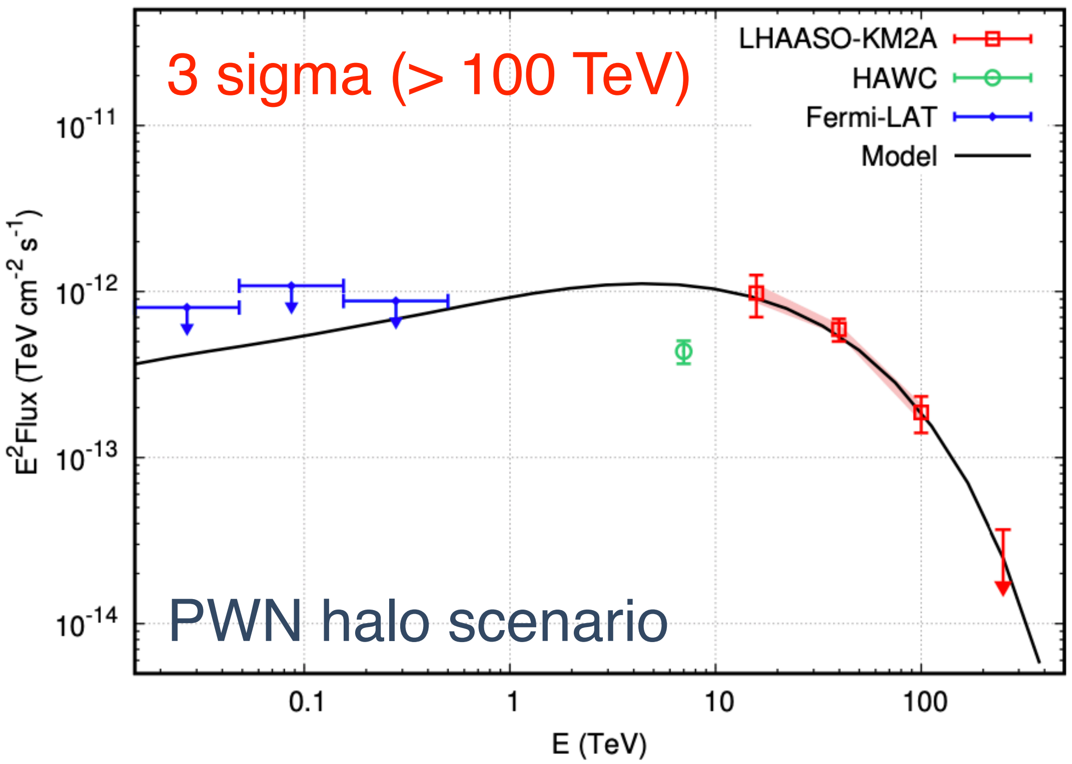


[Abeysekara et al. 2017]

Possible detection of a PWN halo by LHAASO (diffusion template works as a Gaussian template; no counterpart found but OK when taking X-ray flux for Monogem)

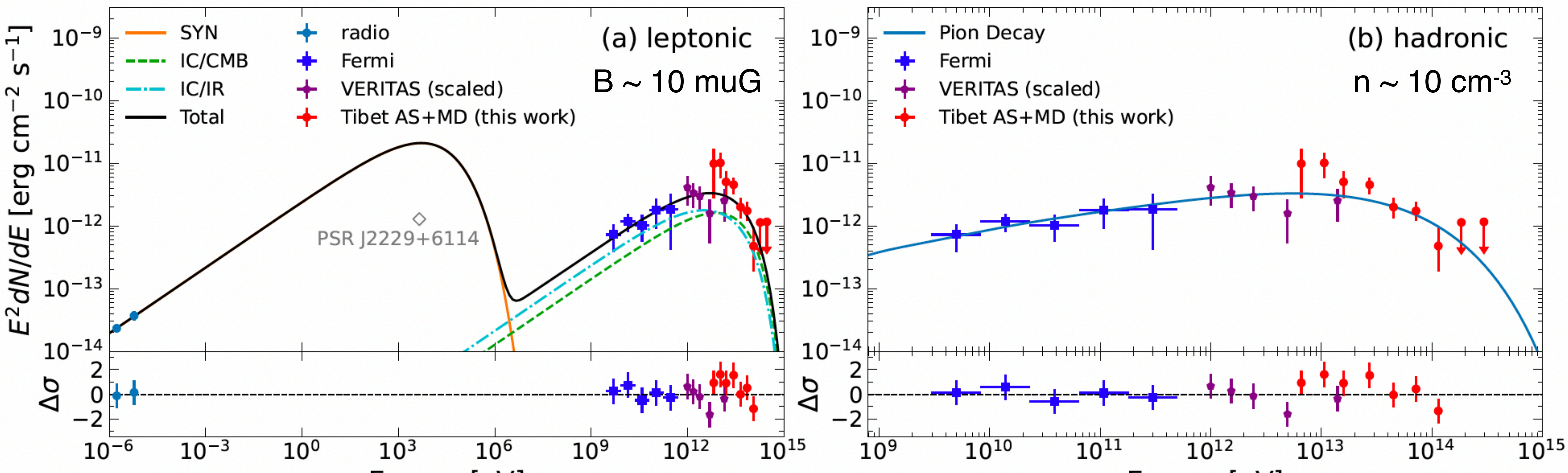
[Aharonian et al. 2021]





J. Devin

Detection of UHE emission towards G106.3+2.7



[Tibet ASg collab. 2021]

$$\alpha = 2.30^{+0.08}_{-0.07} \qquad E_{\rm cut} = 190^{+127}_{-66}\ \mathrm{TeV}$$

$$\alpha = 1.79^{+0.08}_{-0.09} \qquad E_{\rm cut} = 499^{+382}_{-180}\ \mathrm{TeV}$$

e- freshly accelerated within t_{sync} ~ 1 kyr

Possibly $E_{cut,p}$ ~1.6 PeV (at 1 kyr) but hard spectrum difficult to explain

(PWN scenario still very plausible)

Both hadronic and leptonic models work:

➡ Need X-ray observations to constrain the synchrotron spectrum

➡ CTA (with a better PSF) will help understand the origin of the emission (**SNR/PWN**)

J. Devin