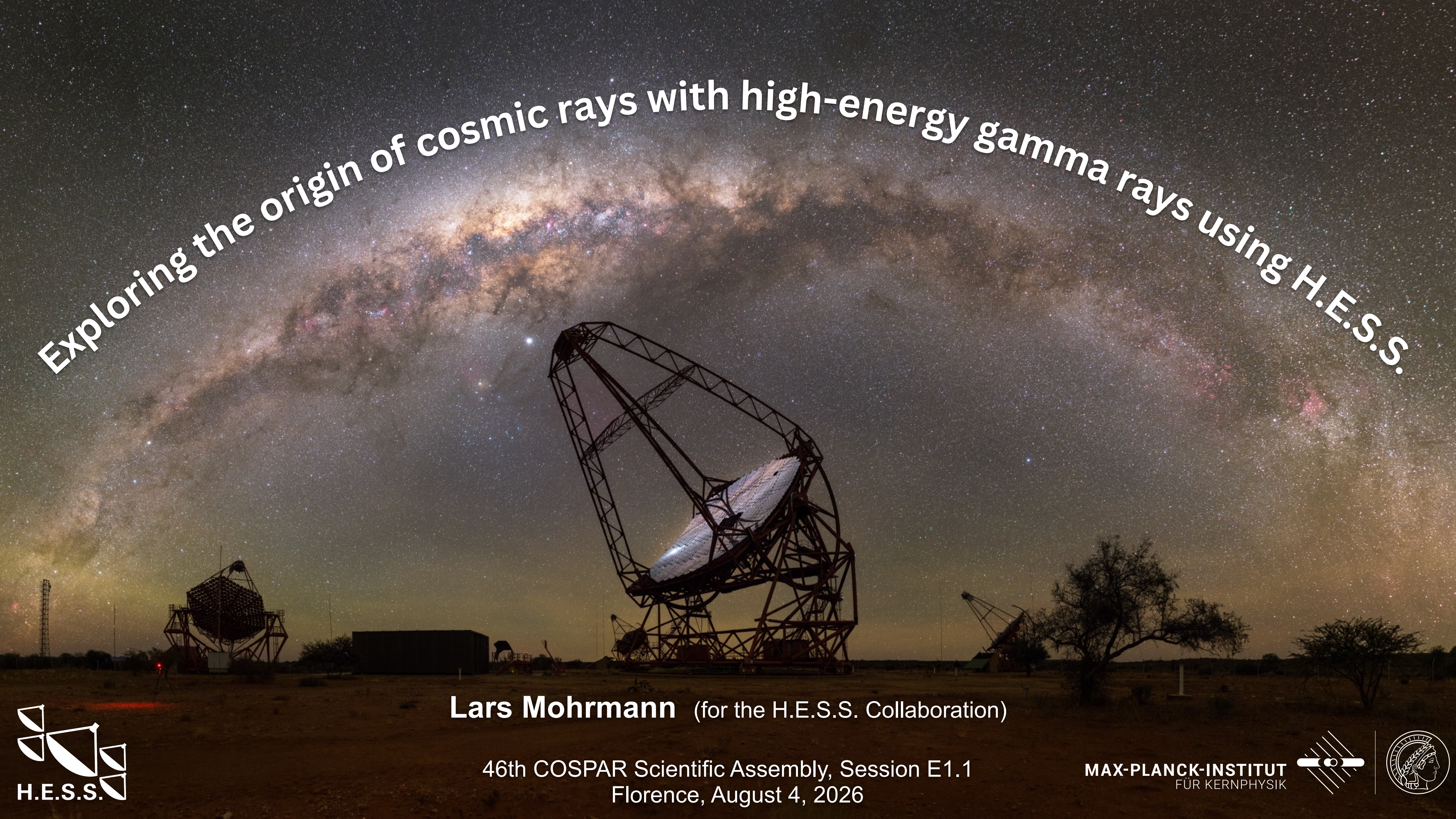




Exploring the origin of cosmic rays with high-energy gamma rays using H.E.S.S.

Lars Mohrmann (for the H.E.S.S. Collaboration)

46th COSPAR Scientific Assembly, Session E1.1
Florence, August 4, 2026



MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK



High Energy Stereoscopic System (H.E.S.S.)

Khomas Highland, Namibia



High Energy Stereoscopic System (H.E.S.S.)

Khomas Highland, Namibia



12-m telescopes — since 2004
(upgraded 2016)

High Energy Stereoscopic System (H.E.S.S.)

Khomas Highland, Namibia

28-m telescope — since 2012
(upgraded 2019)

12-m telescopes — since 2004
(upgraded 2016)



High Energy Stereoscopic System (H.E.S.S.)

Khomas Highland, Namibia

Energy range:
~50 GeV – 100 TeV
(VHE)

28-m telescope — since 2012
(upgraded 2019)

12-m telescopes — since 2004
(upgraded 2016)



High Energy Stereoscopic System (H.E.S.S.)

Khomas Highland, Namibia

28-m telescope — since 2012
(upgraded 2019)

Energy range:
~50 GeV – 100 TeV
(VHE)

Excellent resolution:
- angular ($\lesssim 0.1^\circ$)
- energy ($\lesssim 20\%$)

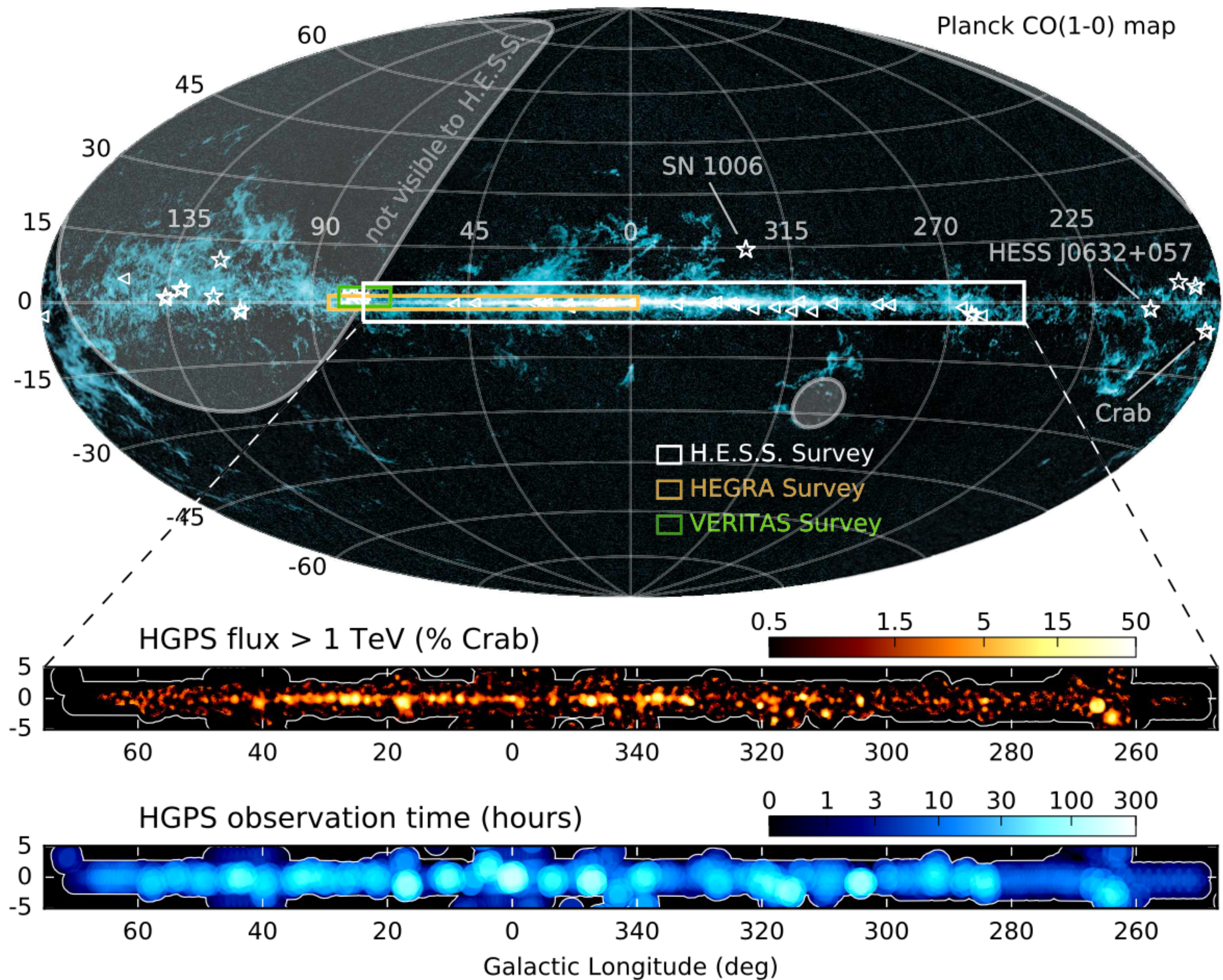
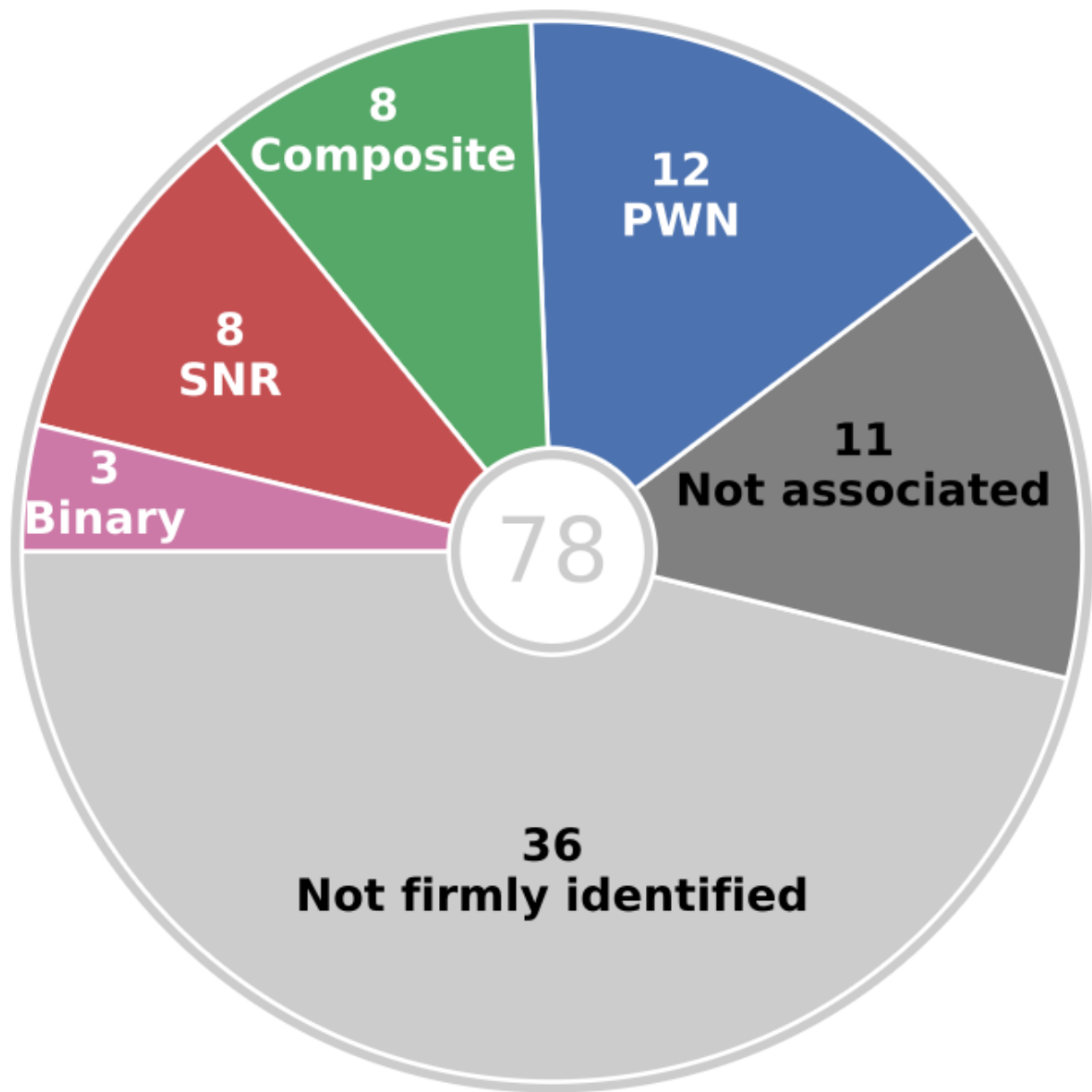
12-m telescopes — since 2004
(upgraded 2016)



The H.E.S.S. Galactic Plane Survey (HGPS)

H.E.S.S. 2018
A&A 612, A1

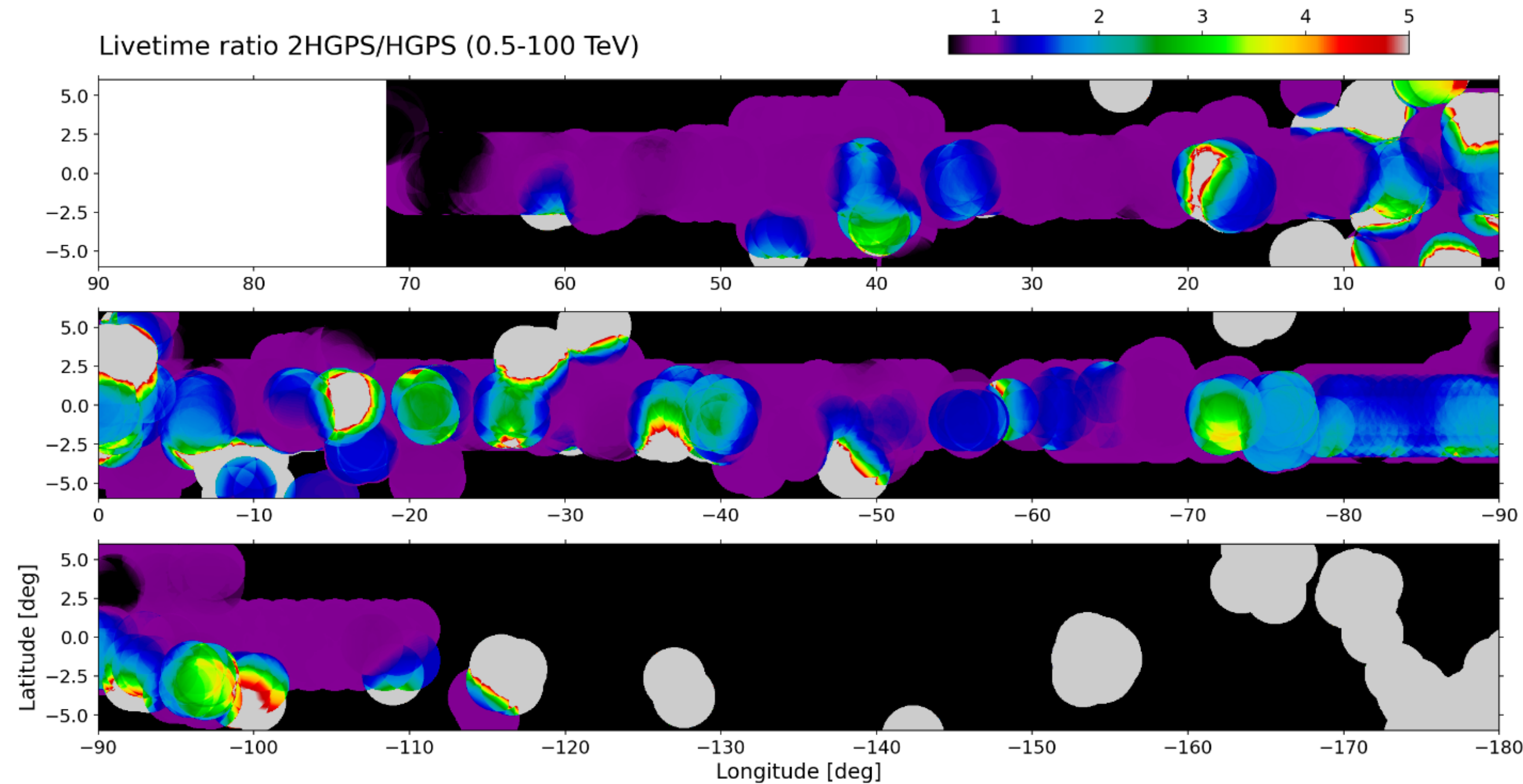
- **Largest VHE survey carried out to date**
 - 2004–2013 (2673 hours of observation)
- **Sensitivity better than 2% Crab**
in range $l = 283^\circ$ to 58°
- **78 sources**
 - many unidentified



Coming soon — the 2HGPS!

Remy et al. on behalf of H.E.S.S.,
ICRC 2023

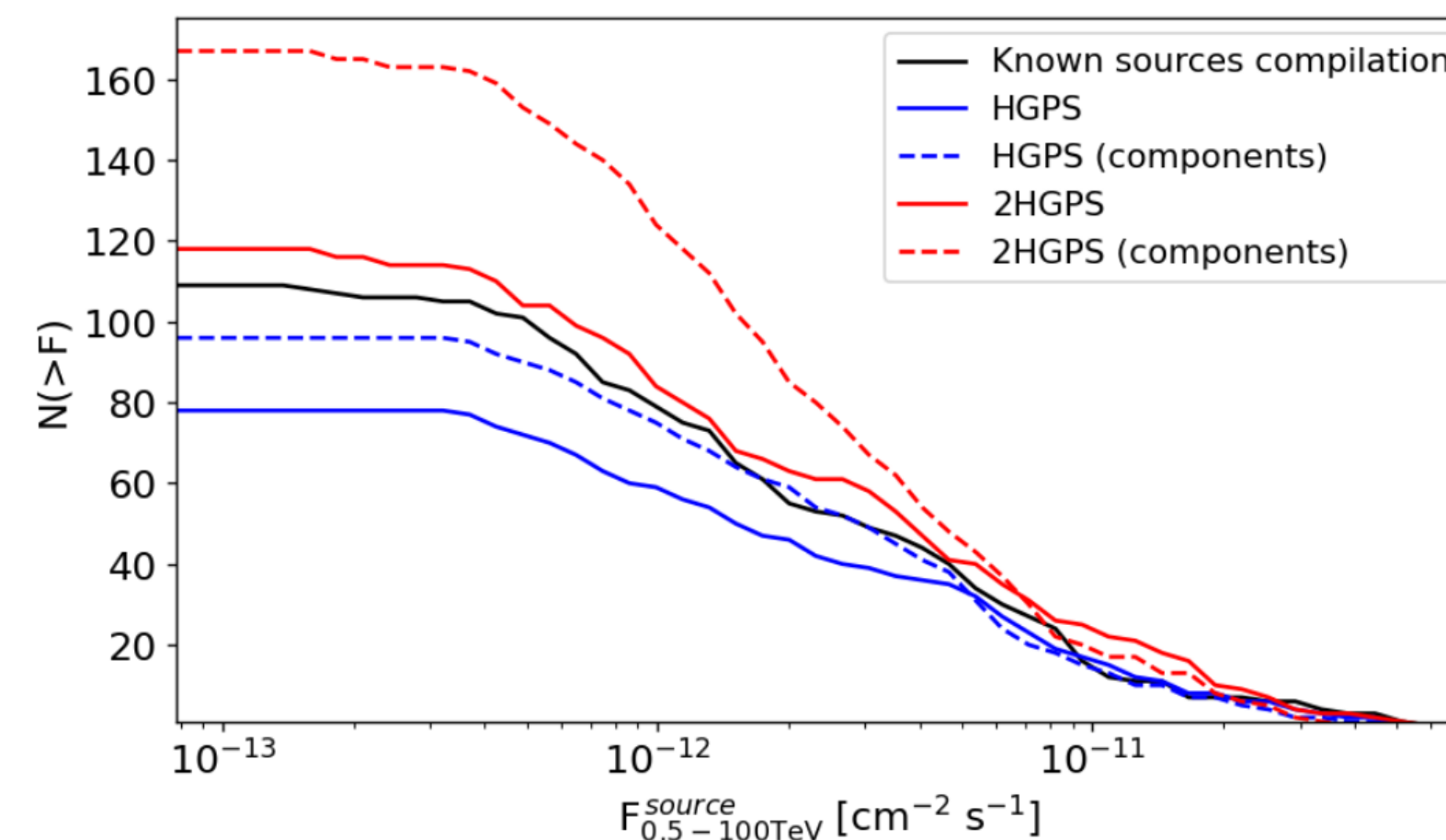
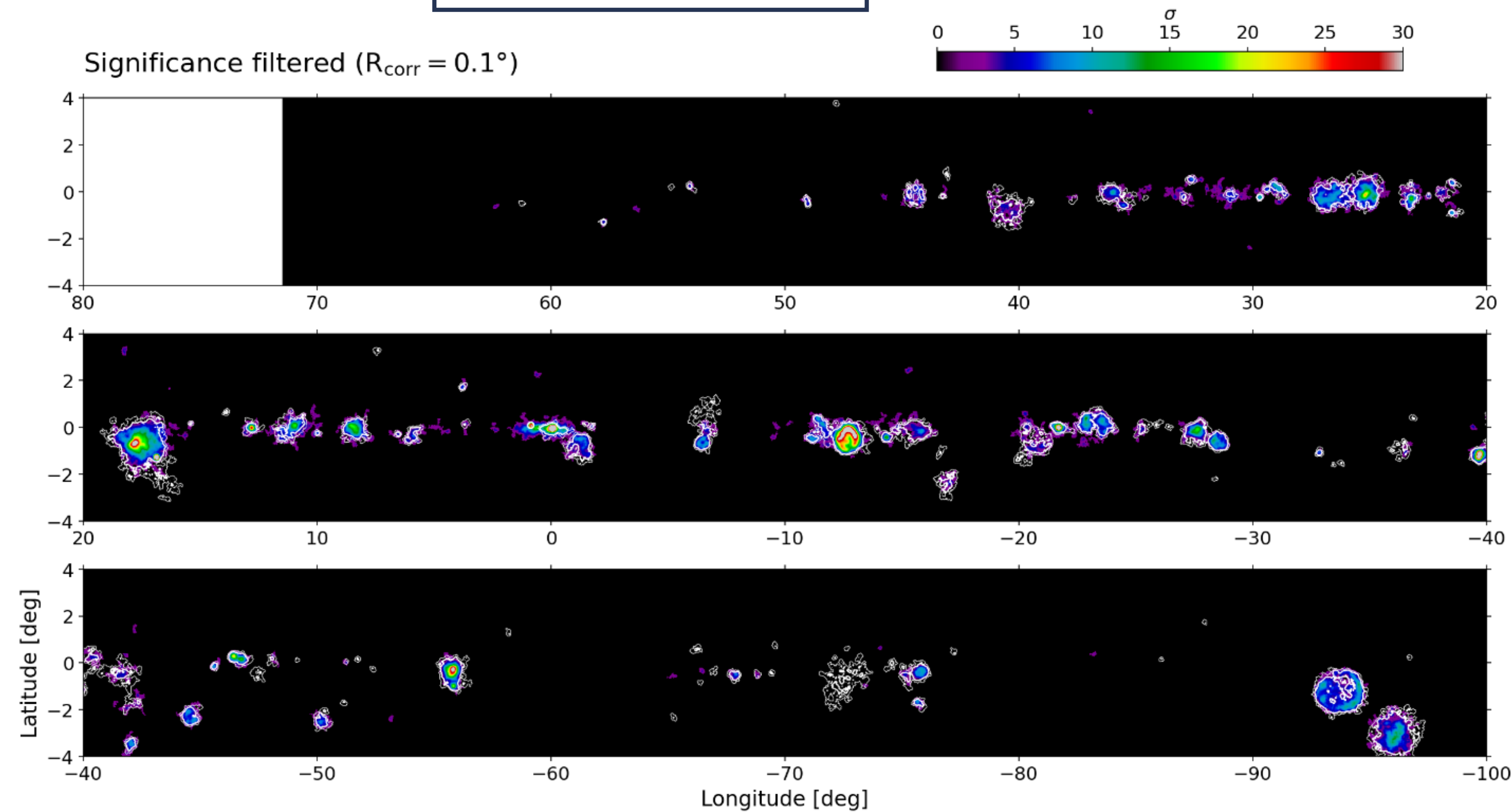
- **Improved event reconstruction**
 - template-based likelihood fit
- **Better treatment of backgrounds**
 - field-of-view hadronic background model
 - physically motivated diffuse emission model
- **More sophisticated modelling**
 - full 3D spectro-morphological analysis
- **Larger data set**
 - 2004–2019 (5171 hours of observation)



Coming soon — the 2HGPS!

Remy et al. on behalf of H.E.S.S.,
ICRC 2023

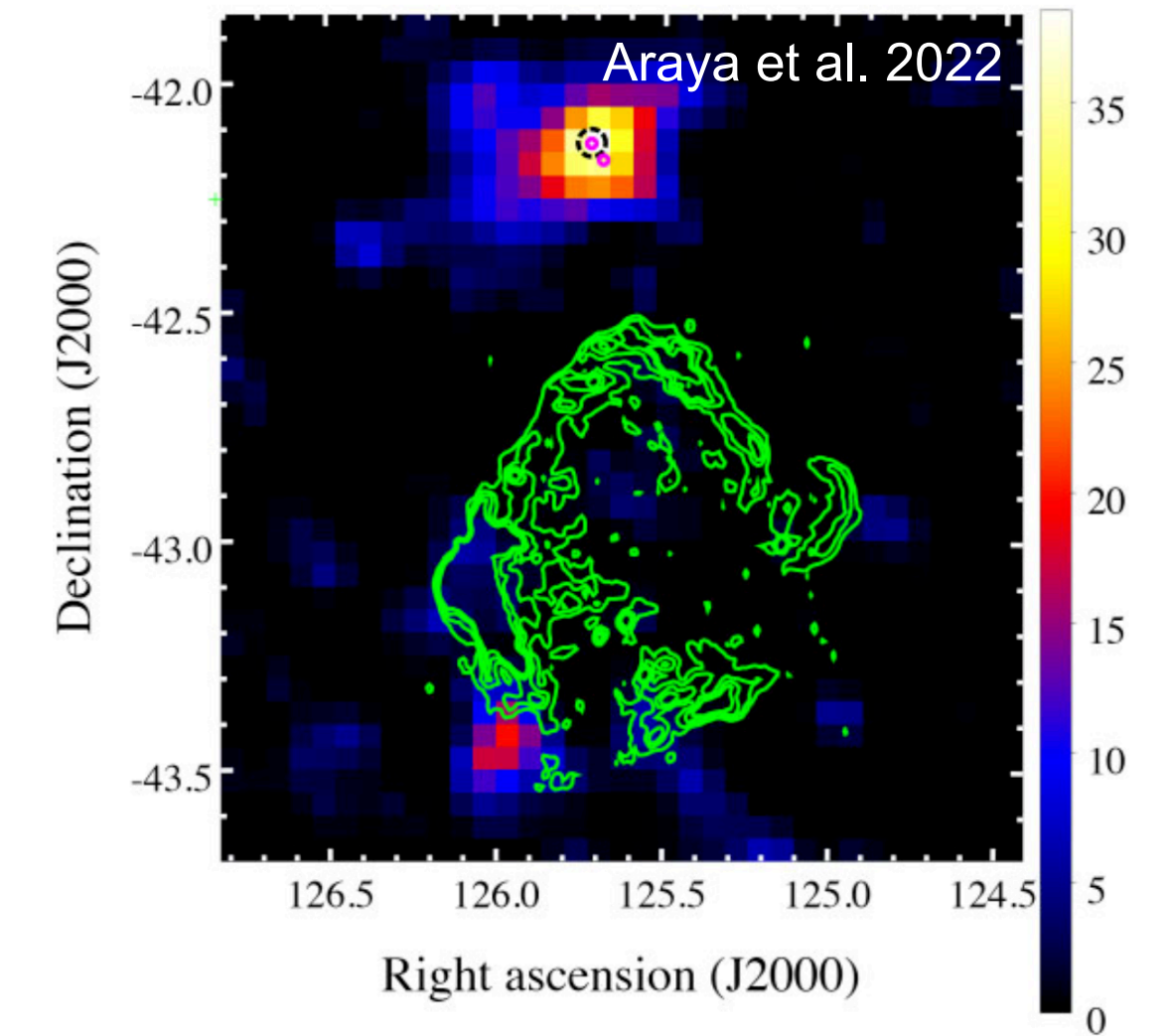
- **Improved event reconstruction**
 - template-based likelihood fit
- **Better treatment of backgrounds**
 - field-of-view hadronic background model
 - physically motivated diffuse emission model
- **More sophisticated modelling**
 - full 3D spectro-morphological analysis
- **Larger data set**
 - 2004–2019 (5171 hours of observation)
- **More sources**
 - ~120 sources / ~170 components
- **Paper in preparation**
 - comprehensive release of auxiliary data sets planned



4FGL J0822.8–4207 — the first TeV detection of a young stellar object?

■ 4FGL J0822.8–4207

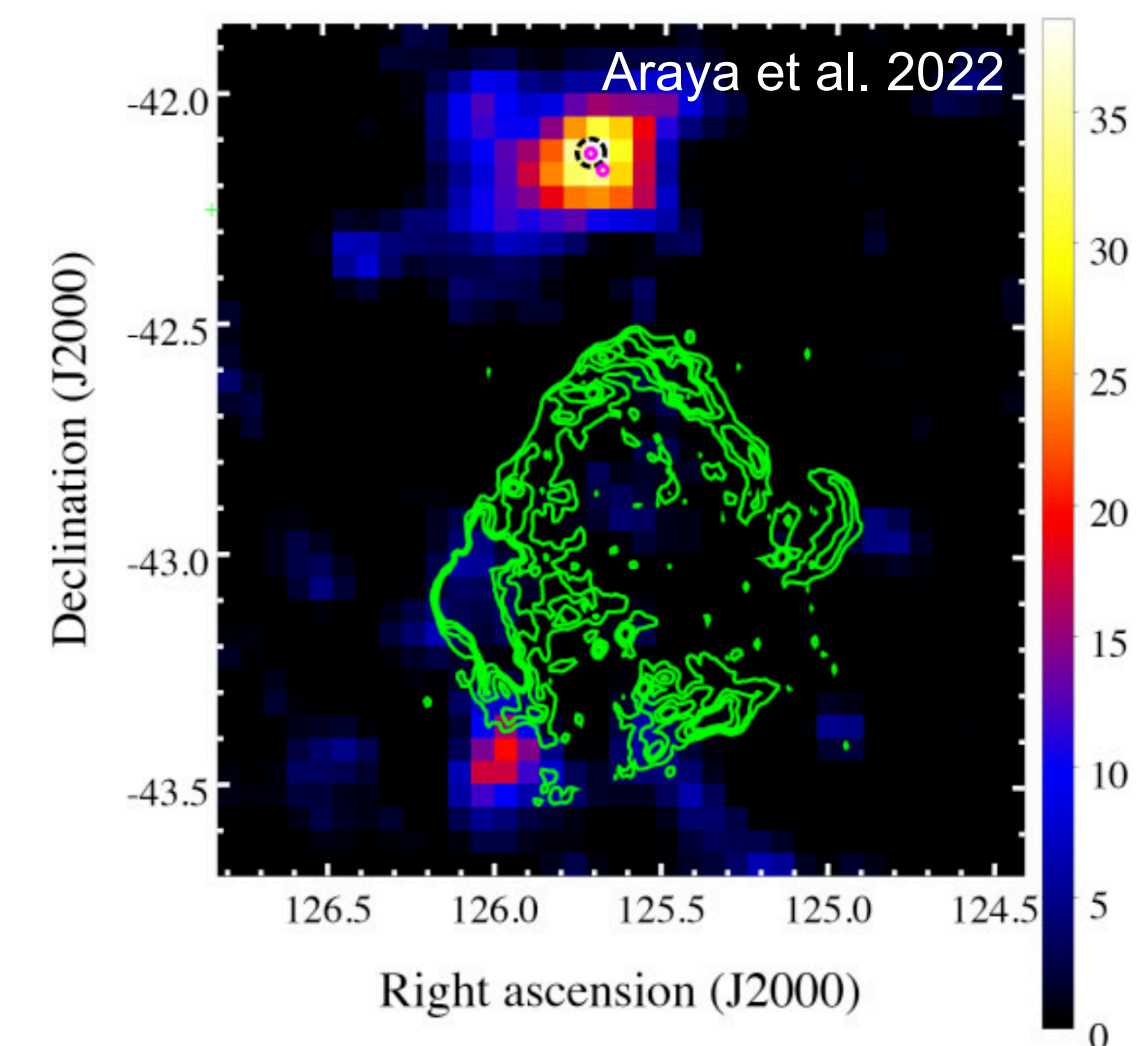
- ▶ point-like source in 4FGL-DR2 catalogue, $\sim 0.5^\circ$ north of Puppis A
- ▶ Araya et al. 2022: coincident with a YSO (IRAS 08211–4158) & molecular cloud
→ two scenarios considered:
 - CRs escape from Puppis A;
 - CRs are accelerated in-situ by YSO



4FGL J0822.8–4207 — the first TeV detection of a young stellar object?

■ 4FGL J0822.8–4207

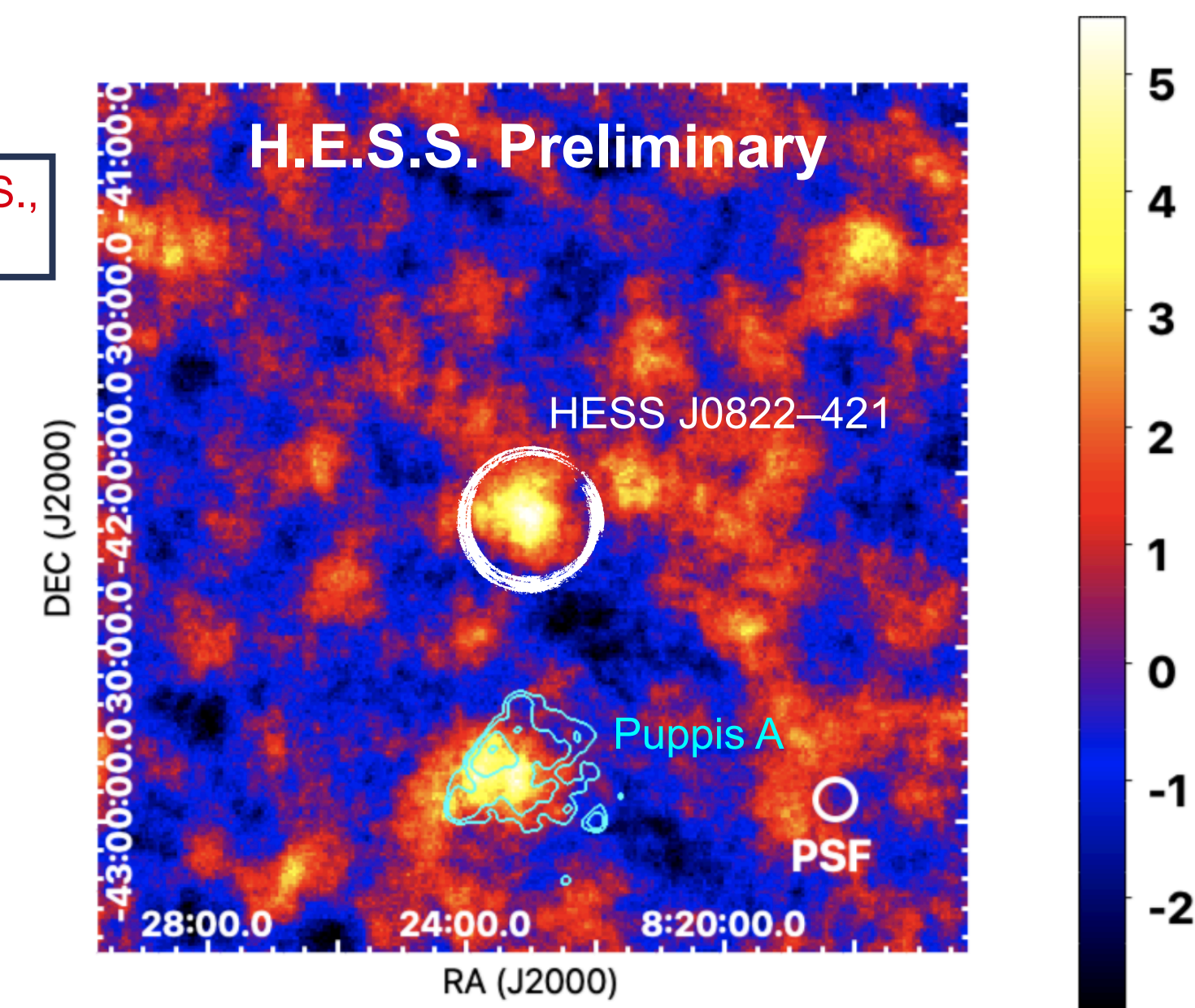
- ▶ point-like source in 4FGL-DR2 catalogue, $\sim 0.5^\circ$ north of Puppis A
- ▶ Araya et al. 2022: coincident with a YSO (IRAS 08211–4158) & molecular cloud
→ two scenarios considered:
 - CRs escape from Puppis A;
 - CRs are accelerated in-situ by YSO



■ HESS J0822–421 (new!)

- ▶ TeV detection of 4FGL J0822.8–4207 (5.3σ in ~ 87 hours)
- ▶ marginally extended (4.1 arcmin / 1.8 pc)
- ▶ spectral index -2.8
- ▶ (hint of signal from Puppis A but still below detection threshold)

Vink et al. on behalf of H.E.S.S.,
EAS 2026

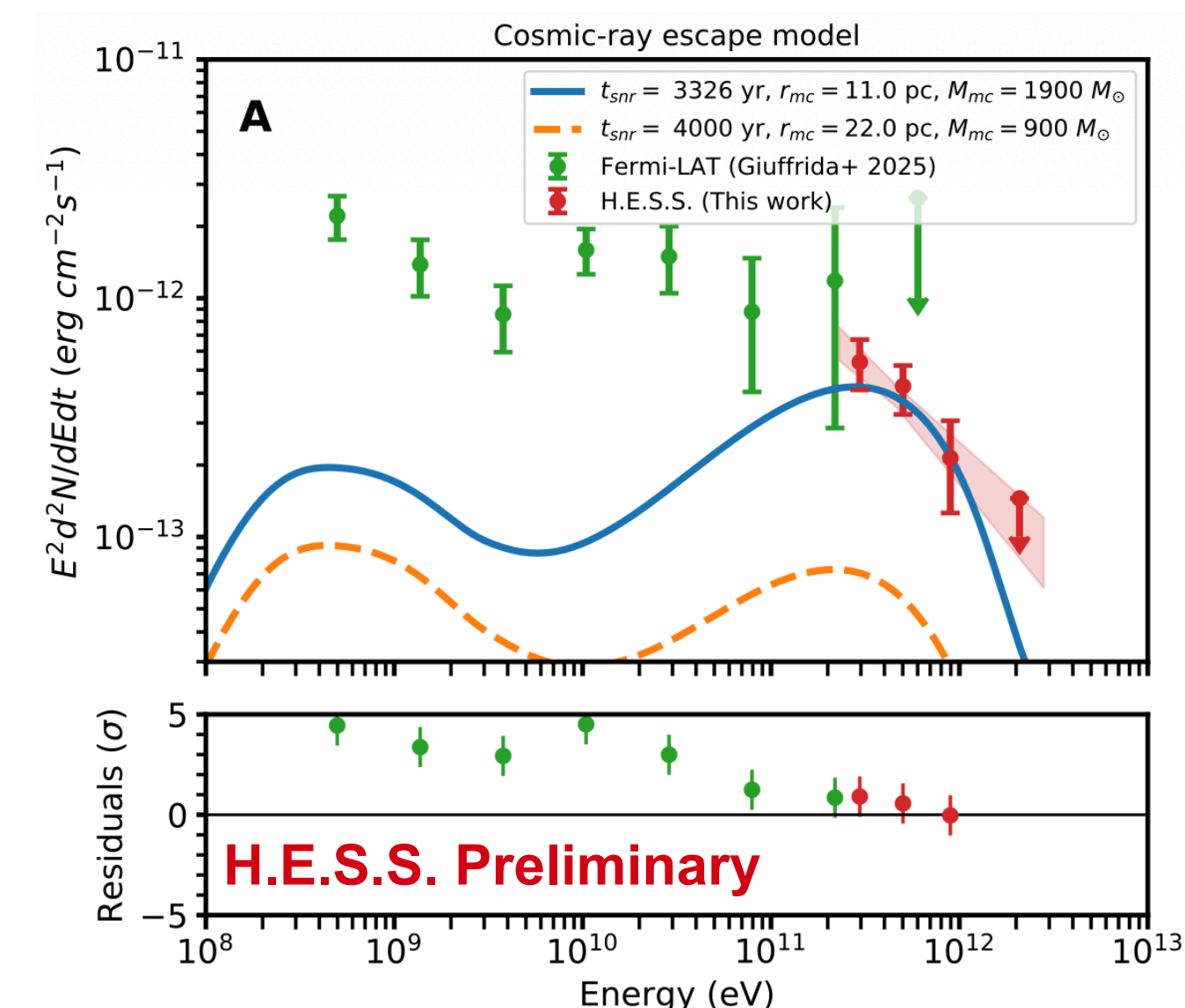


4FGL J0822.8–4207 — the first TeV detection of a young stellar object?

■ Escape scenario

- ▶ assume 10% of SN energy (10^{51} erg) available for CR acceleration + energy-dependent diffusion
 - ▶ cannot fit GeV + TeV SED
 - ▶ other molecular clouds nearby are not detected with H.E.S.S.
 - ▶ GeV SED of Puppis A not suggestive of significant escape of low-energy CRs
- scenario not favoured

Vink et al. on behalf of H.E.S.S.,
EAS 2026



4FGL J0822.8–4207 — the first TeV detection of a young stellar object?

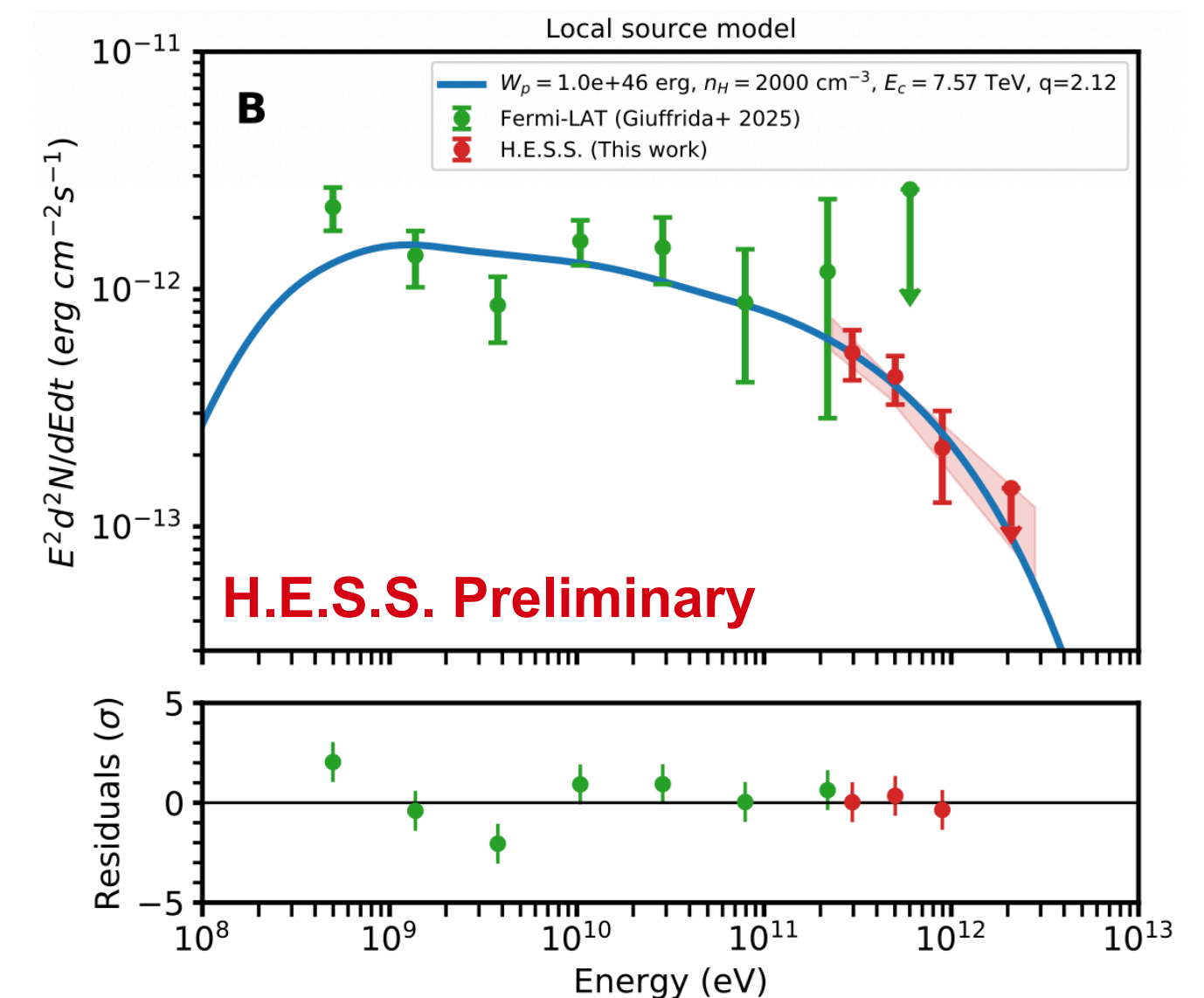
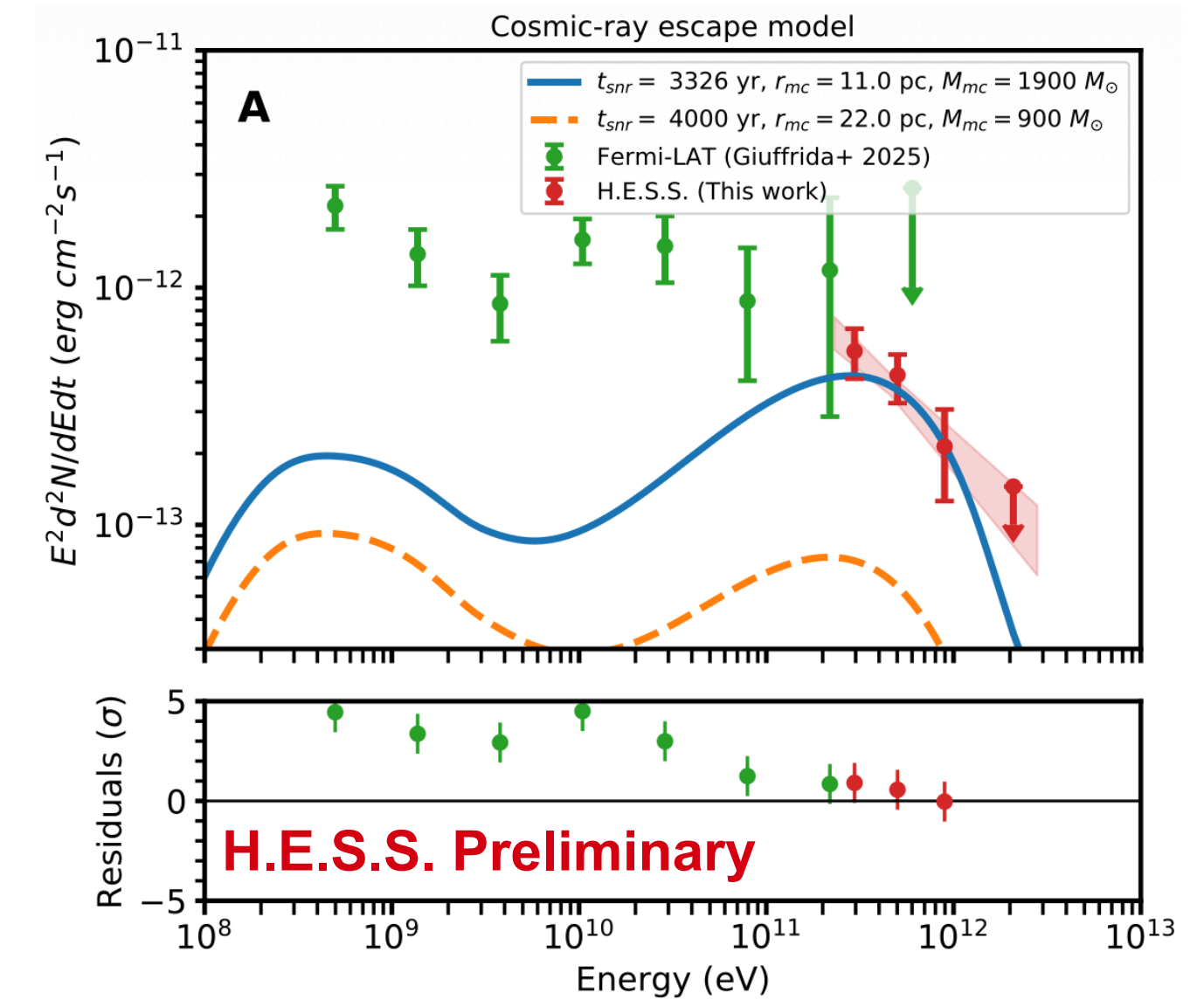
■ Escape scenario

- ▶ assume 10% of SN energy (10^{51} erg) available for CR acceleration + energy-dependent diffusion
 - ▶ cannot fit GeV + TeV SED
 - ▶ other molecular clouds nearby are not detected with H.E.S.S.
 - ▶ GeV SED of Puppis A not suggestive of significant escape of low-energy CRs
- scenario not favoured

Vink et al. on behalf of H.E.S.S.,
EAS 2026

■ Local source model (YSO)

- ▶ CRs accelerated in-situ — YSO is most energetic counterpart
 - fairly massive ($M \approx 6.5 M_{\odot}$), fairly close-by ($d \approx 1.5$ kpc)
 - two-sided jet, $v \sim 1,200 \text{ km s}^{-1}$, $L_{\text{IR}} \sim 10^3 L_{\odot}$
 - ▶ $W_p \sim 10^{46} (n/2000 \text{ cm}^{-3})^{-1} \text{ erg}$, $E_{p,\text{cut}} = 7.6^{+14.6}_{-2.5} \text{ TeV}$
 - ▶ requires 1–10% acceleration efficiency
- scenario plausible!



4FGL J0822.8–4207 — the first TeV detection of a young stellar object?

■ Escape scenario

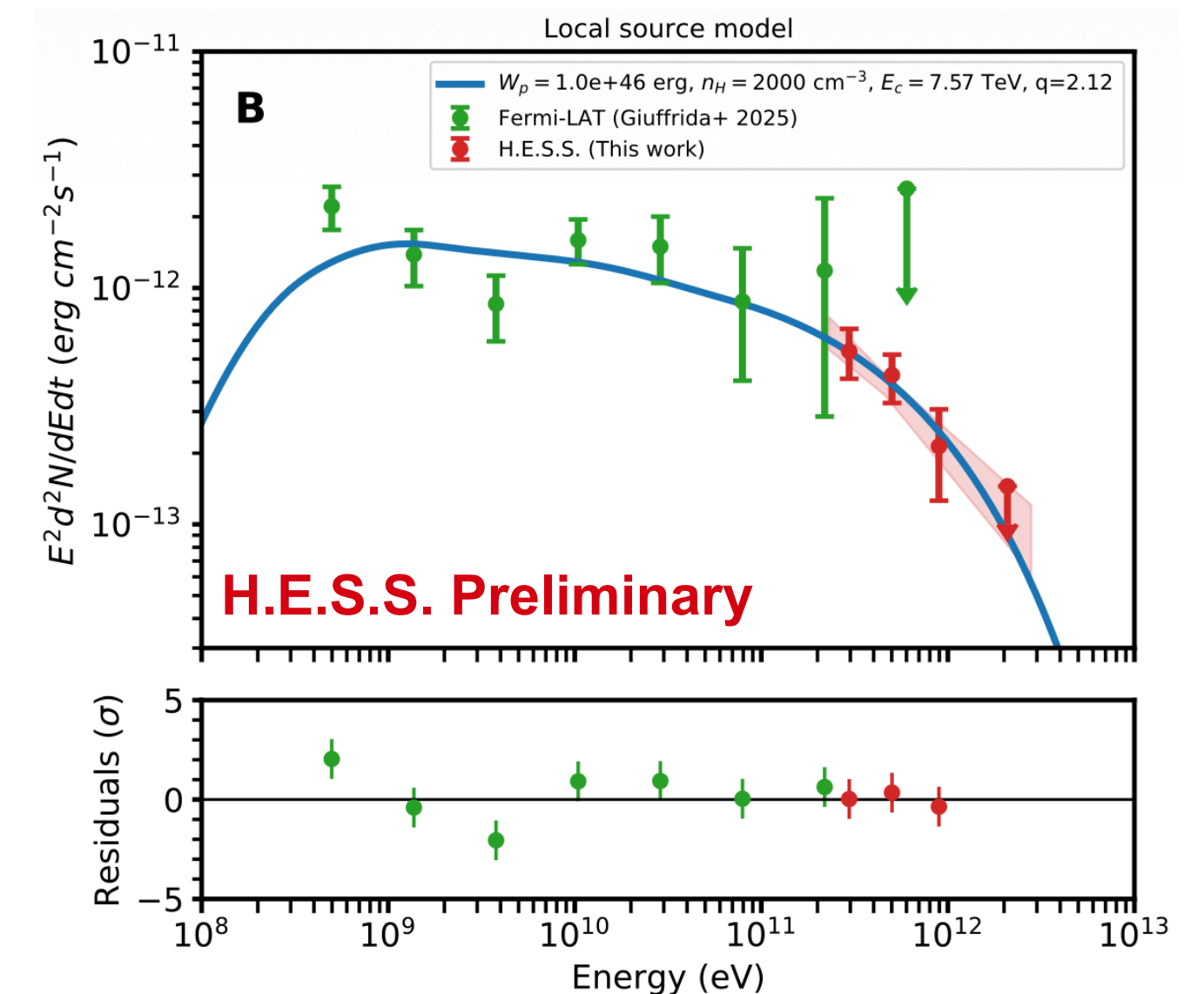
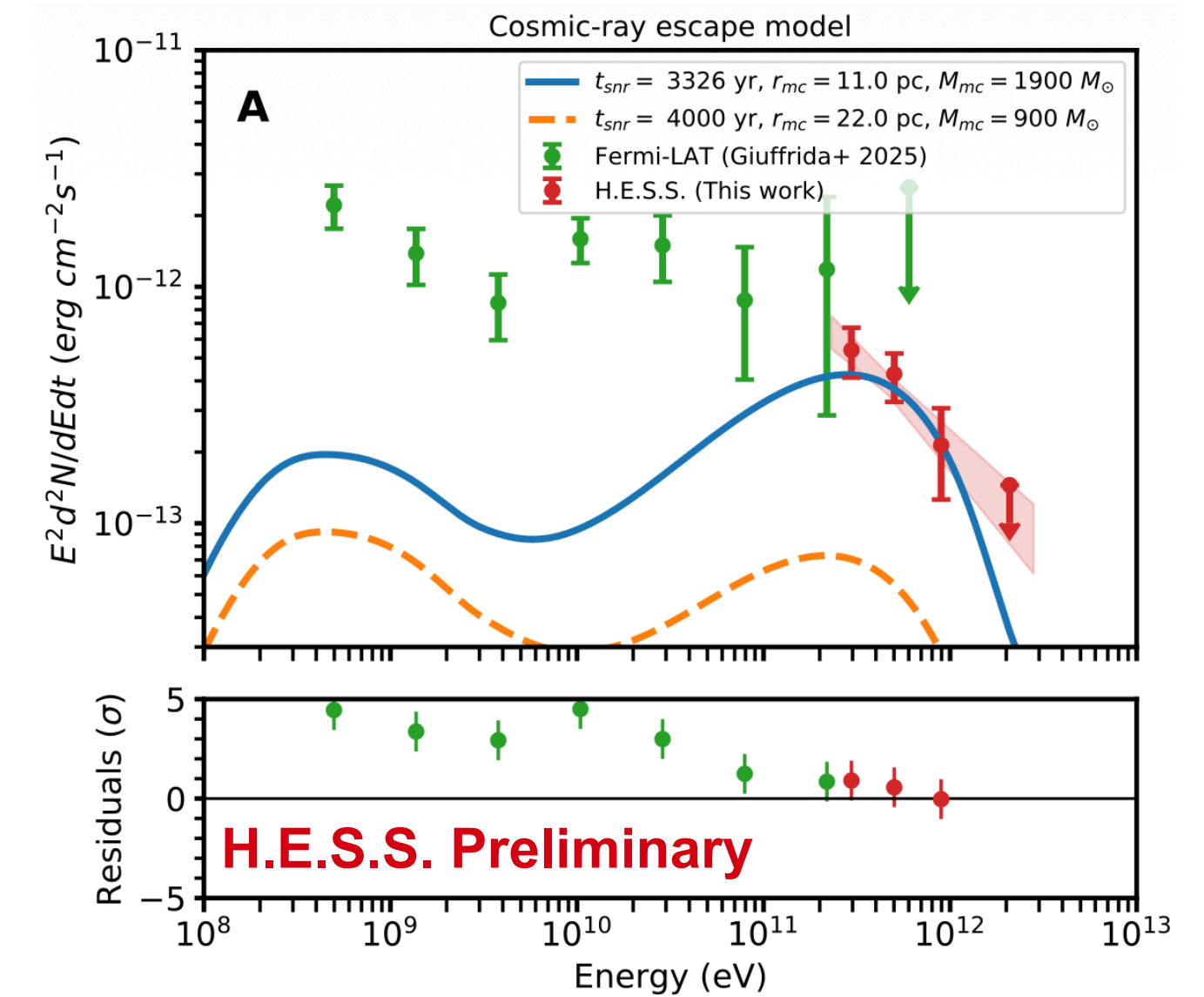
- ▶ assume 10% of SN energy (10^{51} erg) available for CR acceleration + energy-dependent diffusion
 - ▶ cannot fit GeV + TeV SED
 - ▶ other molecular clouds nearby are not detected with H.E.S.S.
 - ▶ GeV SED of Puppis A not suggestive of significant escape of low-energy CRs
- scenario not favoured

Vink et al. on behalf of H.E.S.S.,
EAS 2026

■ Local source model (YSO)

- ▶ CRs accelerated in-situ — YSO is most energetic counterpart
 - fairly massive ($M \approx 6.5 M_{\odot}$), fairly close-by ($d \approx 1.5$ kpc)
 - two-sided jet, $v \sim 1,200 \text{ km s}^{-1}$, $L_{\text{IR}} \sim 10^3 L_{\odot}$
 - ▶ $W_p \sim 10^{46} (n/2000 \text{ cm}^{-3})^{-1} \text{ erg}$, $E_{p,\text{cut}} = 7.6^{+14.6}_{-2.5} \text{ TeV}$
 - ▶ requires 1–10% acceleration efficiency
- scenario plausible!

■ If common feature of YSOs: expect feedback on star formation!



4FGL J0822.8–4207 — the fi

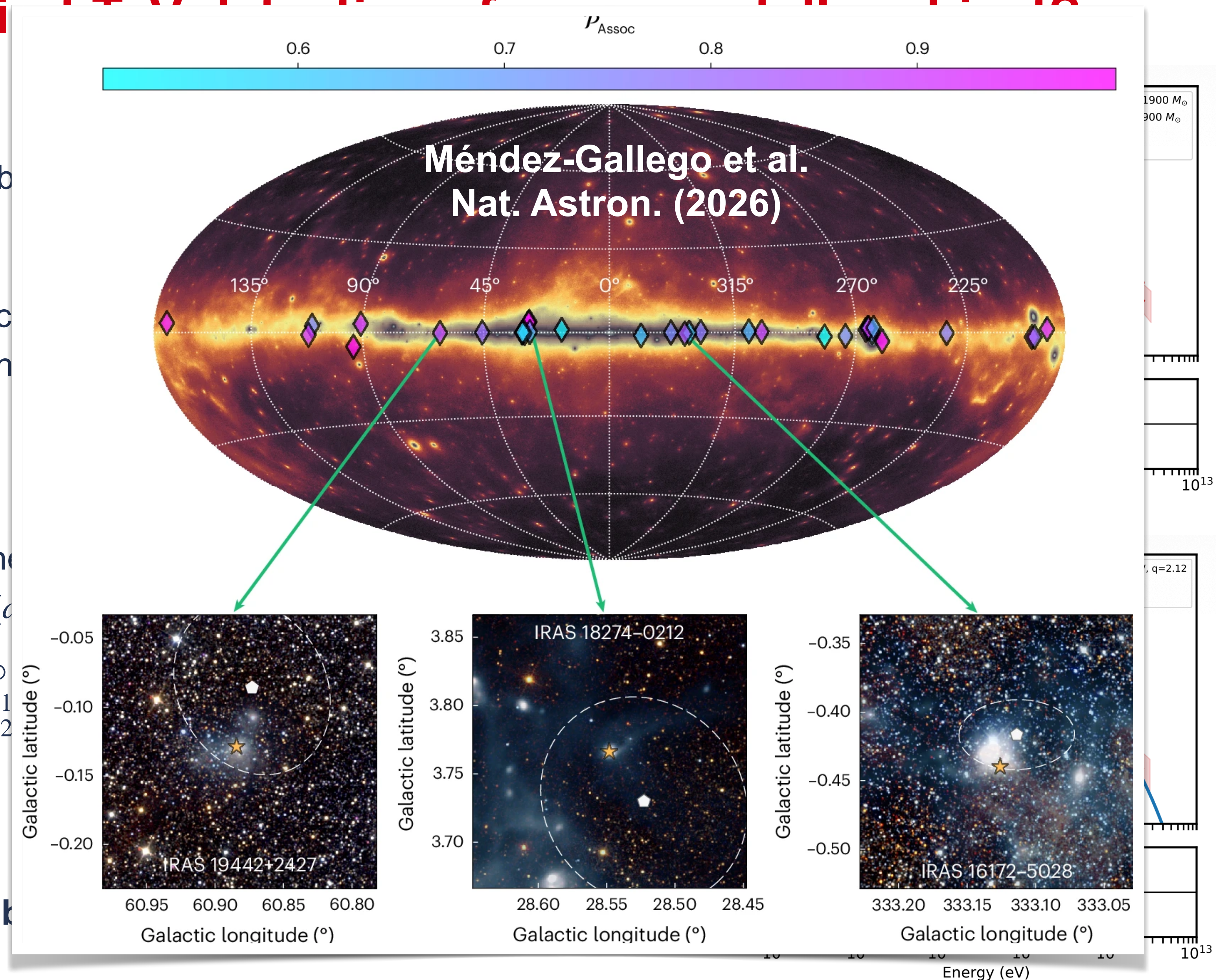
■ Escape scenario

- ▶ assume 10% of SN energy (10^{51} erg) available for energy-dependent diffusion
- ▶ cannot fit GeV + TeV SED
- ▶ other molecular clouds nearby are not detected
- ▶ GeV SED of Puppis A not suggestive of sign
- scenario not favoured

■ Local source model (YSO)

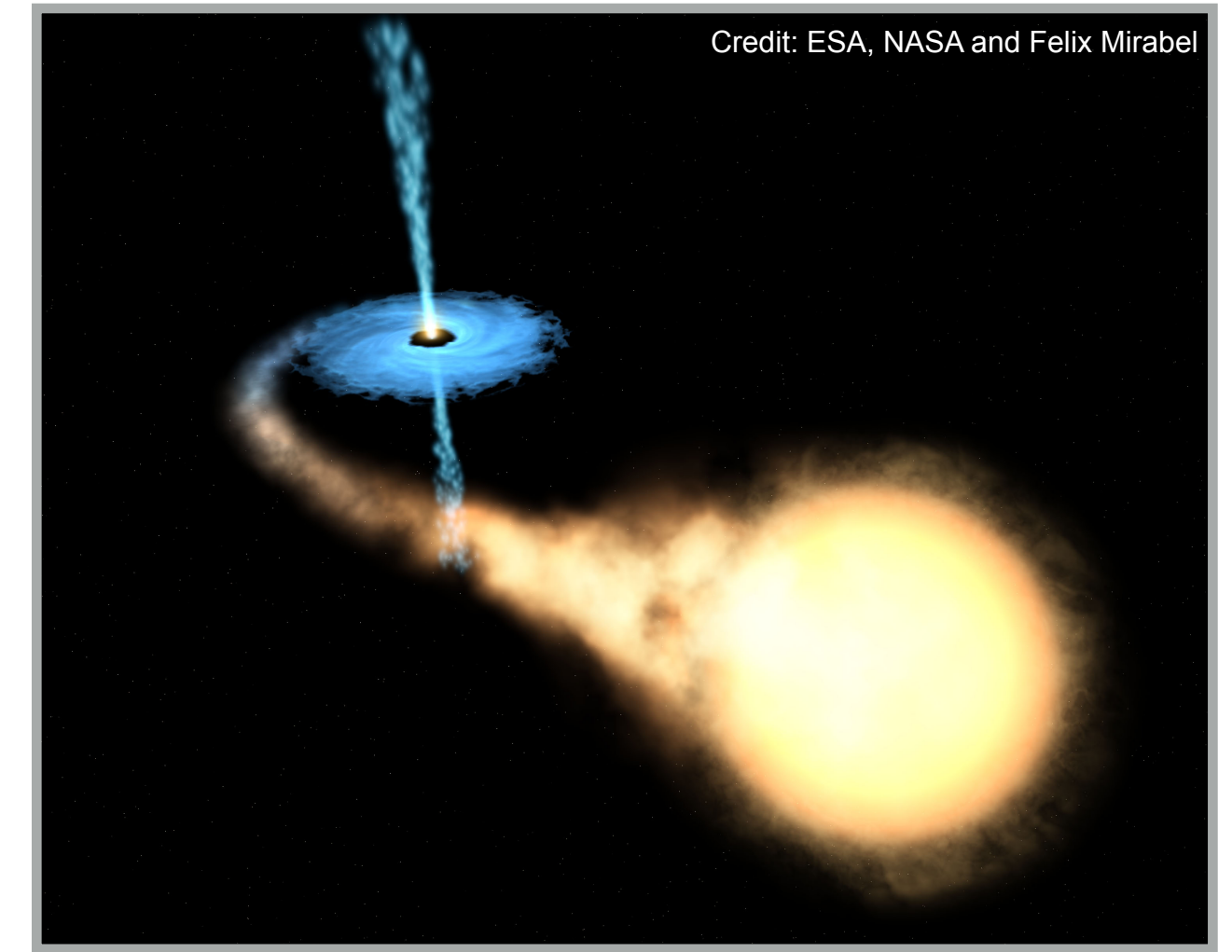
- ▶ CRs accelerated in-situ — YSO is most energetic
- fairly massive ($M \approx 6.5 M_{\odot}$), fairly close-by (distance ~ 100 pc)
- two-sided jet, $v \sim 1,200 \text{ km s}^{-1}$, $L_{\text{IR}} \sim 10^3 L_{\odot}$
- ▶ $W_p \sim 10^{46} (n/2000 \text{ cm}^{-3})^{-1} \text{ erg}$, $E_{p,\text{cut}} = 7.6^{+1.1}_{-2.2} \text{ TeV}$
- ▶ requires 1–10% acceleration efficiency
- scenario plausible!

■ If common feature of YSOs: expect feedback



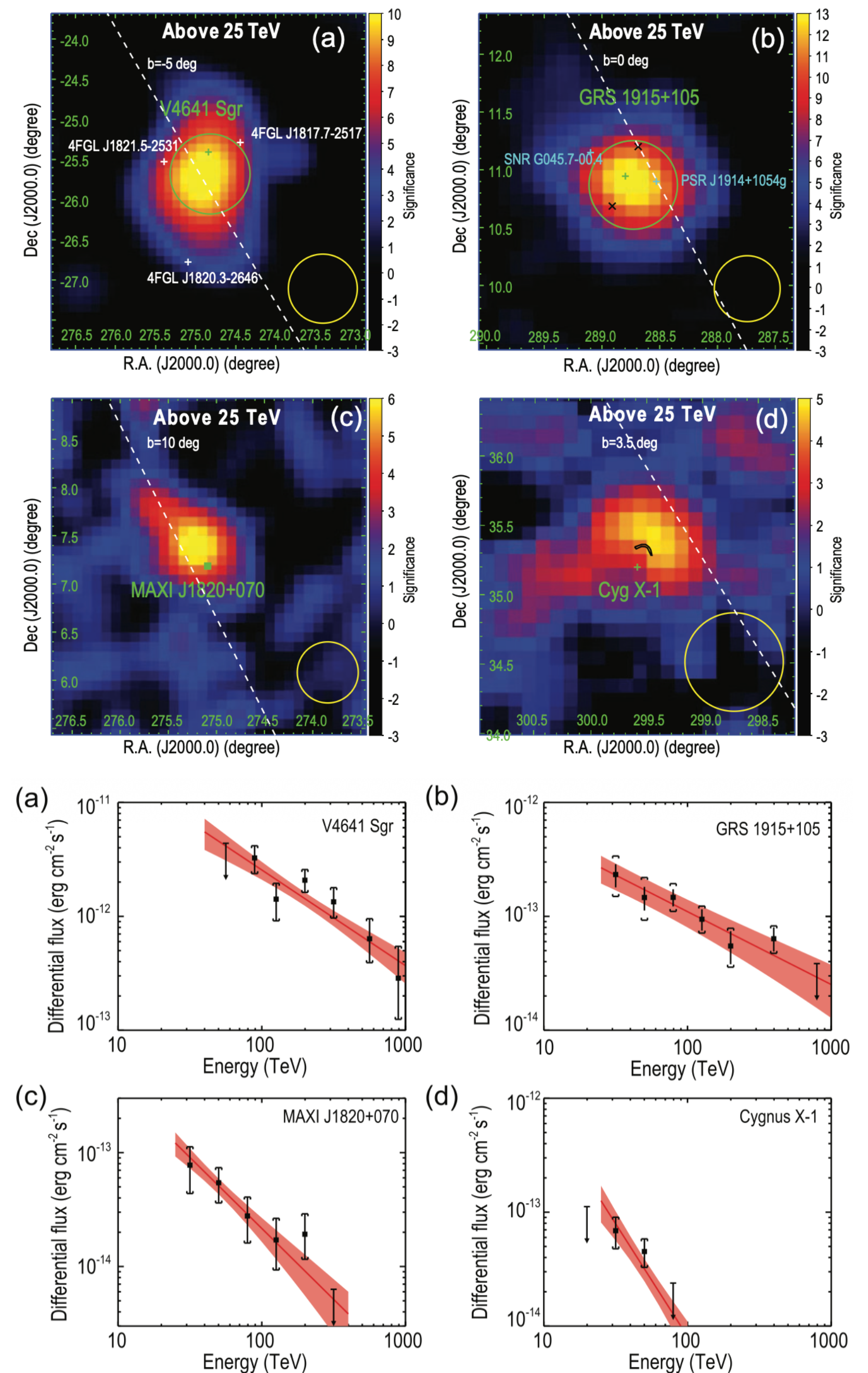
Microquasars (X-ray binaries)

- Binary system consisting of compact object and companion star
→ formation of:
 - ▶ accretion disk
 - ▶ (semi-)relativistic jets
- Long hypothesised to be *transient* gamma-ray emitters
 - ▶ (unsuccessfully) targeted after radio or X-ray flares only



Microquasars (X-ray binaries)

- Binary system consisting of compact object and companion star
→ formation of:
 - ▶ accretion disk
 - ▶ (semi-)relativistic jets
- Long hypothesised to be *transient* gamma-ray emitters
 - ▶ (unsuccessfully) targeted after radio or X-ray flares only
- Recently revealed as *persistent* UHE sources
 - ▶ HAWC 2018, 2024, LHAASO 2025
 - ▶ reaching energies of several 100 TeV in some cases



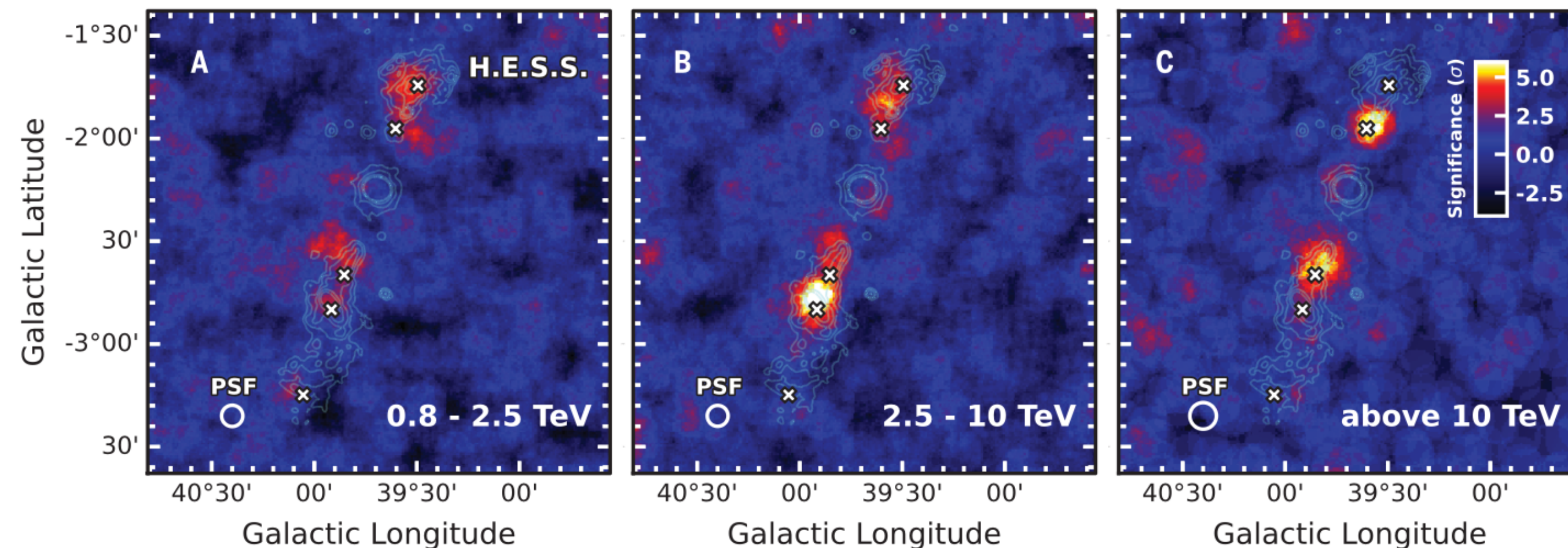
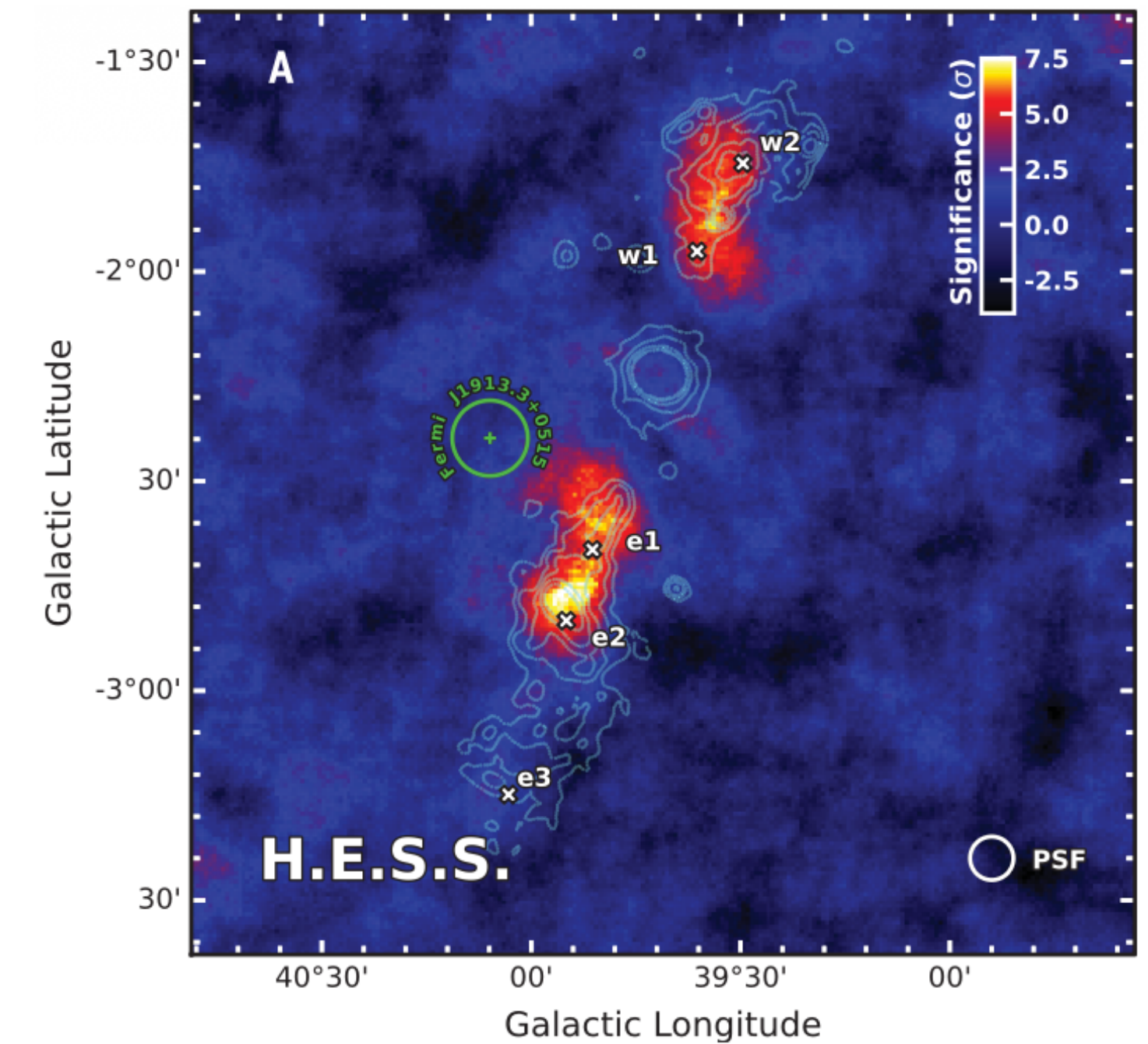
LHAASO 2025

Microquasars (X-ray binaries)

- Binary system consisting of compact object and companion star
→ formation of:
 - ▶ accretion disk
 - ▶ (semi-)relativistic jets
- Long hypothesised to be *transient* gamma-ray emitters
 - ▶ (unsuccessfully) targeted after radio or X-ray flares only
- Recently revealed as *persistent* UHE sources
 - ▶ HAWC 2018, 2024, LHAASO 2025
 - ▶ reaching energies of several 100 TeV in some cases
- H.E.S.S. 2024: detailed study of SS 433
 - ▶ energy-dependent morphology resolved
 - ▶ particle acceleration sites pinpointed to base of large-scale jets

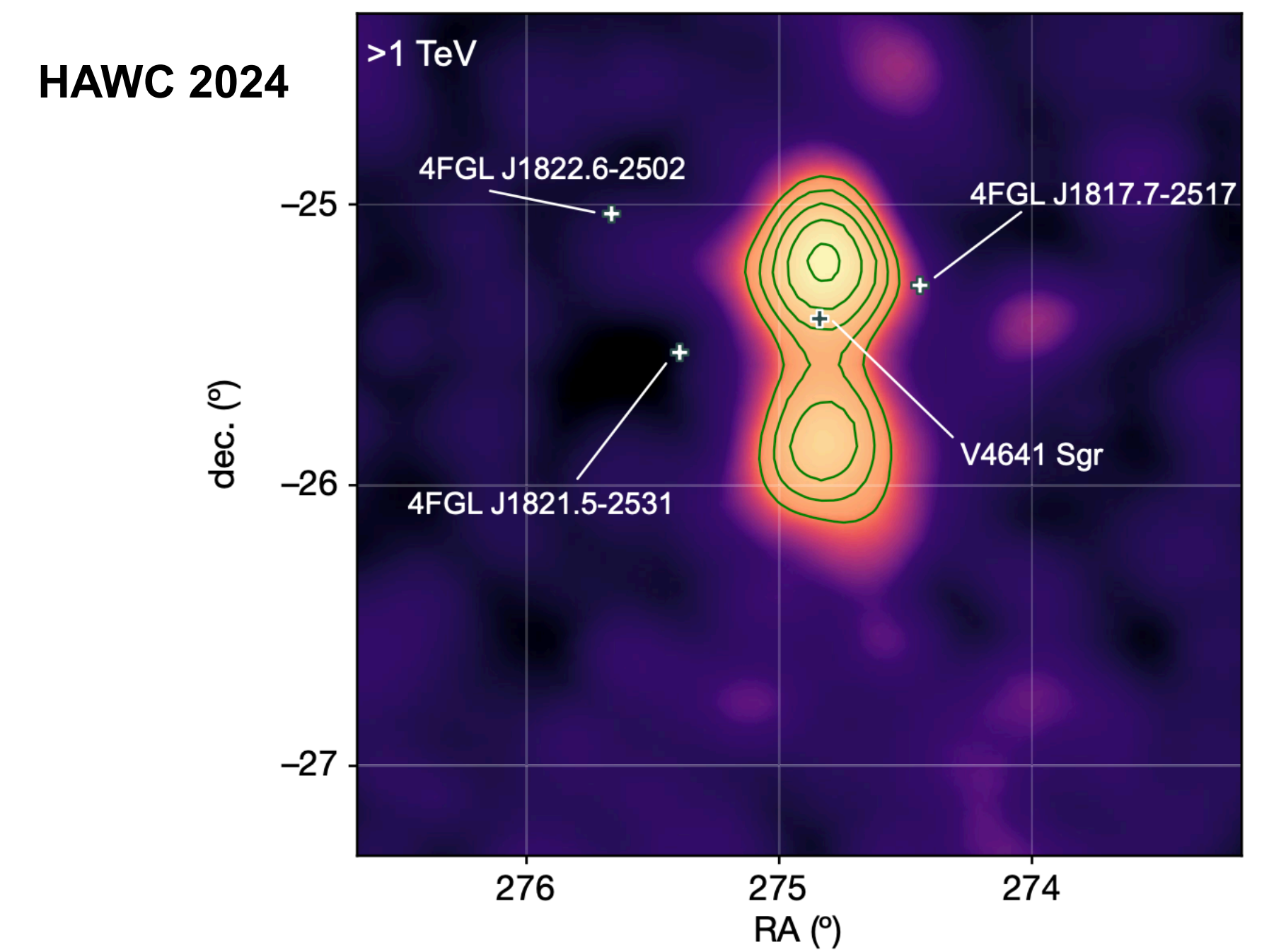
H.E.S.S. 2024
Science 383, 402

SS 433



The microquasar V4641 Sgr

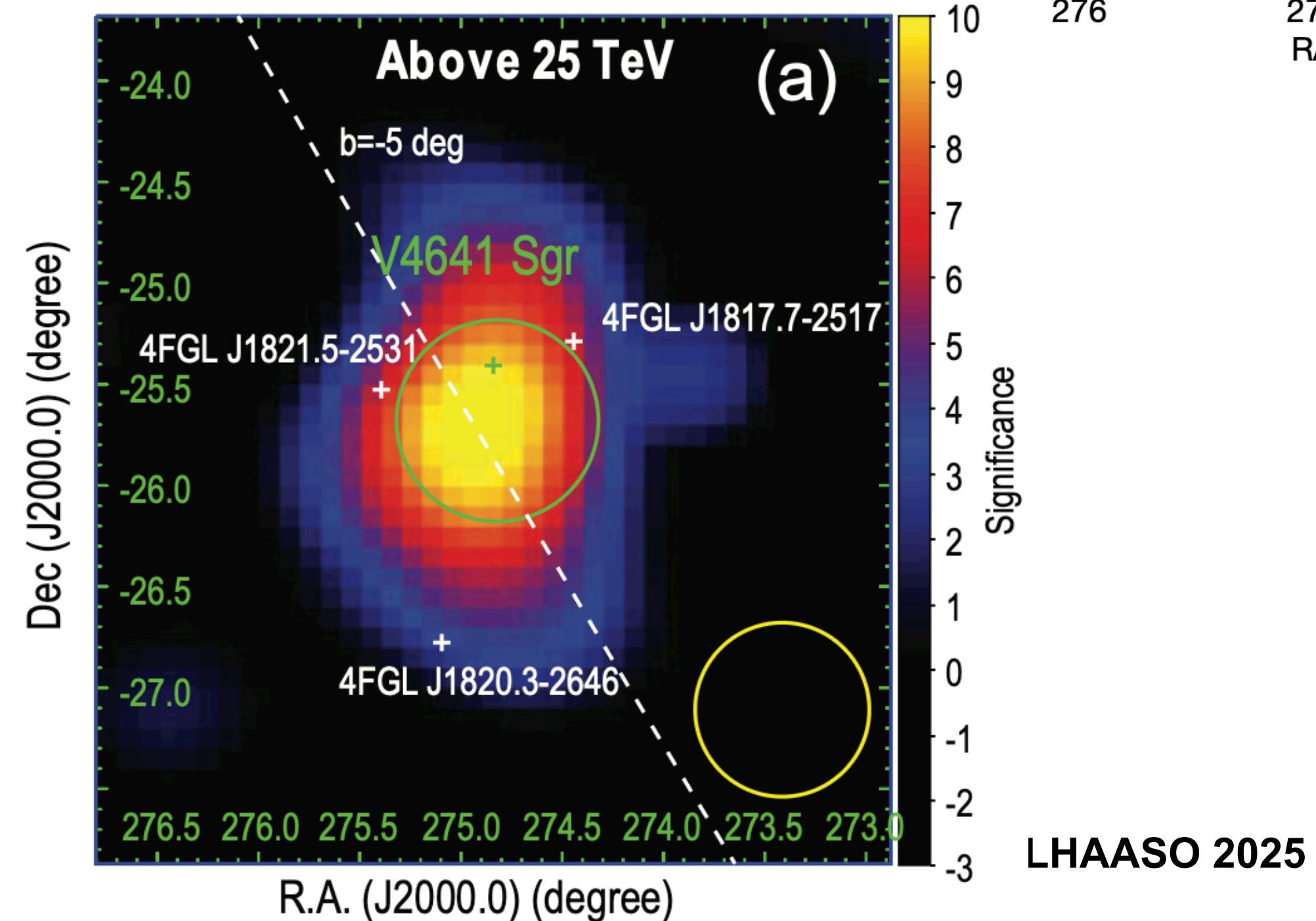
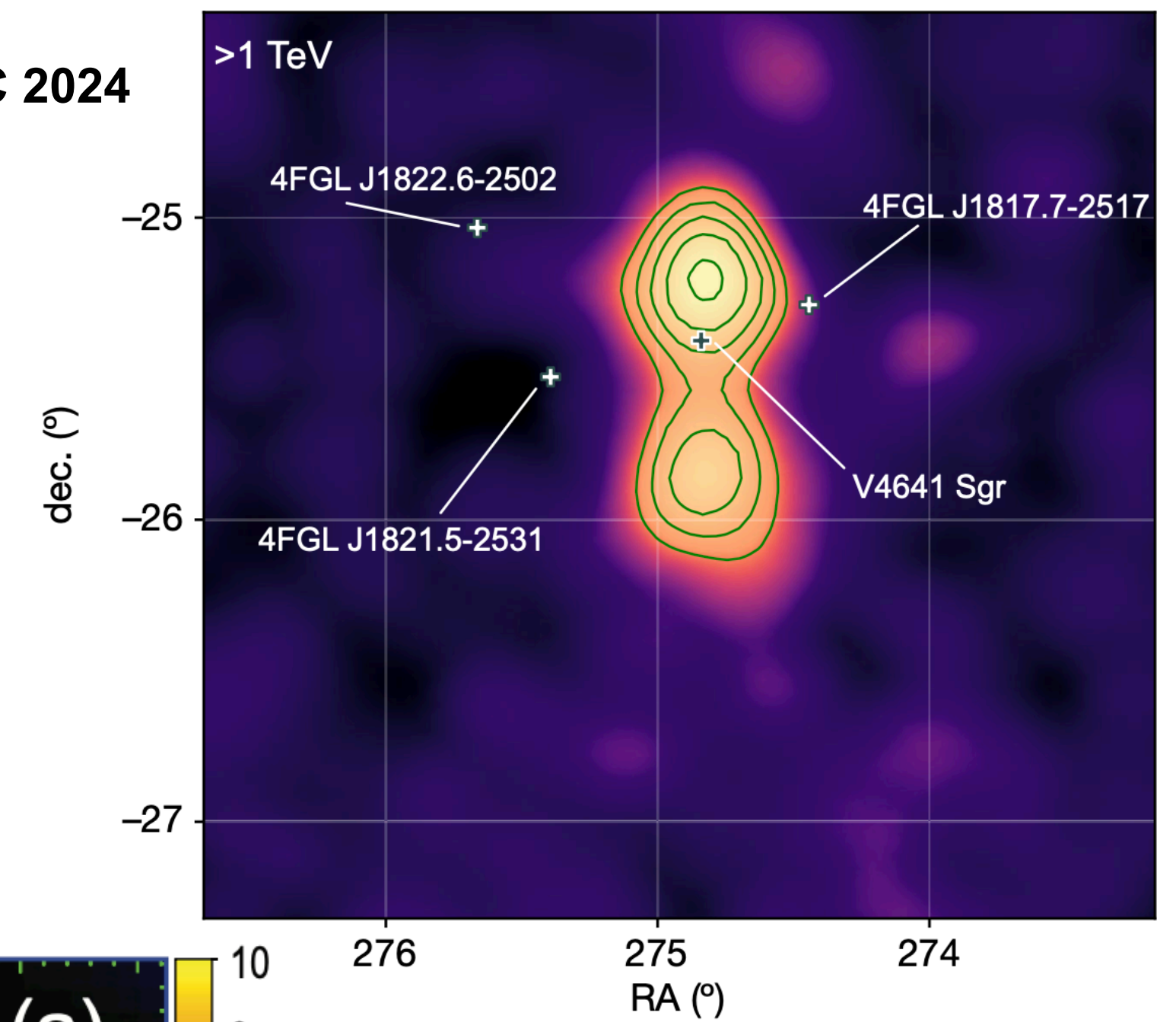
- **Off-plane** ($b = -5^\circ$) microquasar
 - not deemed very remarkable until recently...
- **Detection with HAWC**
 - energy range 18–217 TeV
 - hard spectral index ($\Gamma \approx -2.2$)
 - no clear preference between single elongated component or two point-like sources



The microquasar V4641 Sgr

- **Off-plane** ($b = -5^\circ$) microquasar
 - ▶ not deemed very remarkable until recently...
- **Detection with HAWC**
 - ▶ energy range 18–217 TeV
 - ▶ hard spectral index ($\Gamma \approx -2.2$)
 - ▶ no clear preference between single elongated component or two point-like sources
- **Detection with LHAASO**
 - ▶ energy range 40–800 TeV (!)
 - ▶ softer spectral index ($\Gamma \approx -2.8$)
 - ▶ morphology poorly constrained

HAWC 2024

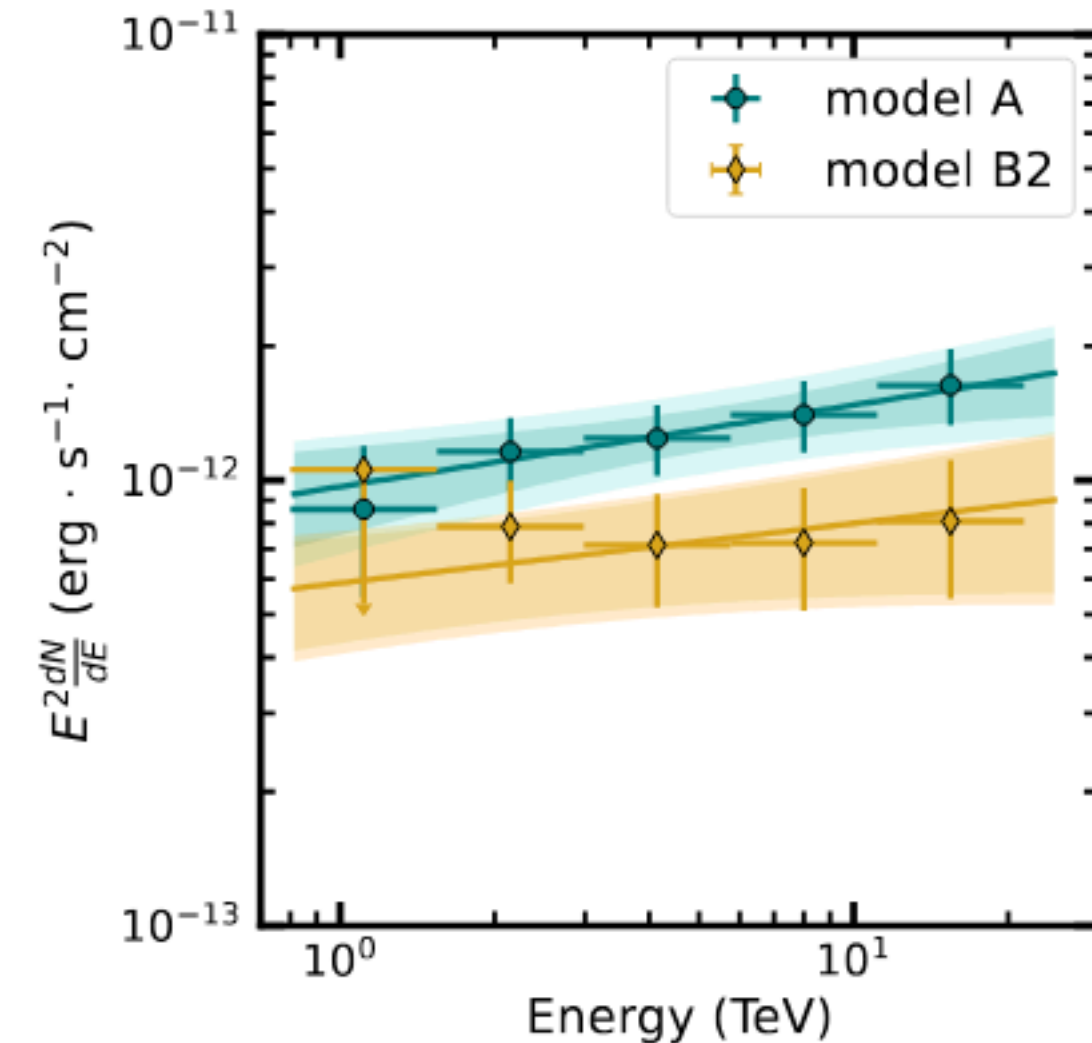
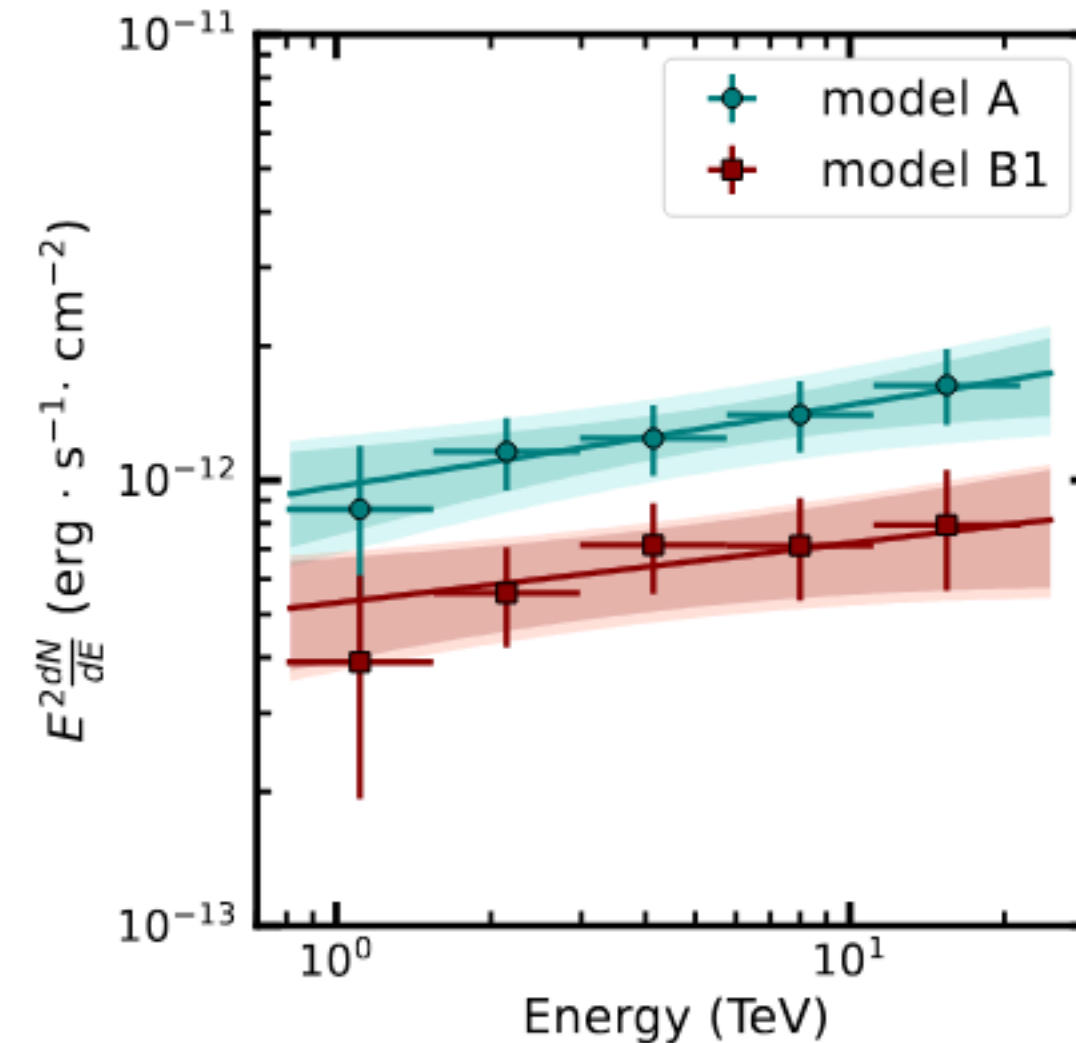
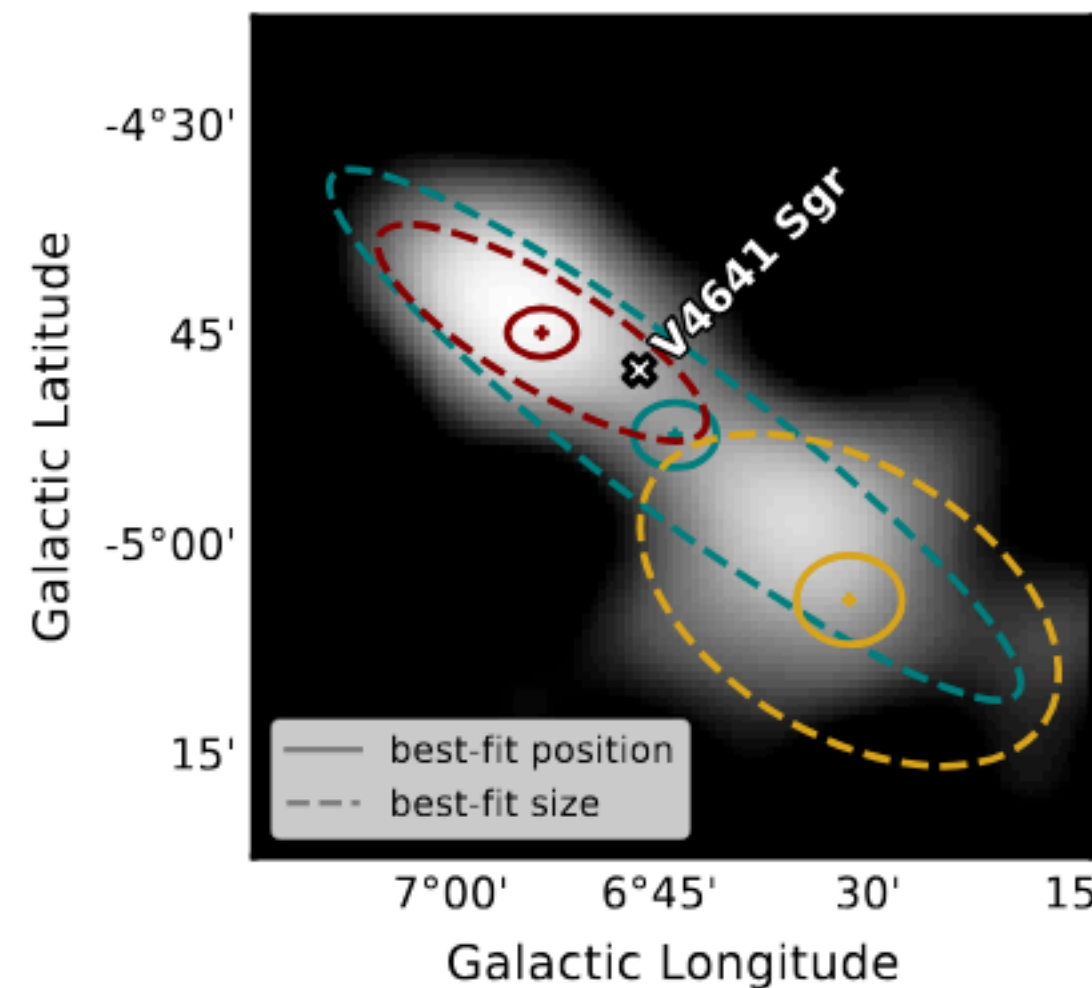
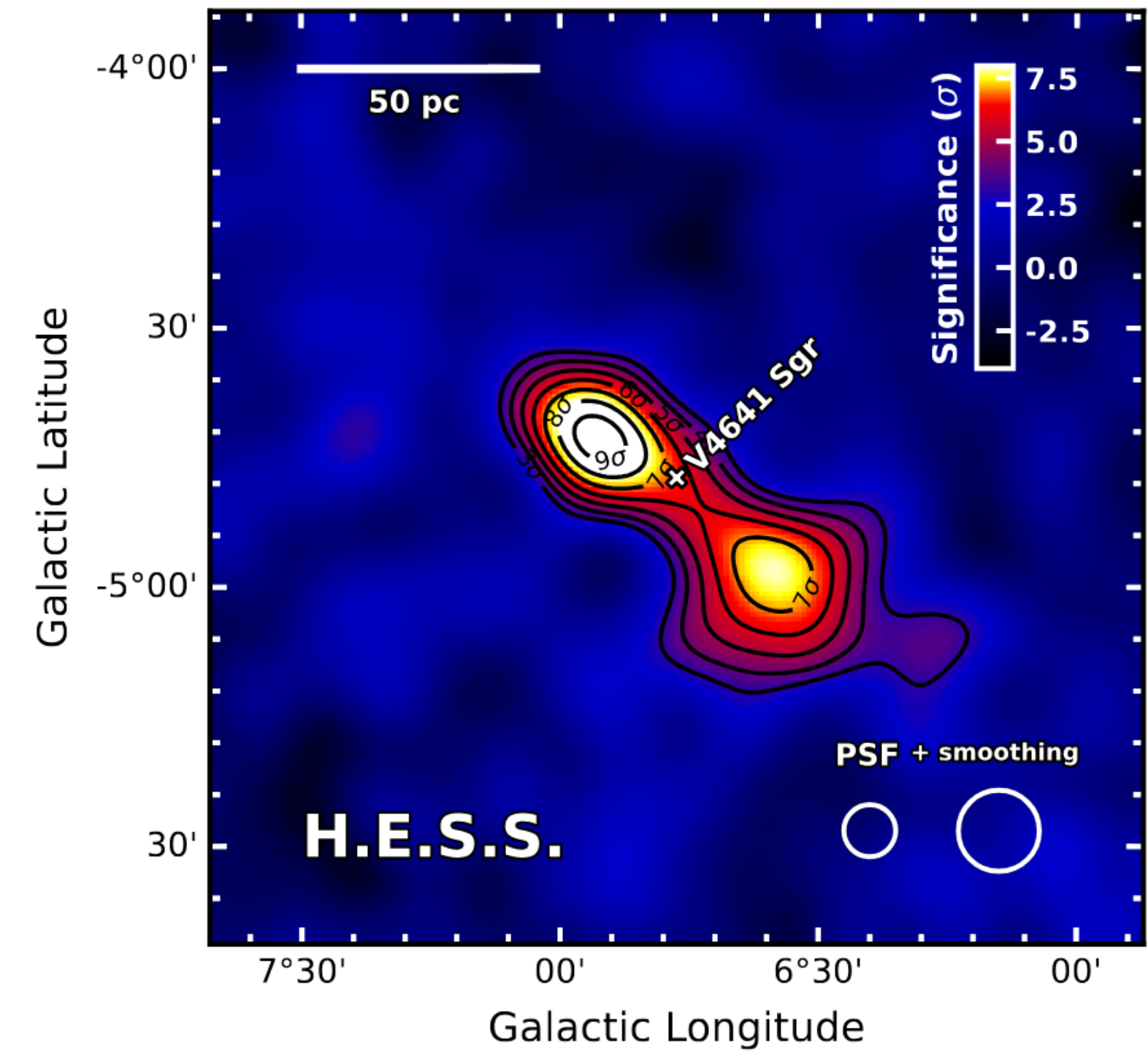


The microquasar V4641 Sgr

H.E.S.S. 2026
A&A 706, A8

■ H.E.S.S. measurement

- ▶ energy range 0.8–22 TeV
- ▶ very hard spectral index ($\Gamma \approx -1.8$)
- ▶ preference (3.2σ) for two separate components
- ▶ both components spatially resolved (i.e. not point-like)



The microquasar V4641 Sgr

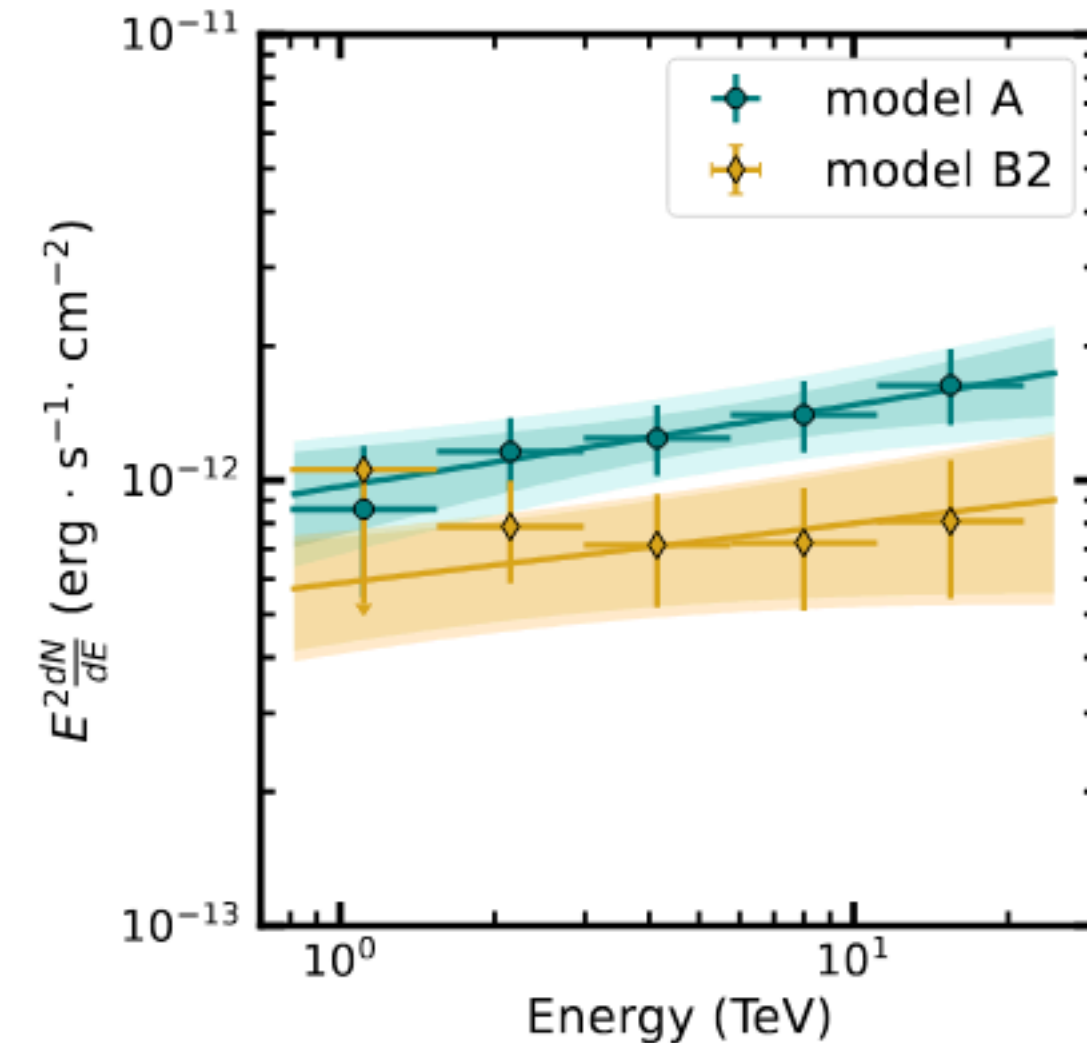
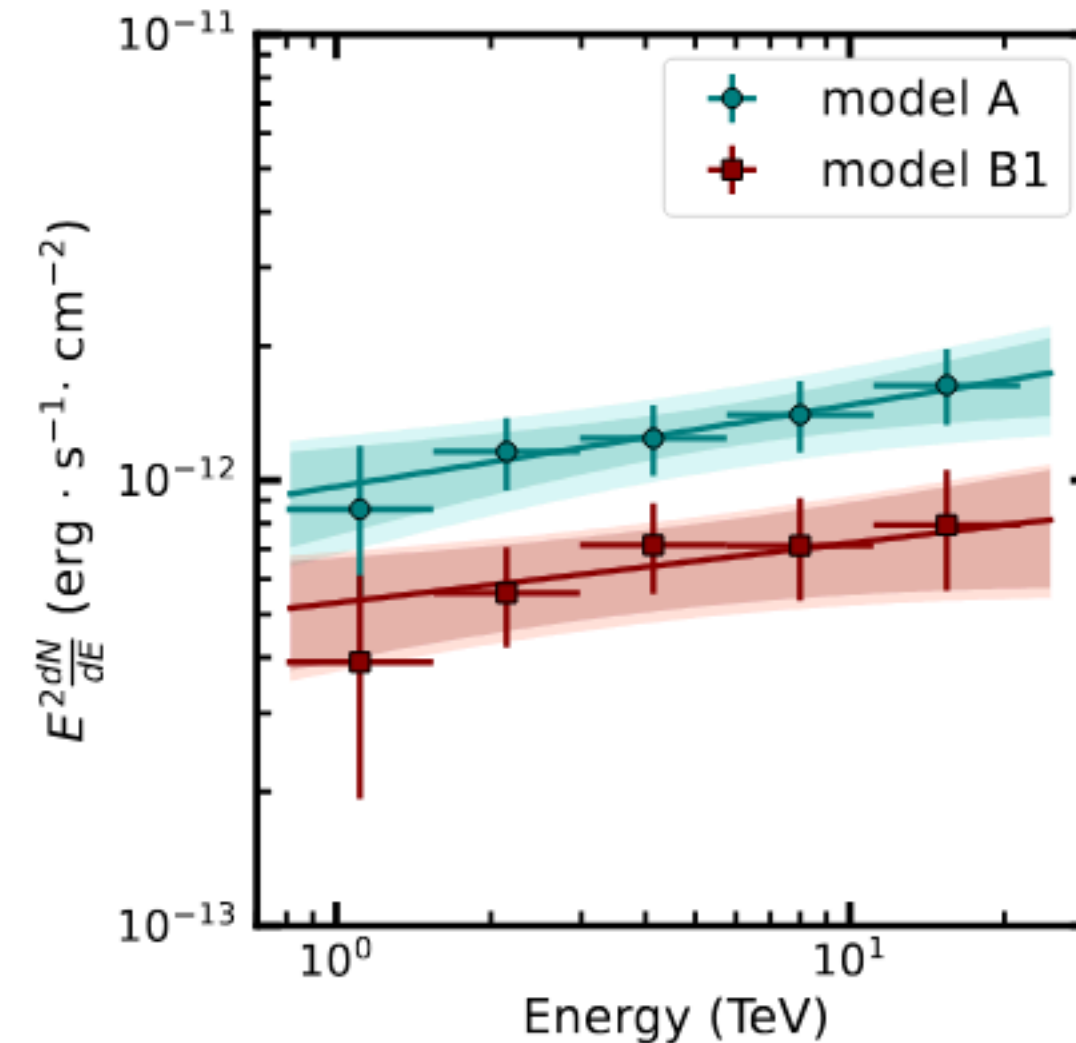
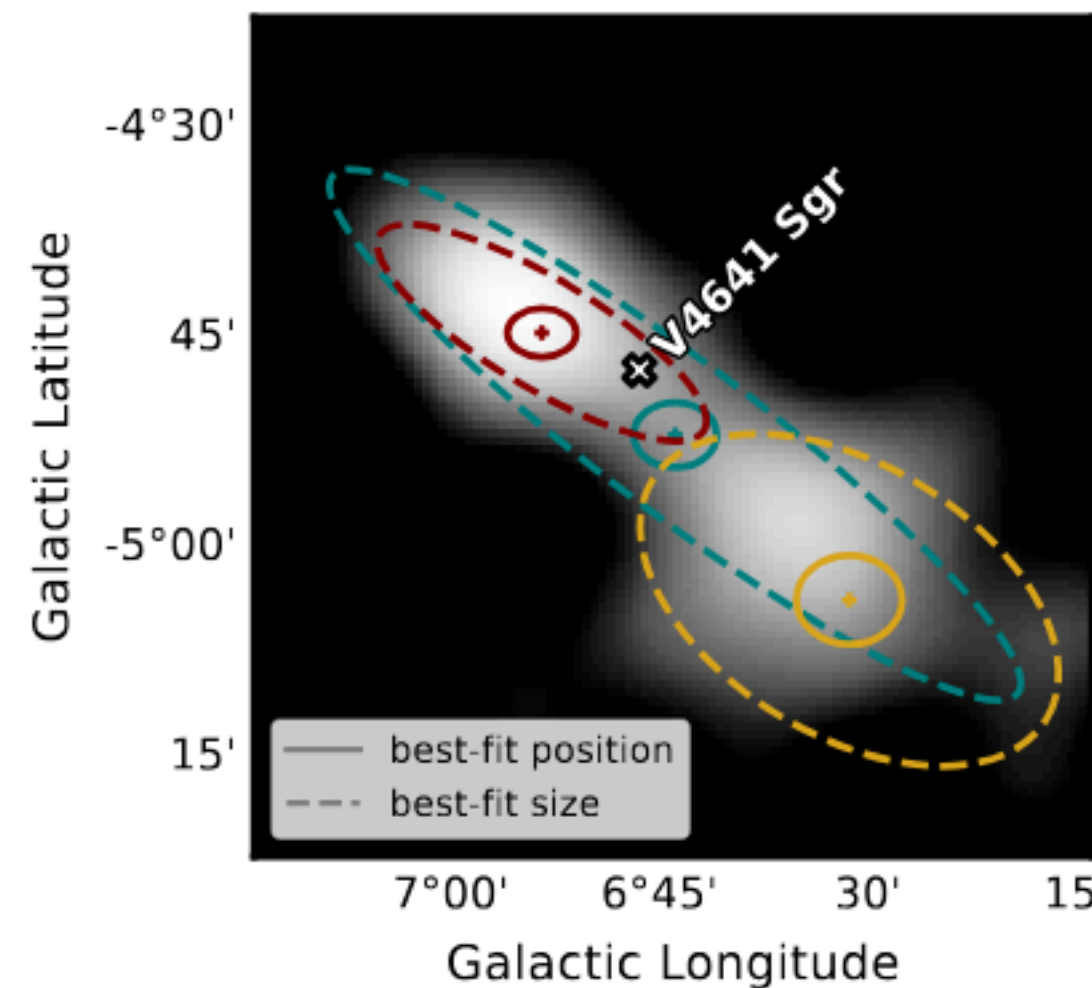
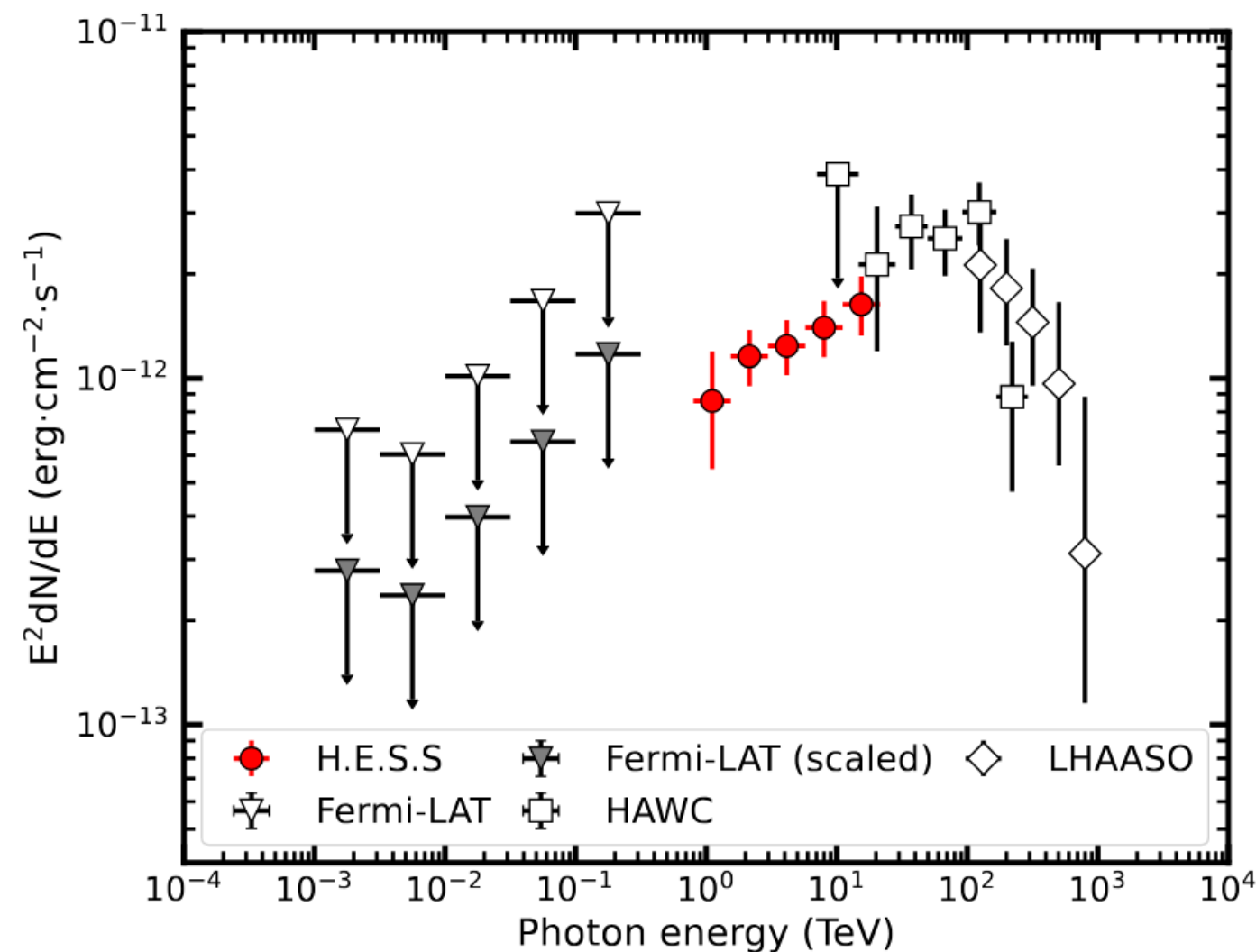
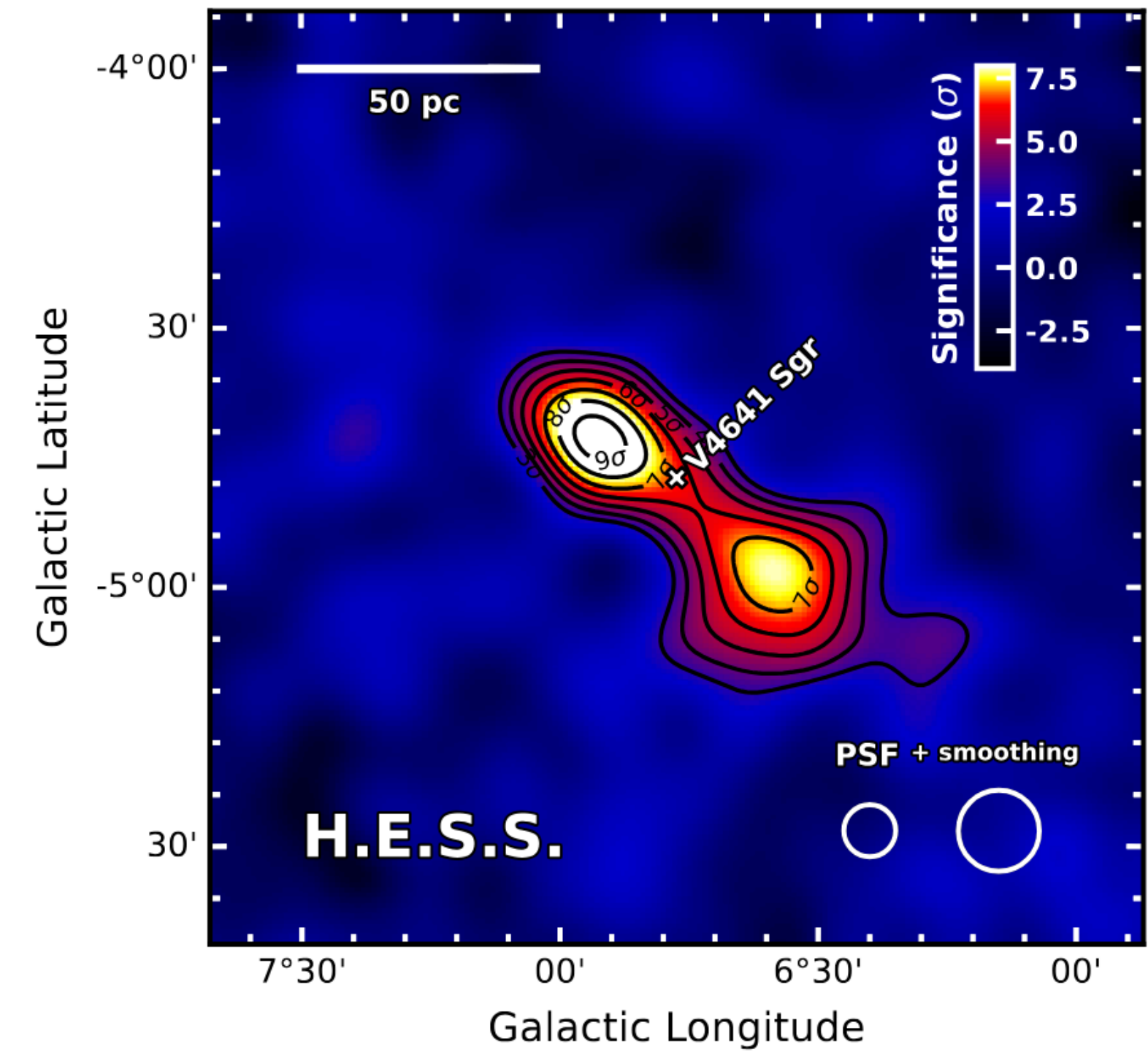
H.E.S.S. 2026
A&A 706, A8

■ H.E.S.S. measurement

- ▶ energy range 0.8–22 TeV
- ▶ very hard spectral index ($\Gamma \approx -1.8$)
- ▶ preference (3.2σ) for two separate components
- ▶ both components spatially resolved (i.e. not point-like)

■ Broad-band spectral energy distribution

- ▶ peaked at ~ 100 TeV
- ▶ V4641 Sgr is an extremely powerful particle accelerator!

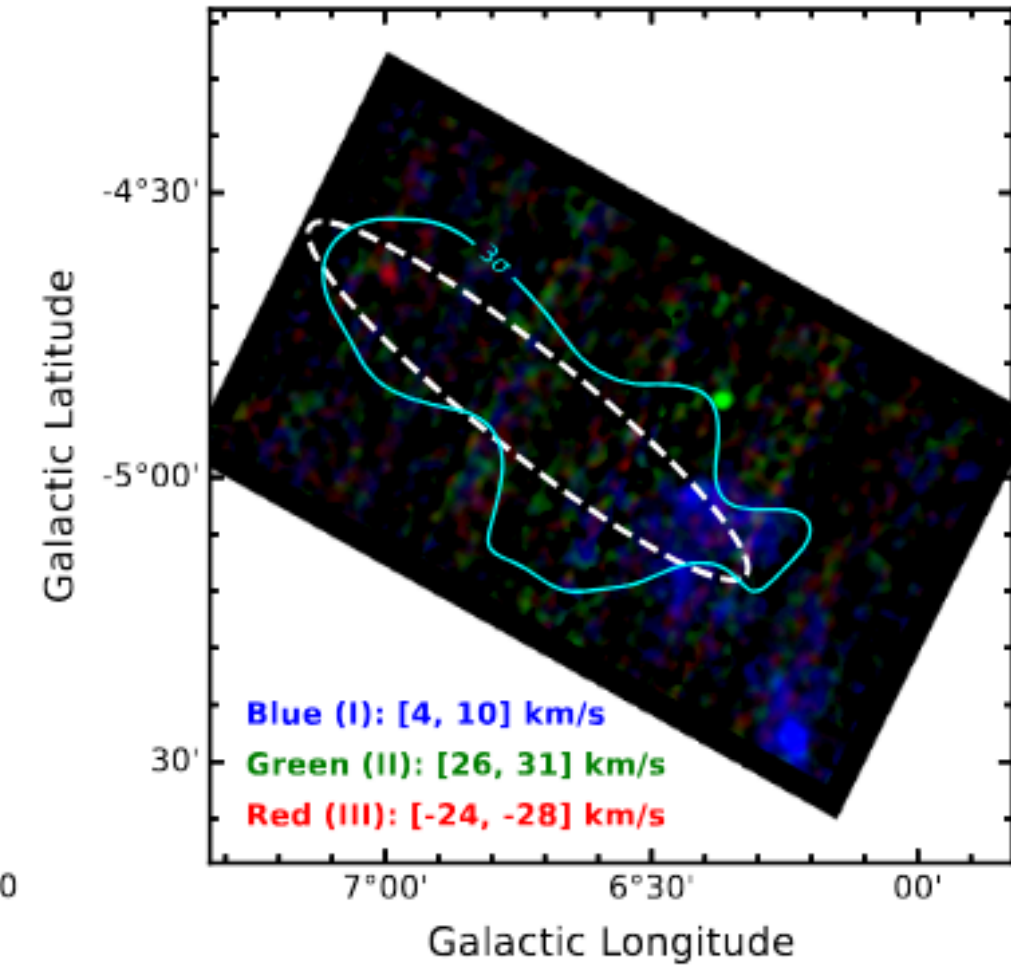
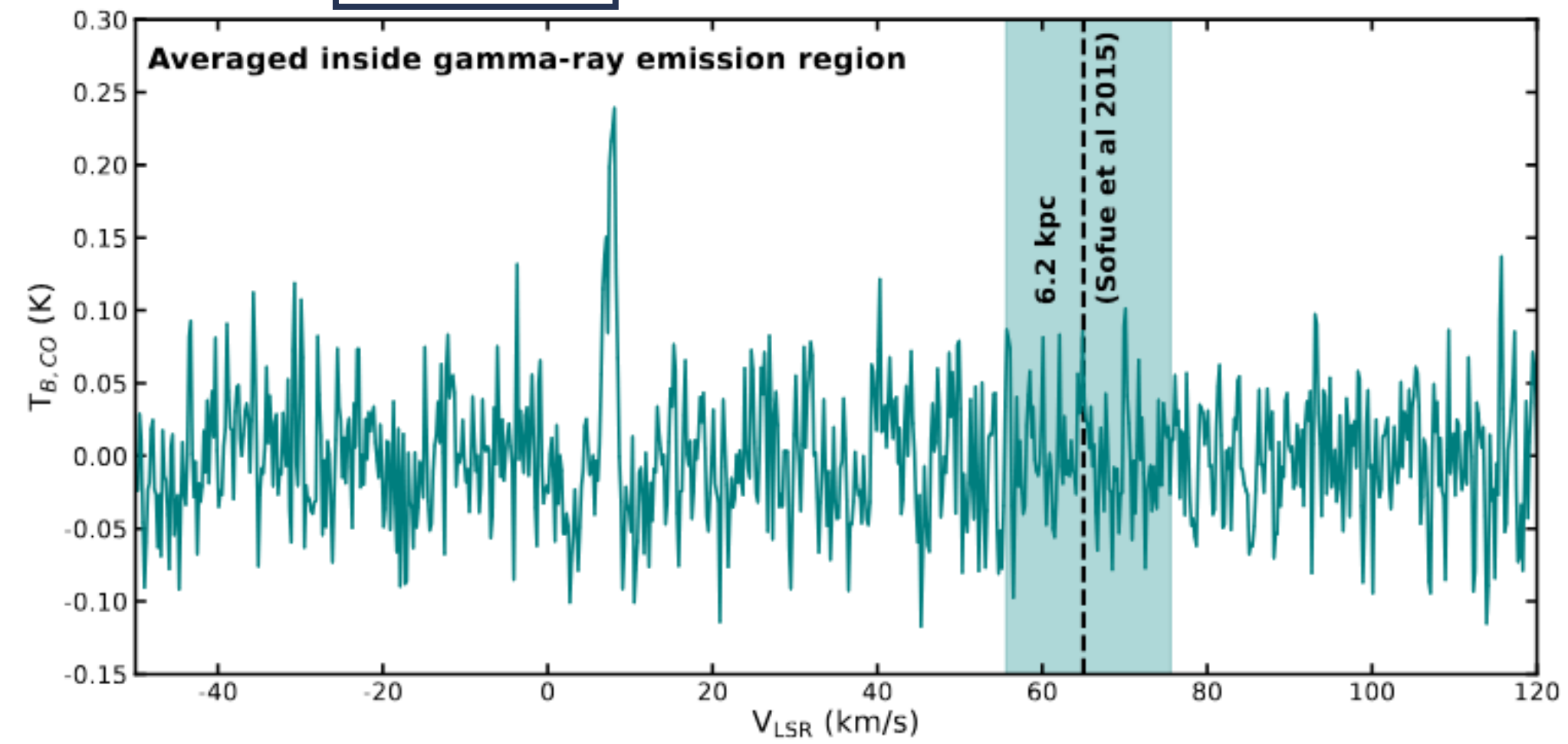


The microquasar V4641 Sgr

■ Search for ambient gas

- ▶ densities very low
- ▶ molecular hydrogen (CO): $n_{\text{gas}} < 0.2 \text{ cm}^{-3}$
- ▶ atomic hydrogen (HI): $n_{\text{gas}} \approx 0.08 \text{ cm}^{-3}$

H.E.S.S. 2026
A&A 706, A8



The microquasar V4641 Sgr

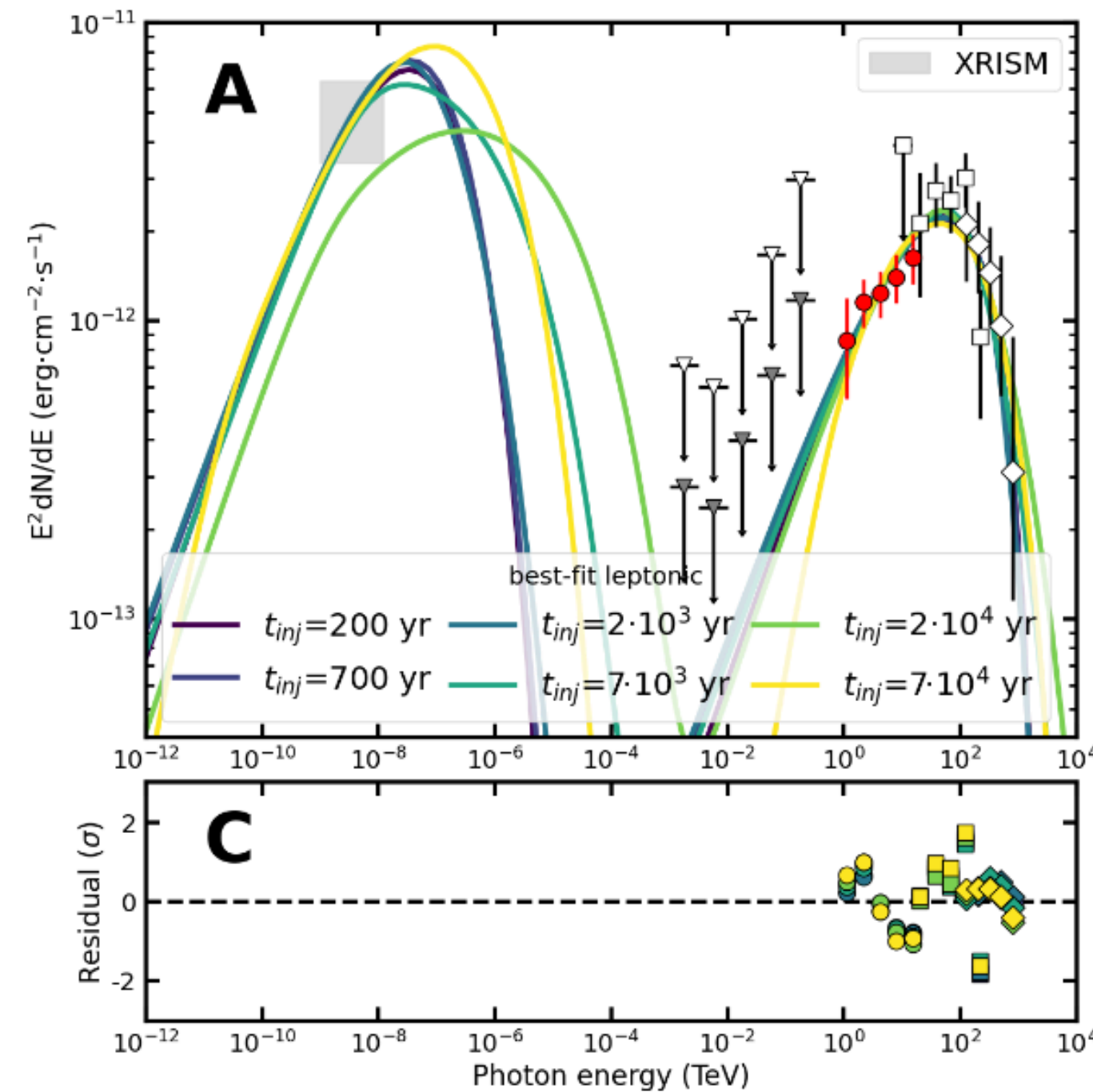
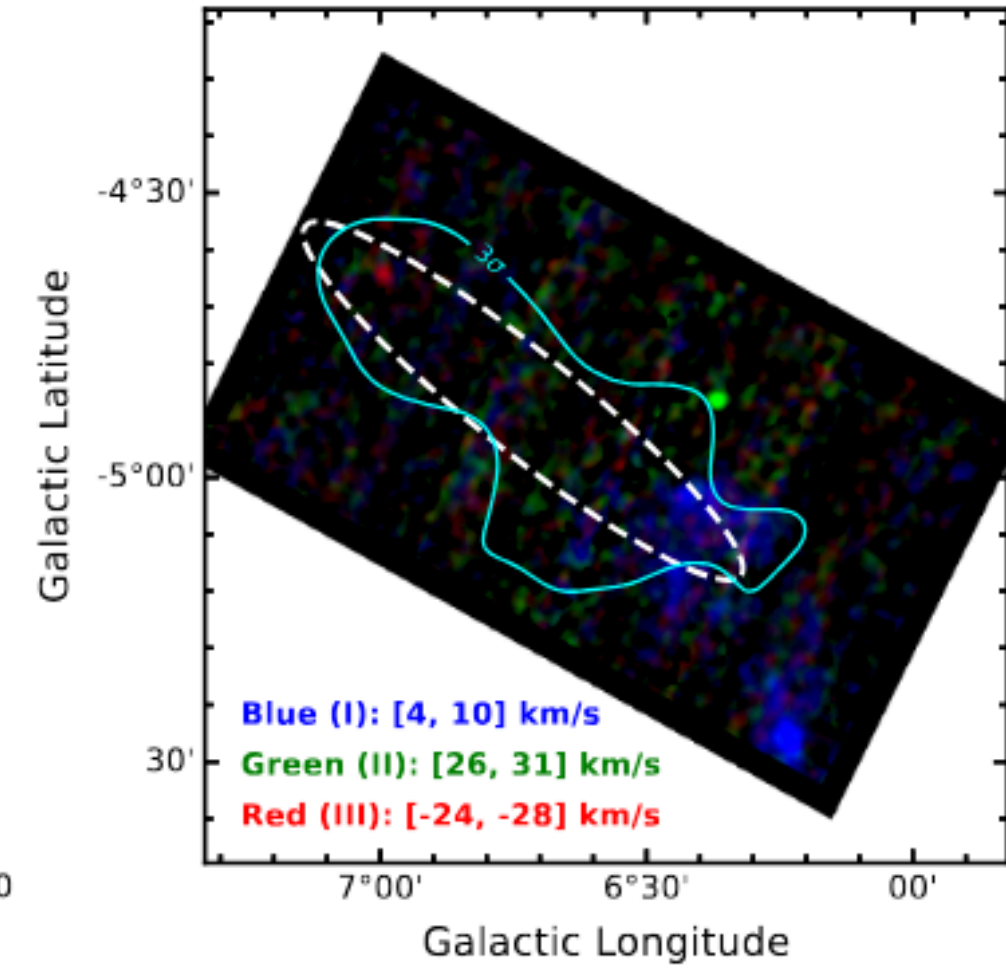
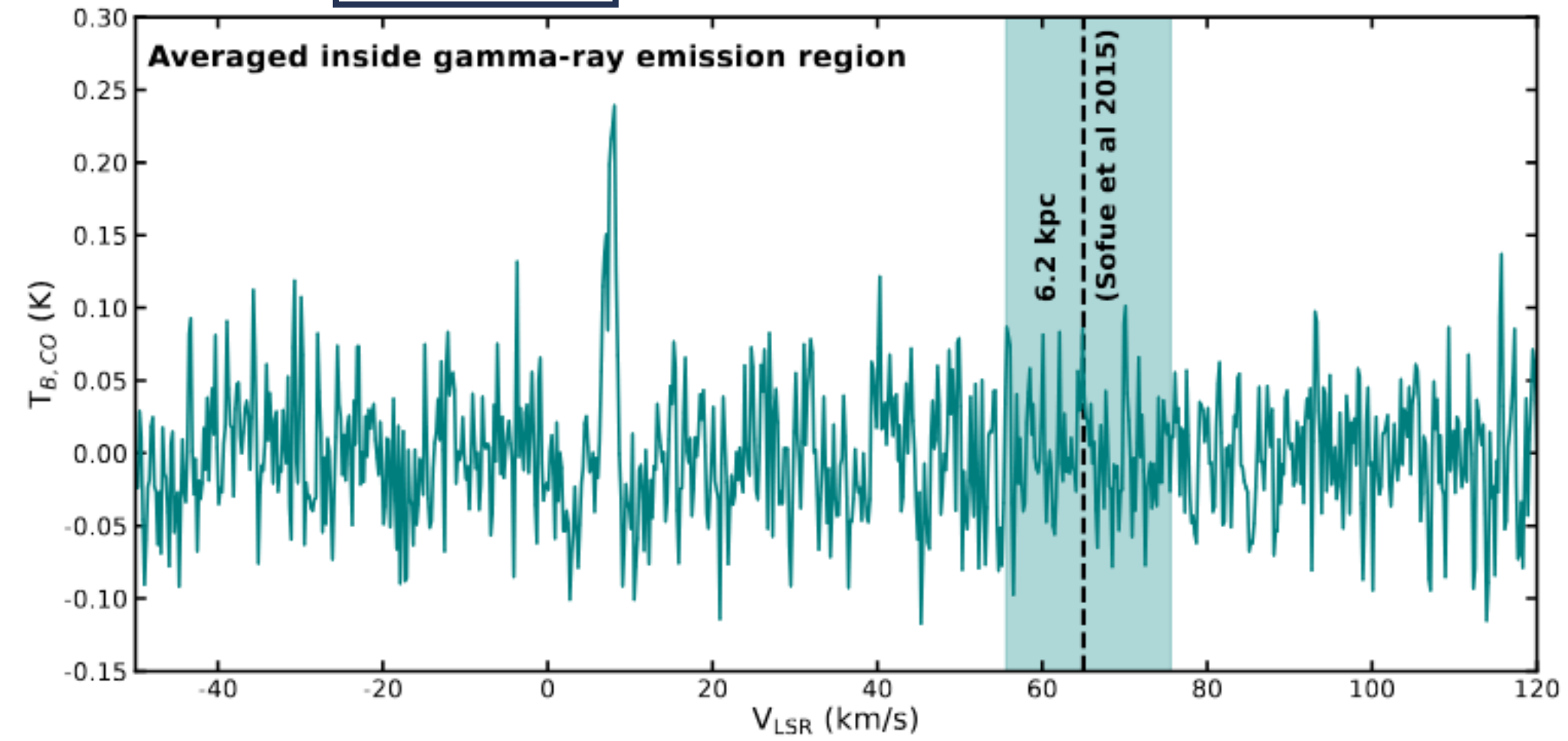
■ Search for ambient gas

- ▶ densities very low
- ▶ molecular hydrogen (CO): $n_{\text{gas}} < 0.2 \text{ cm}^{-3}$
- ▶ atomic hydrogen (HI): $n_{\text{gas}} \approx 0.08 \text{ cm}^{-3}$

■ Leptonic model preferred

- ▶ suggests $B < 3 \mu\text{G}$ and $t_{\text{inj}} \lesssim 10 \text{ kyr}$
- ▶ requires mildly relativistic jet ($v \gtrsim 0.1c$) to explain morphology
- ▶ low B field implies large (pc-scale) acceleration site

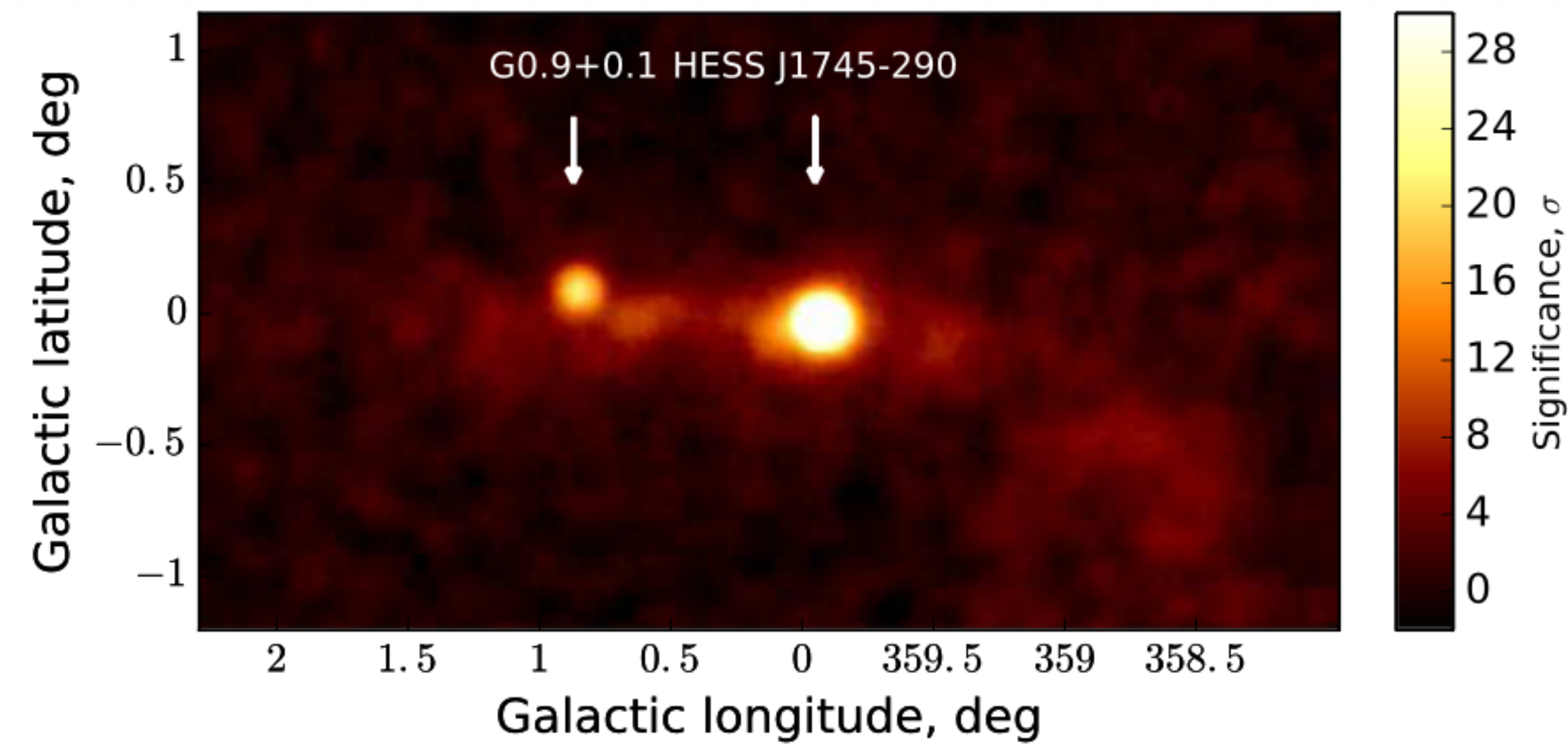
H.E.S.S. 2026
A&A 706, A8



The Galactic Centre

- A region with extremely rich astrophysics!
- Two bright point-like sources
 - G0.9+0.1 — composite SNR
 - HESS J1745–290
 - spatially coincident with Sgr A*...
 - ... but also a PWN candidate, a massive star cluster, ...
 - → no firm association with black hole so far

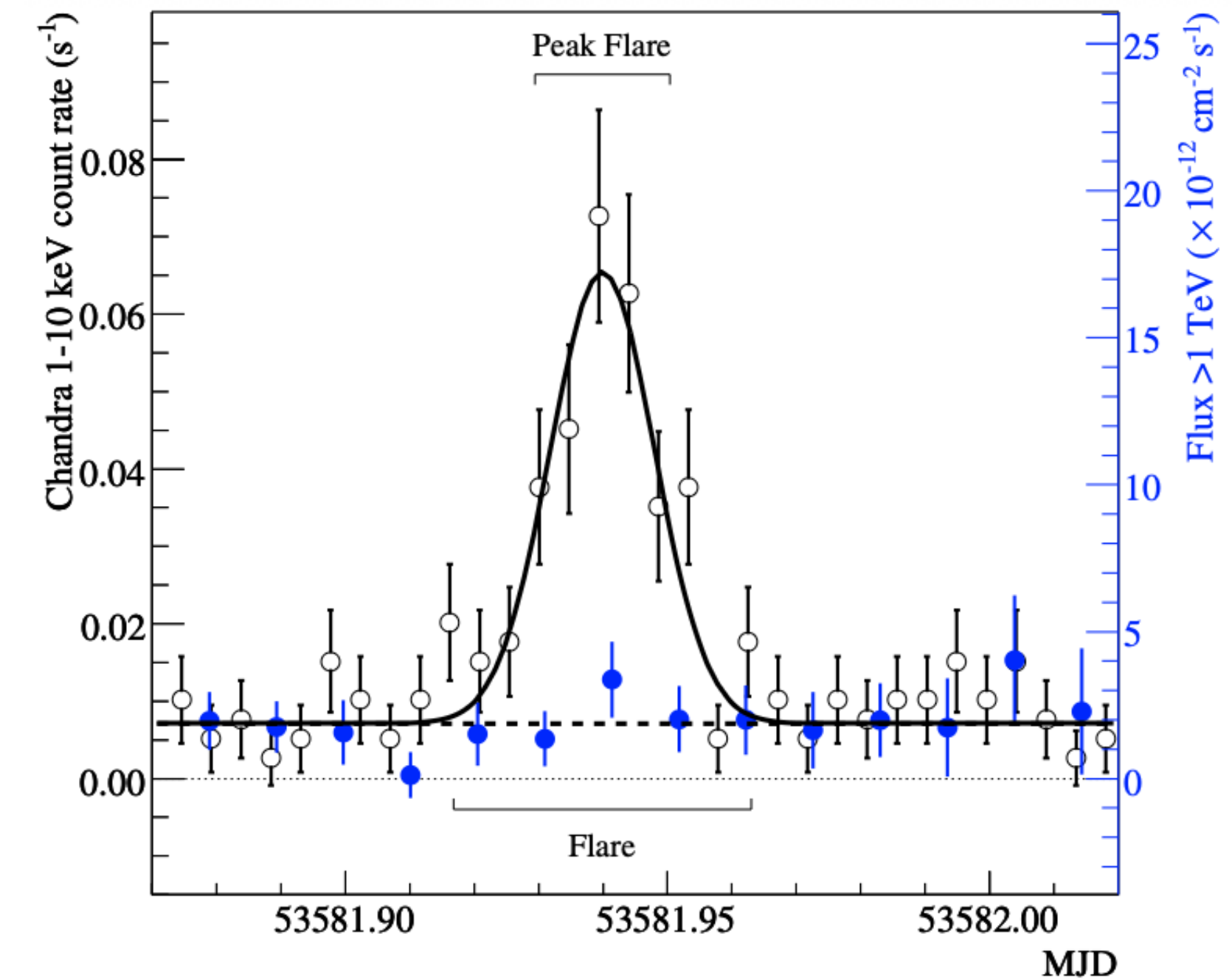
H.E.S.S. 2018
A&A 612, A9



Variability of HESS J1745–290

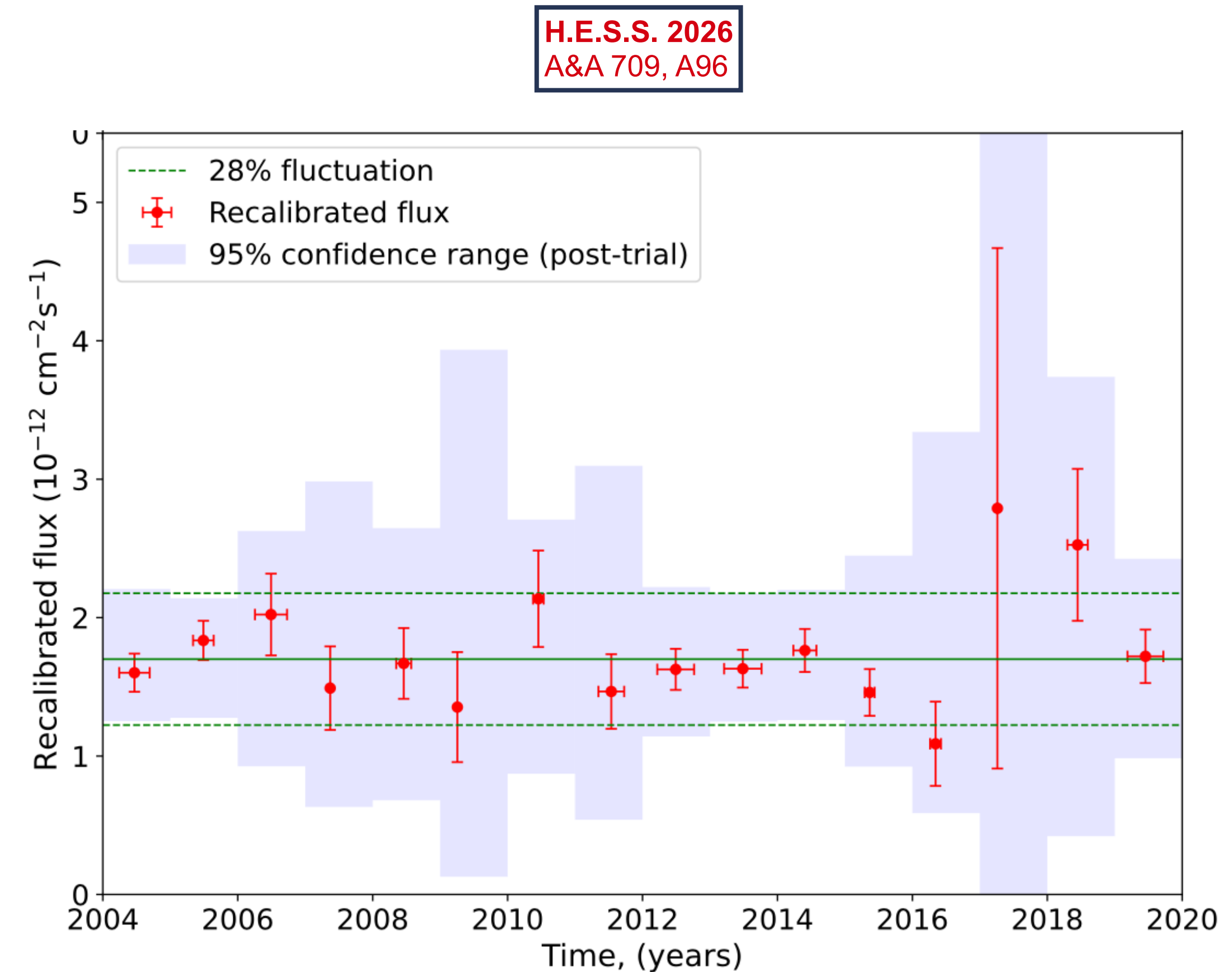
- **Sgr A* shows strong flares in infrared and in X-rays**
 - ▶ connected to accretion flow close to the black hole
- **Variability of gamma-ray emission is a key observable to constrain where cosmic rays are accelerated**
 - ▶ observation of variability would be a smoking gun that HESS J1745–290 is associated with Sgr A*
 - ▶ searches for flares simultaneous with X-rays so far unsuccessful

H.E.S.S. 2008
A&A 492, L25



Variability of HESS J1745–290

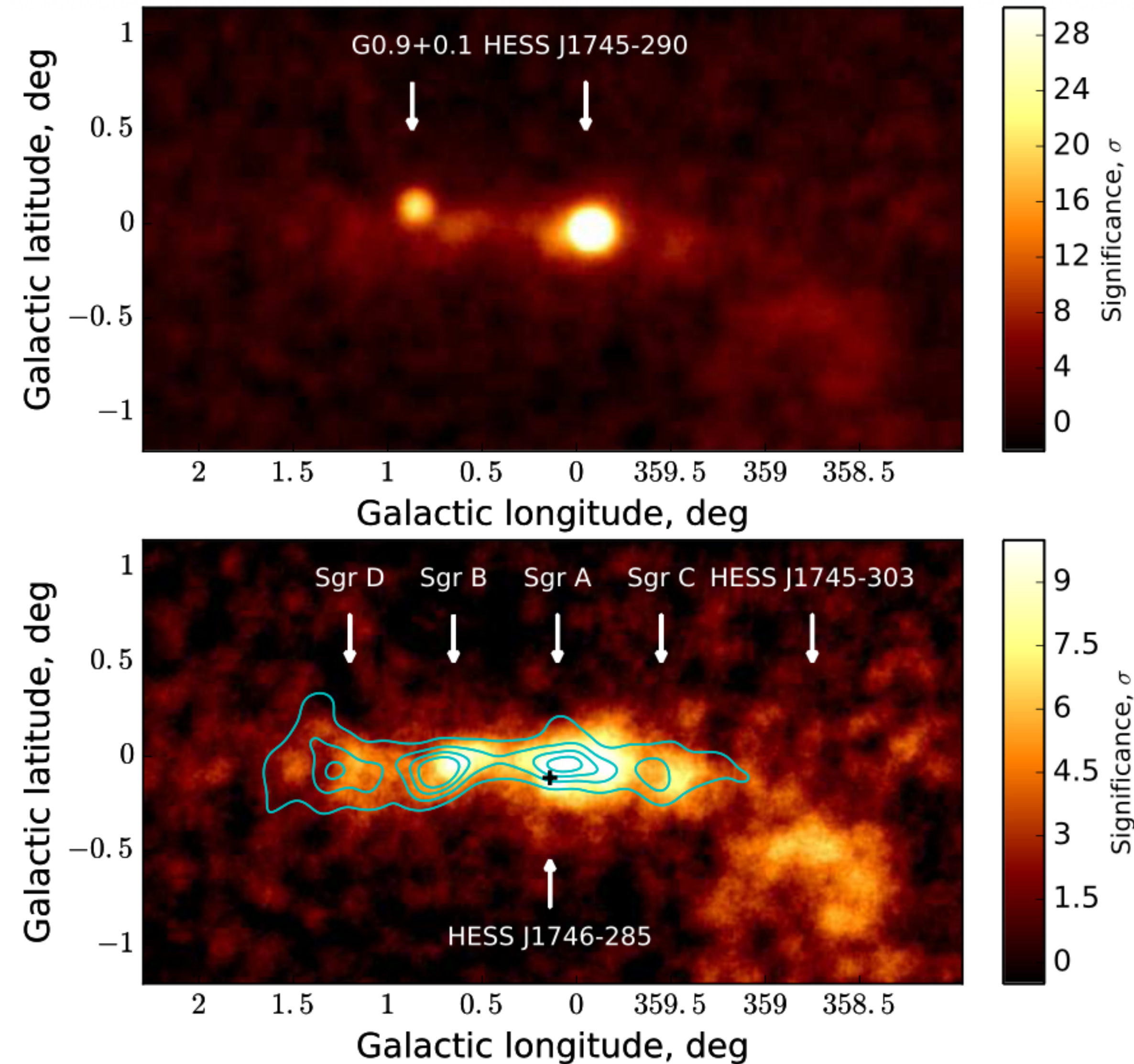
- **Sgr A* shows strong flares in infrared and in X-rays**
 - ▶ connected to accretion flow close to the black hole
- **Variability of gamma-ray emission is a key observable to constrain where cosmic rays are accelerated**
 - ▶ observation of variability would be a smoking gun that HESS J1745–290 is associated with Sgr A*
 - ▶ searches for flares simultaneous with X-rays so far unsuccessful
- **H.E.S.S. has monitored Sgr A* for more than a decade now**
 - ▶ study long-term variability over ~16 years
 - ▶ use large-scale diffuse emission as “calibration source” to filter out instrumental effects
 - ▶ no variability or trend observed
 - gamma-ray flux is constant within ~30%



The Galactic Centre

- A region with extremely rich astrophysics!
- Two bright point-like sources
 - G0.9+0.1 — composite SNR
 - HESS J1745–290
 - spatially coincident with Sgr A*...
 - ... but also a PWN candidate, a massive star cluster, ...
 - → no firm association with black hole so far
- Diffuse gamma-ray emission
 - correlation with molecular gas clouds (central molecular zone — CMZ)
 - spatial profile and spectrum consistent with a steady proton accelerator at the centre

H.E.S.S. 2018
A&A 612, A9



The Central Molecular Zone (CMZ)

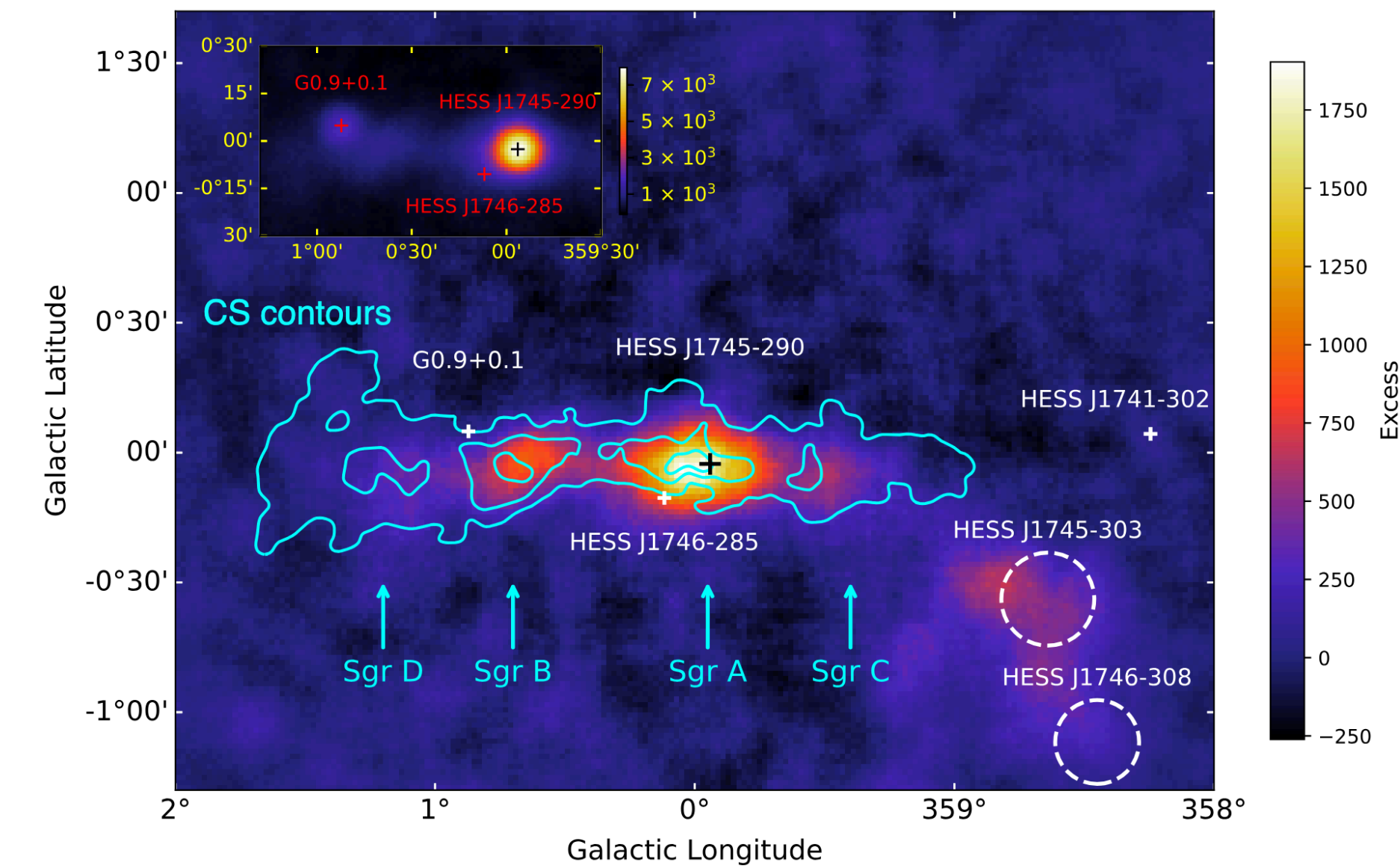
- **Updated study of diffuse emission**

- ▶ now using ~16 years of data

- **Confirms scenario of steady central source**

- ▶ signal consistent with “1/r” radial cosmic ray density profile
- ▶ no spectral variations across CMZ

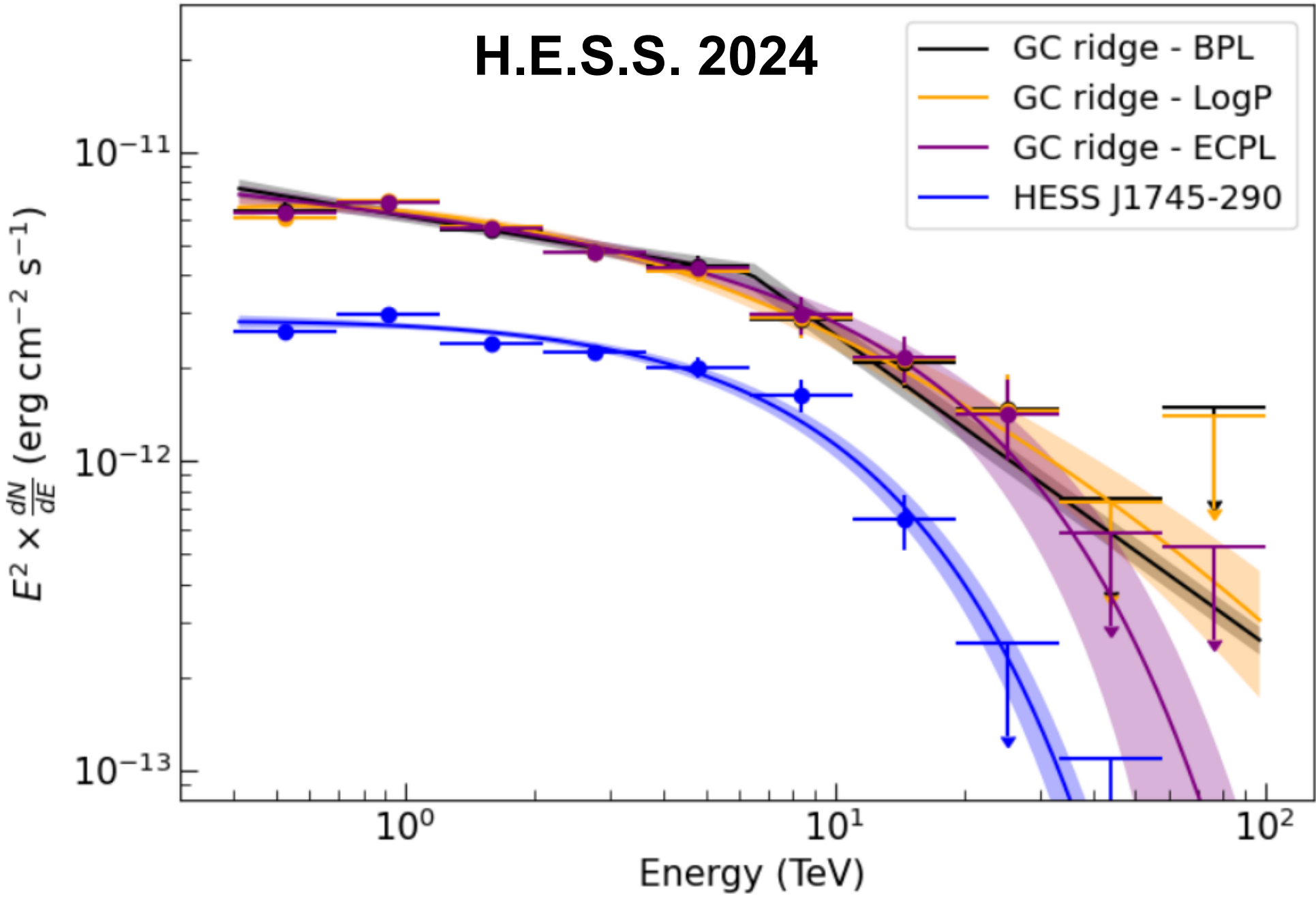
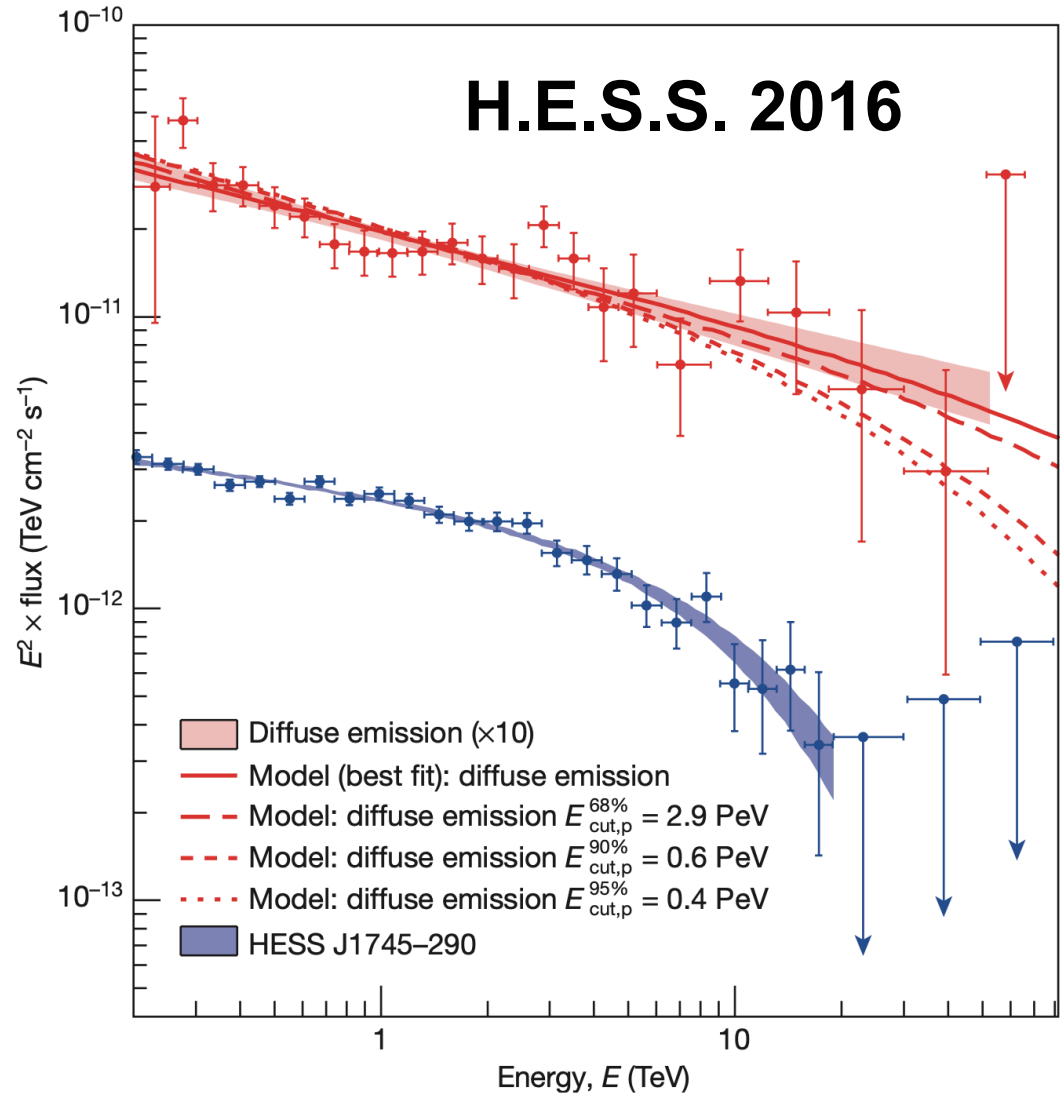
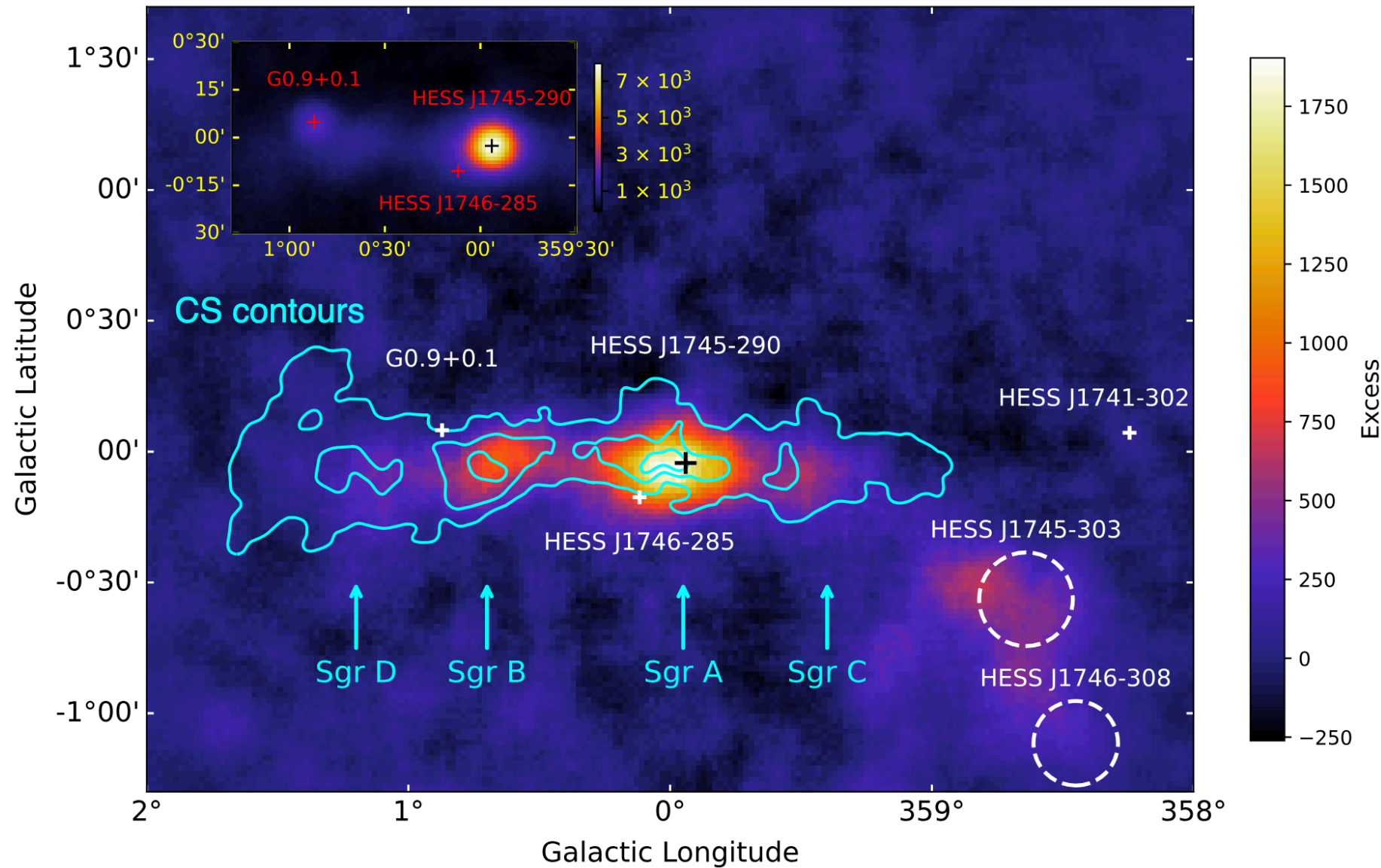
Devin et al. on behalf of H.E.S.S.,
Gamma **2024**
(+ submitted to A&A)



The Central Molecular Zone (CMZ)

- Updated study of diffuse emission
 - ▶ now using ~16 years of data
- Confirms scenario of steady central source
 - ▶ signal consistent with “1/r” radial cosmic ray density profile
 - ▶ no spectral variations across CMZ
- New result
 - ▶ evidence (3σ) for curvature in spectrum of diffuse emission
 - ▶ implies break or cut-off in parent proton spectrum

Devin et al. on behalf of H.E.S.S.,
Gamma 2024
(+ submitted to A&A)



Young massive star clusters

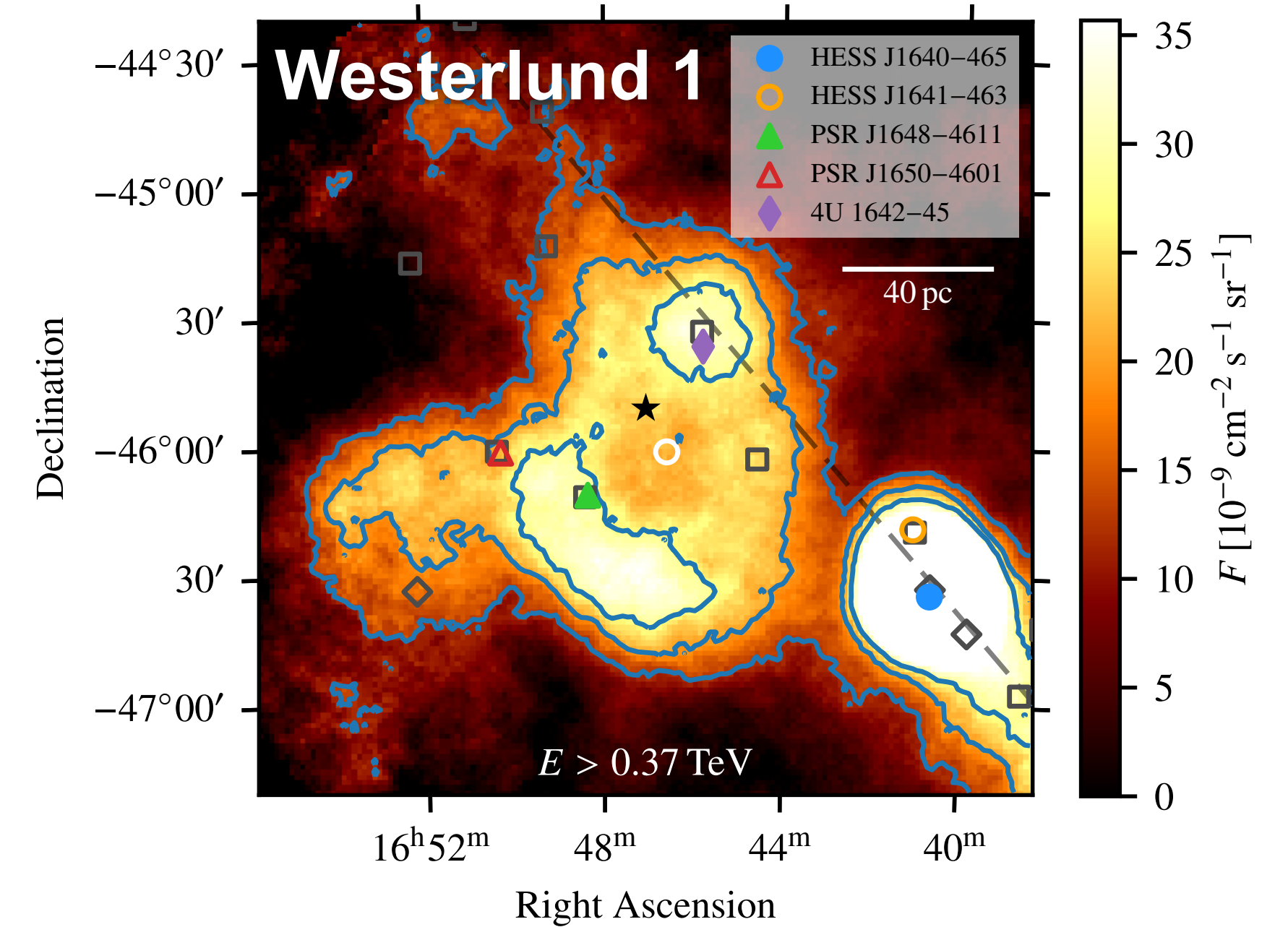
- Long hypothesised as cosmic-ray accelerators...
 - ▶ e.g. Cesarsky 1983, Klepach 2000, Bykov 2001
- ...but a lot of renewed interest recently
 - ▶ Aharonian 2019, Gupta 2020, Morlino 2021, Tatischeff 2021, Vieu 2022, 2023, Härer 2025, ...



Young massive star clusters

- Long hypothesised as cosmic-ray accelerators...
 - ▶ e.g. Cesarsky 1983, Klepach 2000, Bykov 2001
- ...but a lot of renewed interest recently
 - ▶ Aharonian 2019, Gupta 2020, Morlino 2021, Tatischeff 2021, Vieu 2022, 2023, Härer 2025, ...
- **Westerlund 1**
 - ▶ most massive young star cluster in the Milky Way
 - ▶ very extended TeV emission
 - ▶ ring-like structure

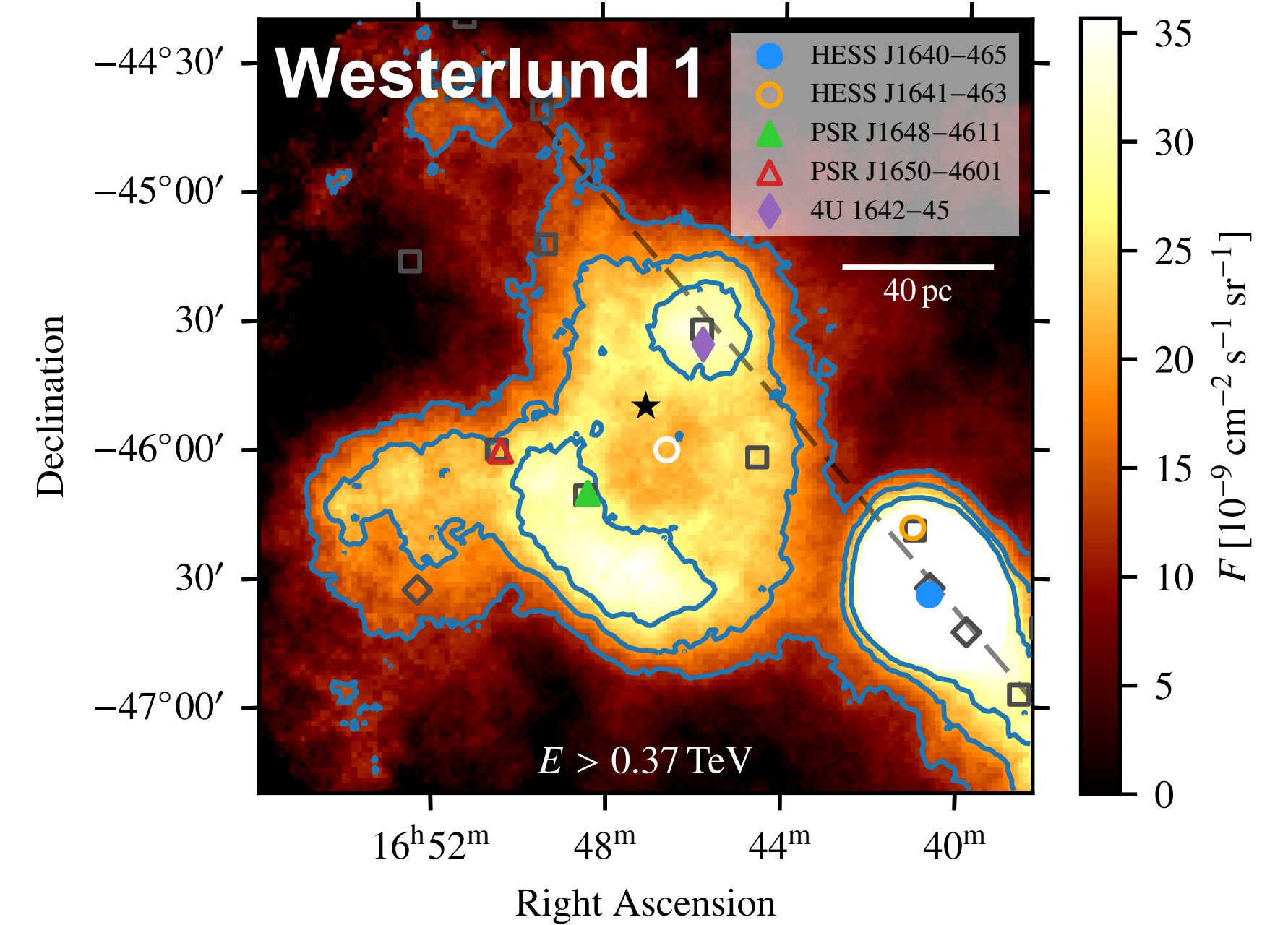
H.E.S.S. 2022
A&A 666, A124



Young massive star clusters

- Long hypothesised as cosmic-ray accelerators...
 - ▶ e.g. Cesarsky 1983, Klepach 2000, Bykov 2001
- ...but a lot of renewed interest recently
 - ▶ Aharonian 2019, Gupta 2020, Morlino 2021, Tatischeff 2021, Vieu 2022, 2023, Härer 2025, ...
- **Westerlund 1**
 - ▶ most massive young star cluster in the Milky Way
 - ▶ very extended TeV emission
 - ▶ ring-like structure

H.E.S.S. 2022
A&A 666, A124



Want to learn more about gamma rays from Westerlund 1?
→ visit talk by **Lucia Härer** (E1.21, Fri 7 Aug, 18:00)!

Young massive star clusters

- Long hypothesised as cosmic-ray accelerators...
 - ▶ e.g. Cesarsky 1983, Klepach 2000, Bykov 2001
- ...but a lot of renewed interest recently
 - ▶ Aharonian 2019, Gupta 2020, Morlino 2021, Tatischeff 2021, Vieu 2022, 2023, Härer 2025, ...

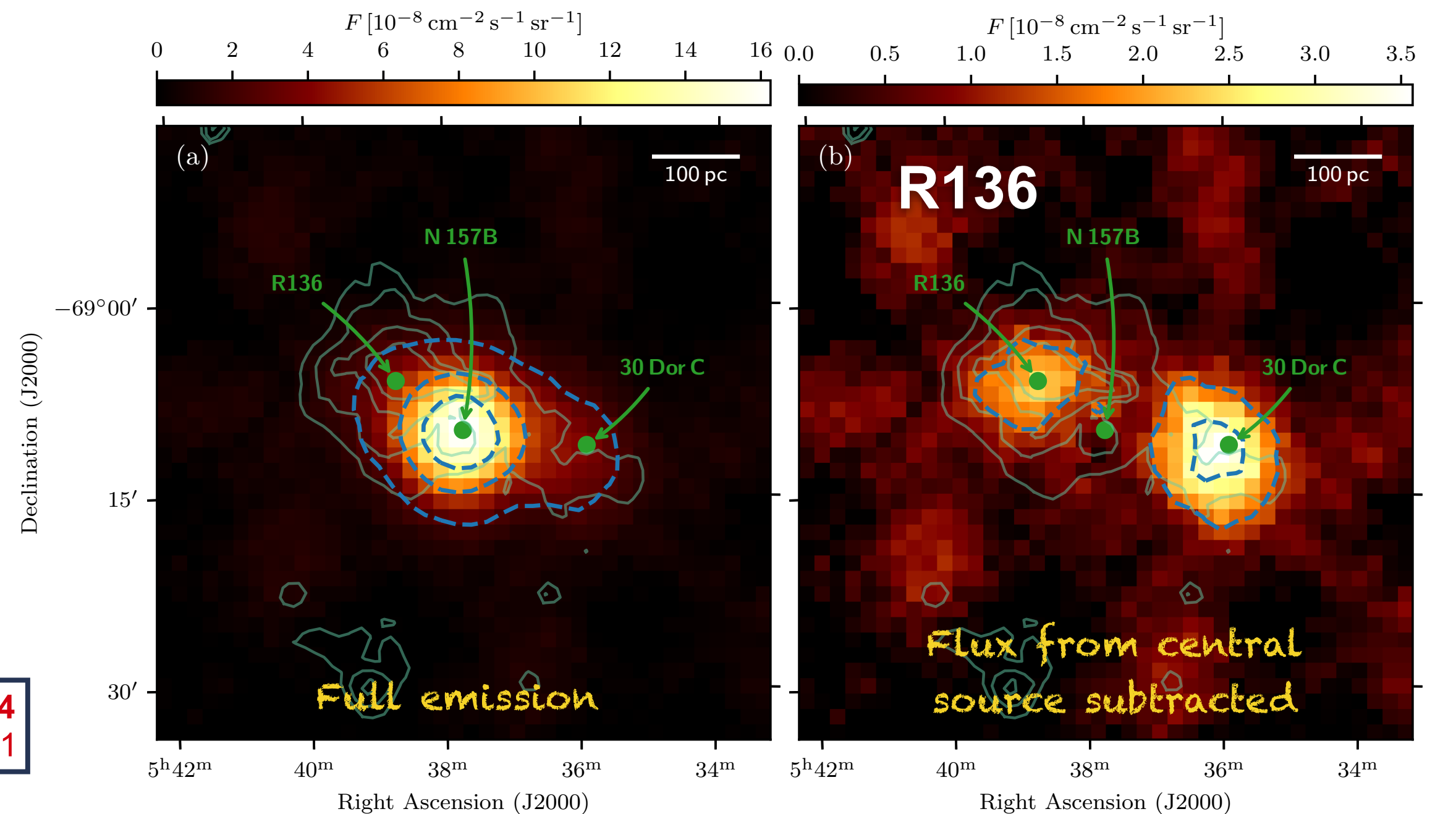
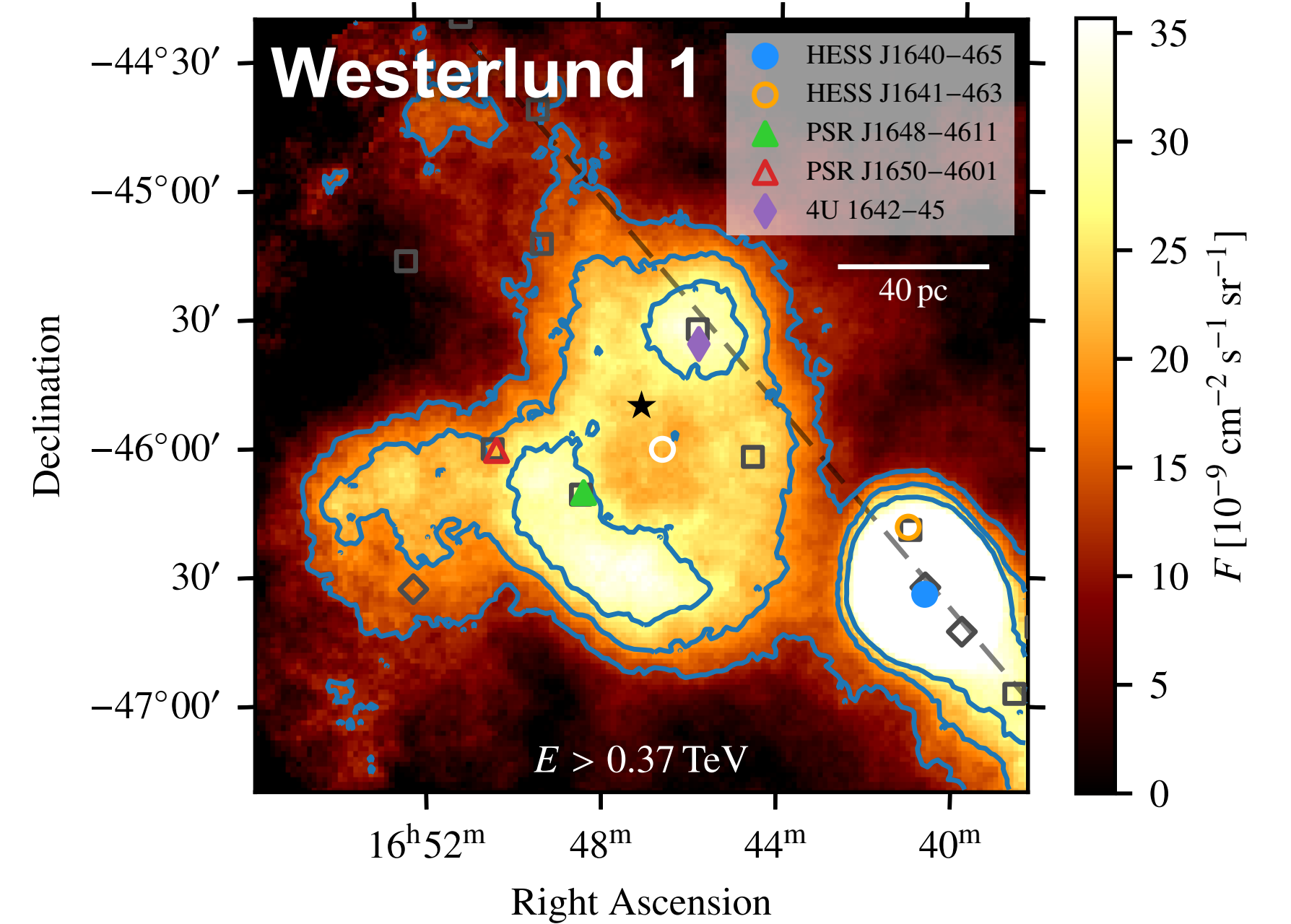
■ Westerlund 1

- ▶ most massive young star cluster in the Milky Way
- ▶ very extended TeV emission
- ▶ ring-like structure

■ R136

- ▶ prominent star cluster in the LMC
- ▶ newly detected
- ▶ more luminous than Westerlund 1!

H.E.S.S. 2022
A&A 666, A124



H.E.S.S. 2024
ApJL 970, L21

Novae with H.E.S.S.

■ RS Ophiuchi

- ▶ symbiotic nova
- ▶ outburst detected in 2022
- ▶ first Galactic VHE transient!

■ Ongoing nova observation program

- ▶ first hint of emission from a classical nova? (YZ Reticuli)

More about novae with Fermi-LAT and H.E.S.S.:
→ visit talk by **Paul Fauverge** (E1.6, Fri 7 Aug, 09:30)!

H.E.S.S. 2022
Science 376, 77–80

Nova RS Ophiuchi (artist's impression)



DESY/H.E.S.S., Science Communication Lab

Multi-wavelength / multi-messenger programs

- **Transients are a key H.E.S.S. science topic**

- ▶ participation in coordinated programs / campaigns crucial

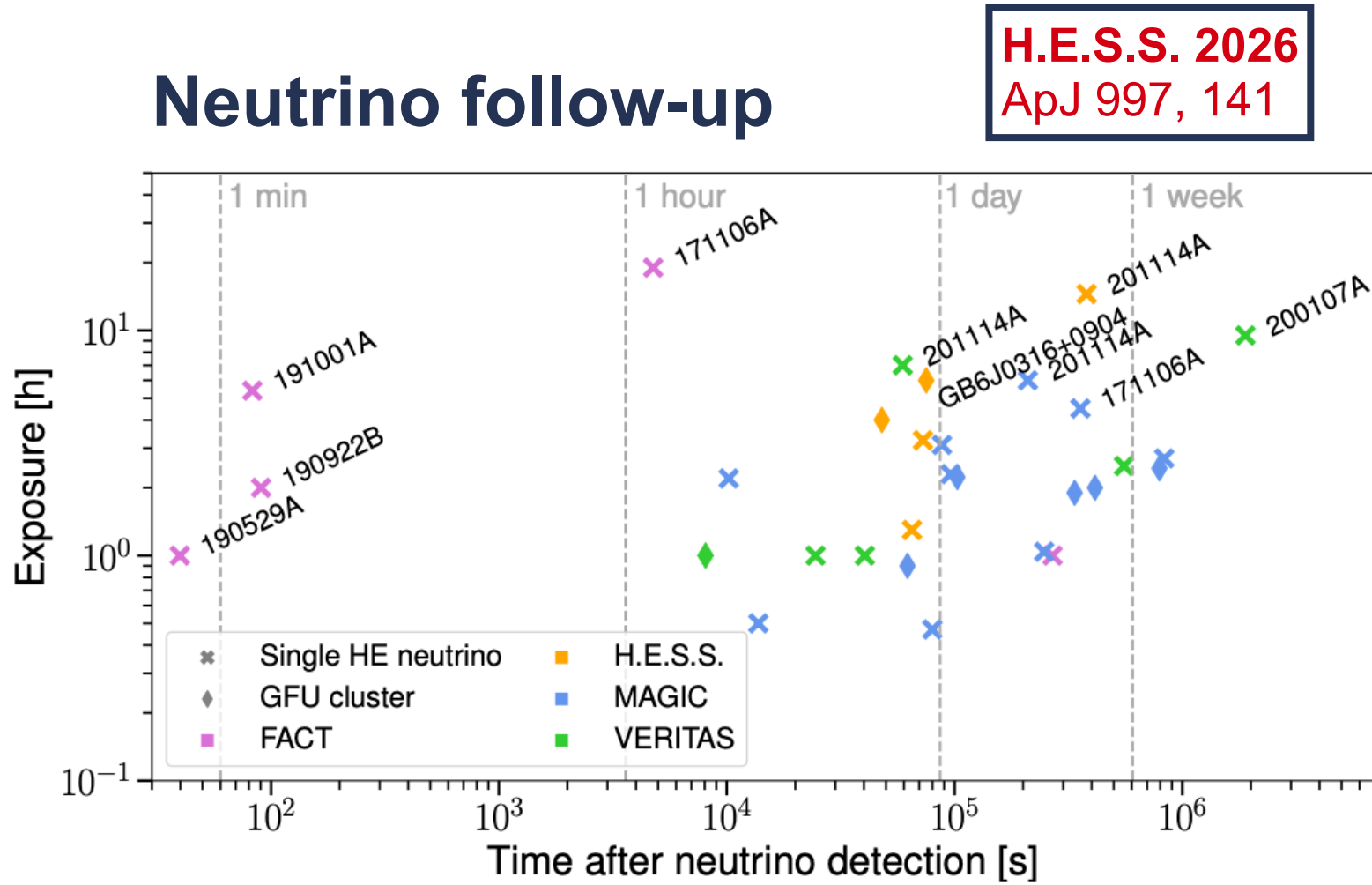
- **Alert streams**

- ▶ IceCube (neutrinos)
- ▶ LIGO/Virgo/KAGRA (gravitational waves)
- ▶ Fermi
 - GBM (keV–MeV)
 - LAT (MeV–GeV)
- ▶ Swift-BAT (hard X-ray)
- ▶ SVOM ECLAIRs (X-ray)

- **Coordinated observation campaigns**

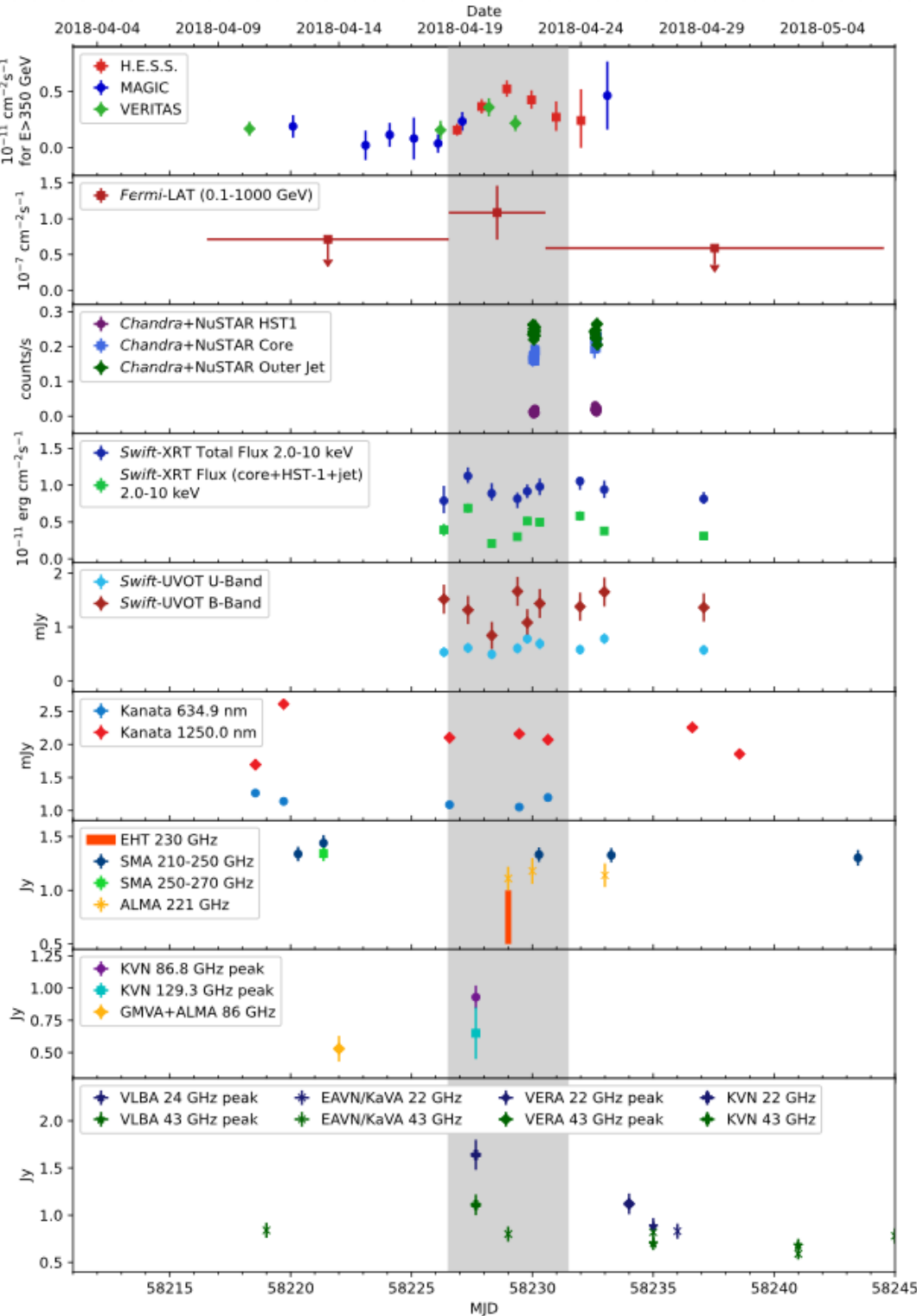
- ▶ Event Horizon Telescope (e.g. M87)
- ▶ MeerKAT (e.g. FRBs)
- ▶ XMM-Newton (X-ray, simultaneous time requests)
- ▶ Swift-XRT (X-ray)
- ▶ SALT (e.g. for optical polarimetry)

▶ ...



**EHT MWL
campaign
on M87**

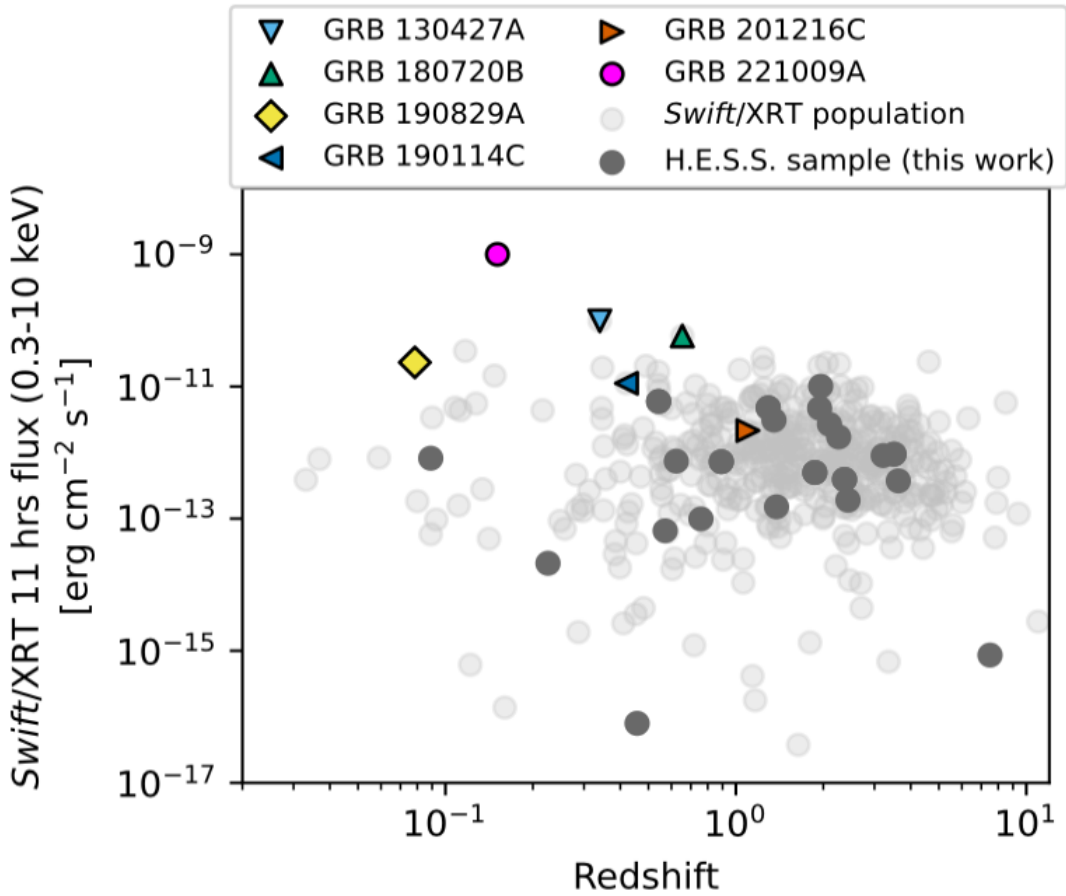
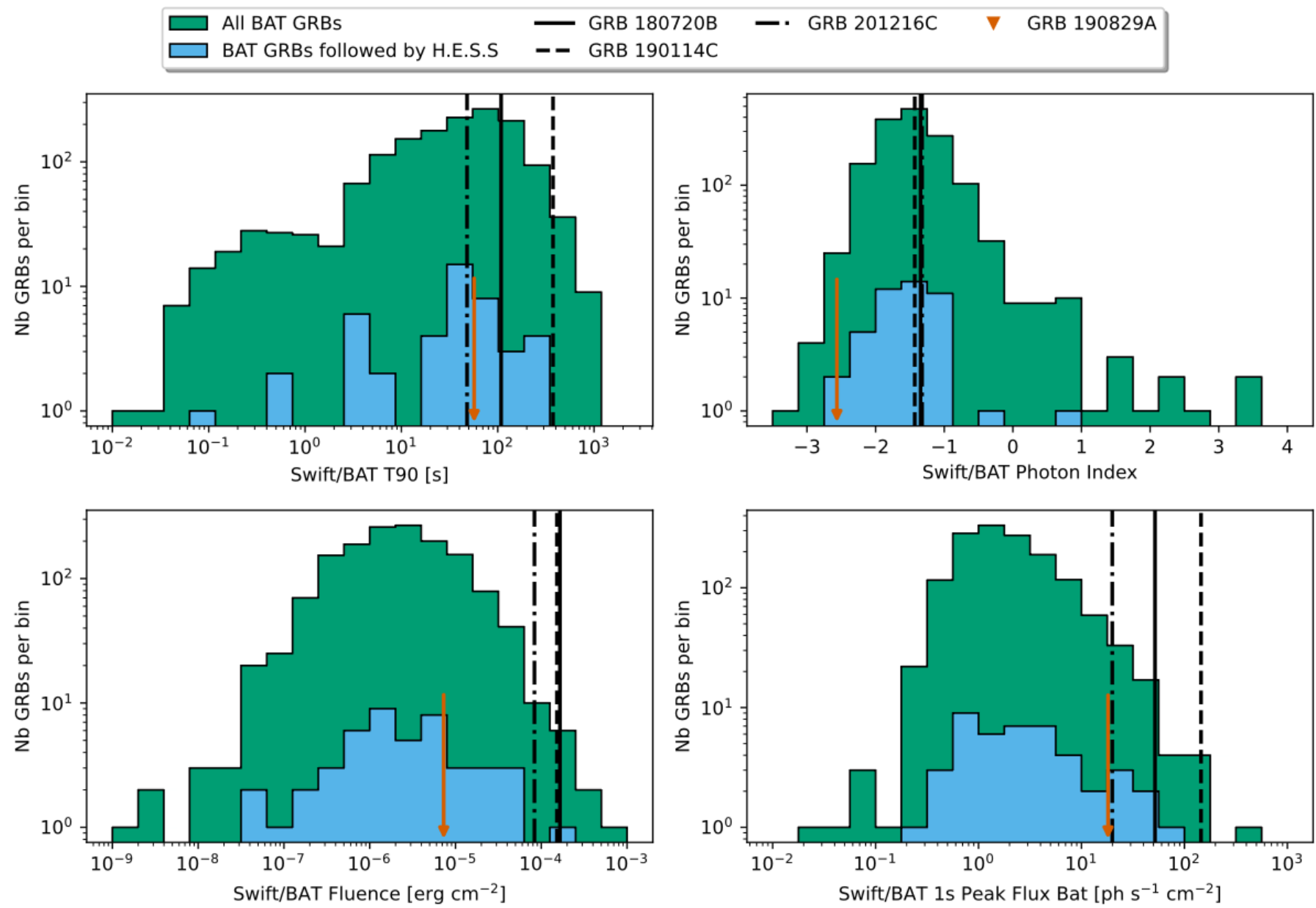
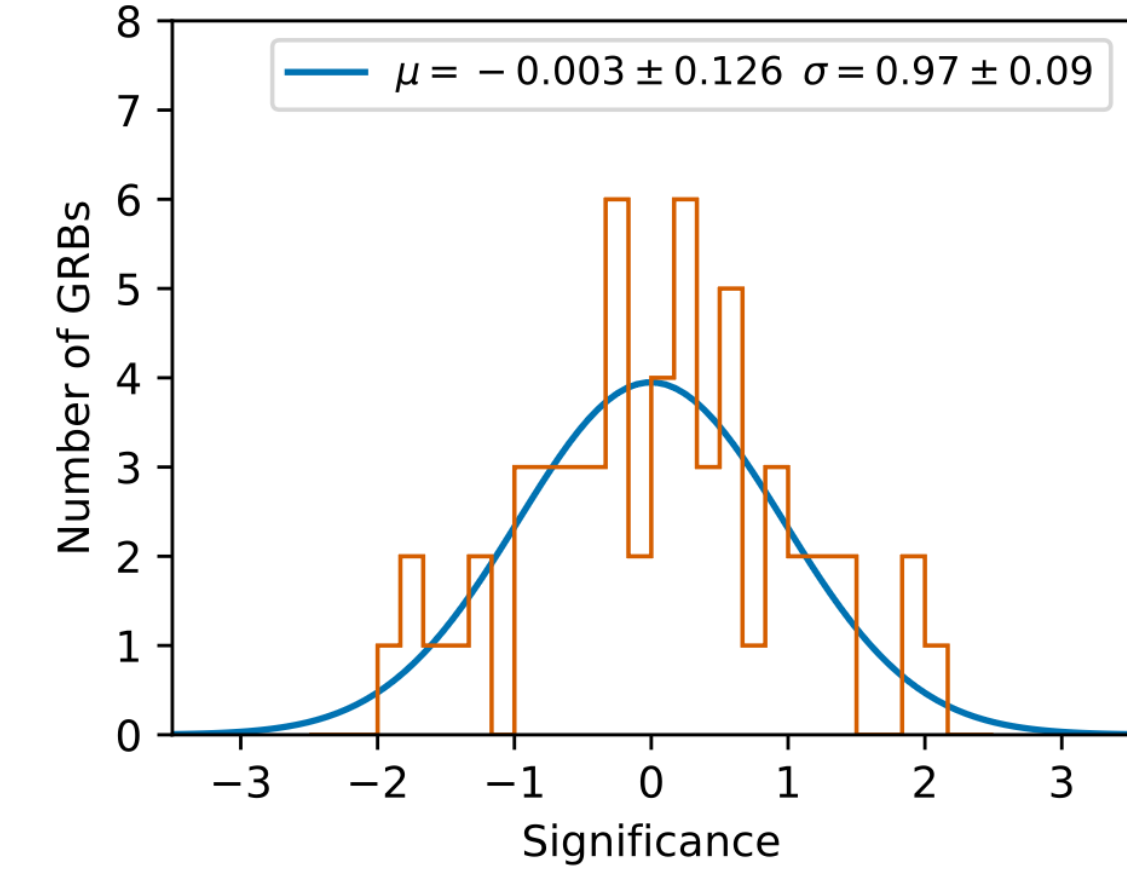
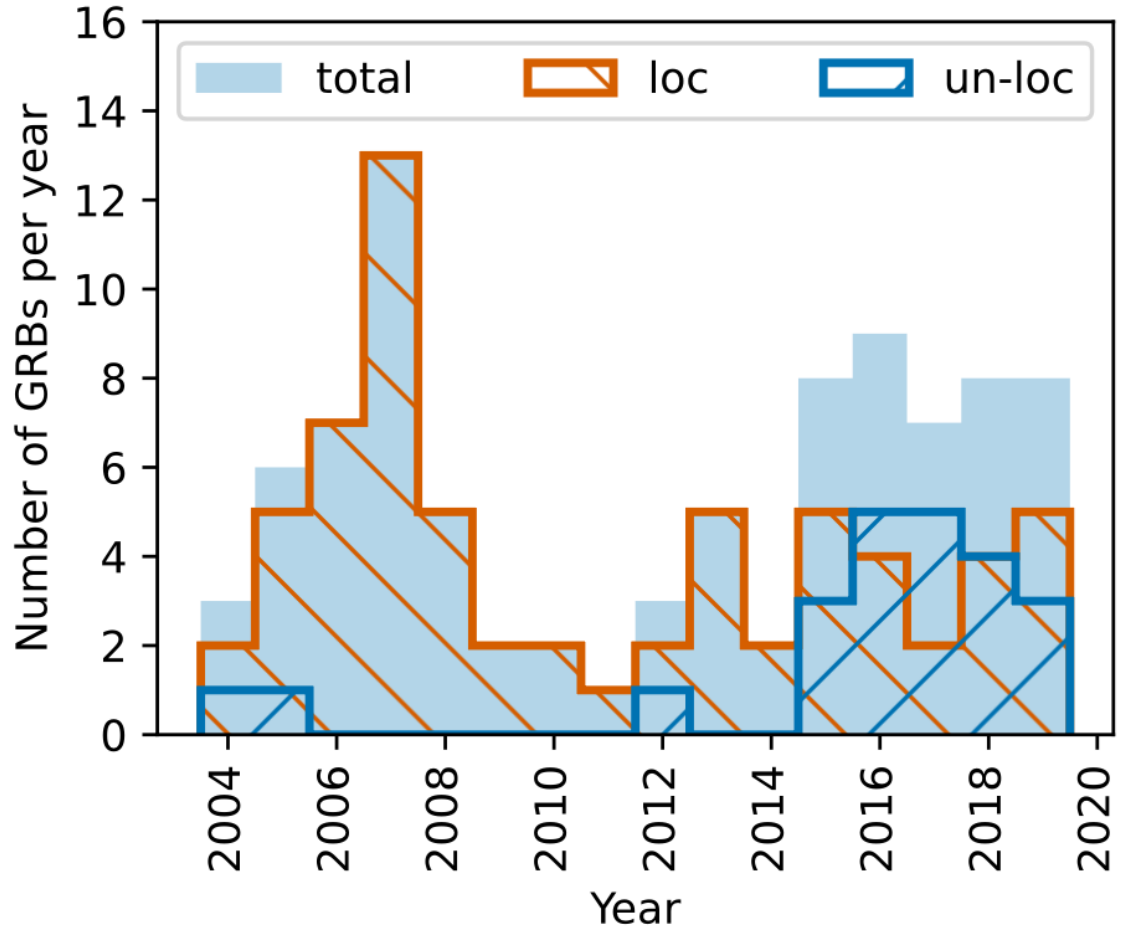
H.E.S.S. 2024
A&A 692, A140



15-year gamma-ray burst catalogue

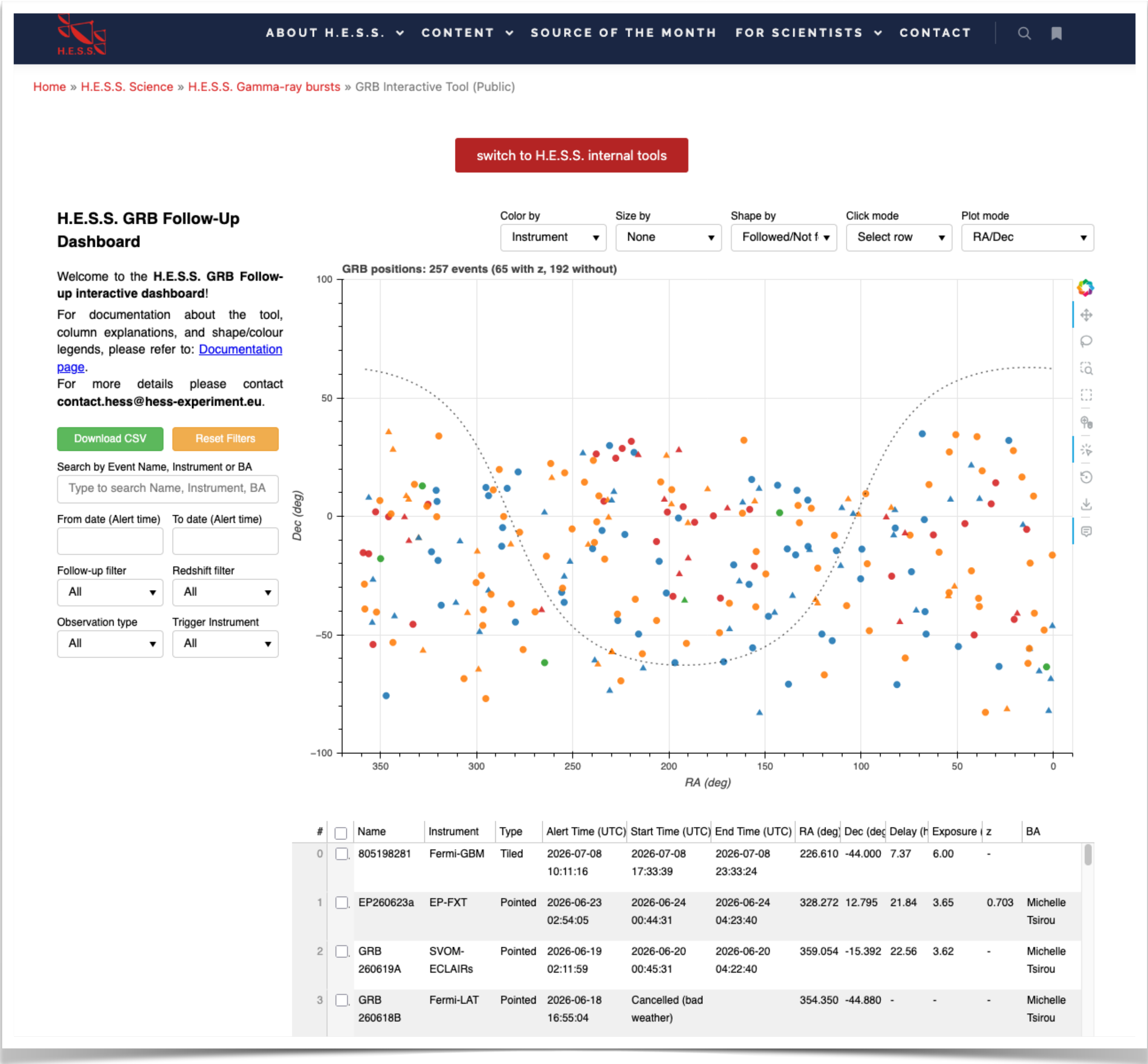
H.E.S.S. 2026
A&A 707, A382

- 89 GRBs between 2004 and 2019
 - ▶ 66 well-localised
- No further detections with H.E.S.S. beyond GRB 180720B and GRB 190829A
 - ▶ also no cumulative signal in a stacked analysis
 - ▶ but understand better which GRBs are promising candidates for TeV emission



Interactive GRB tool

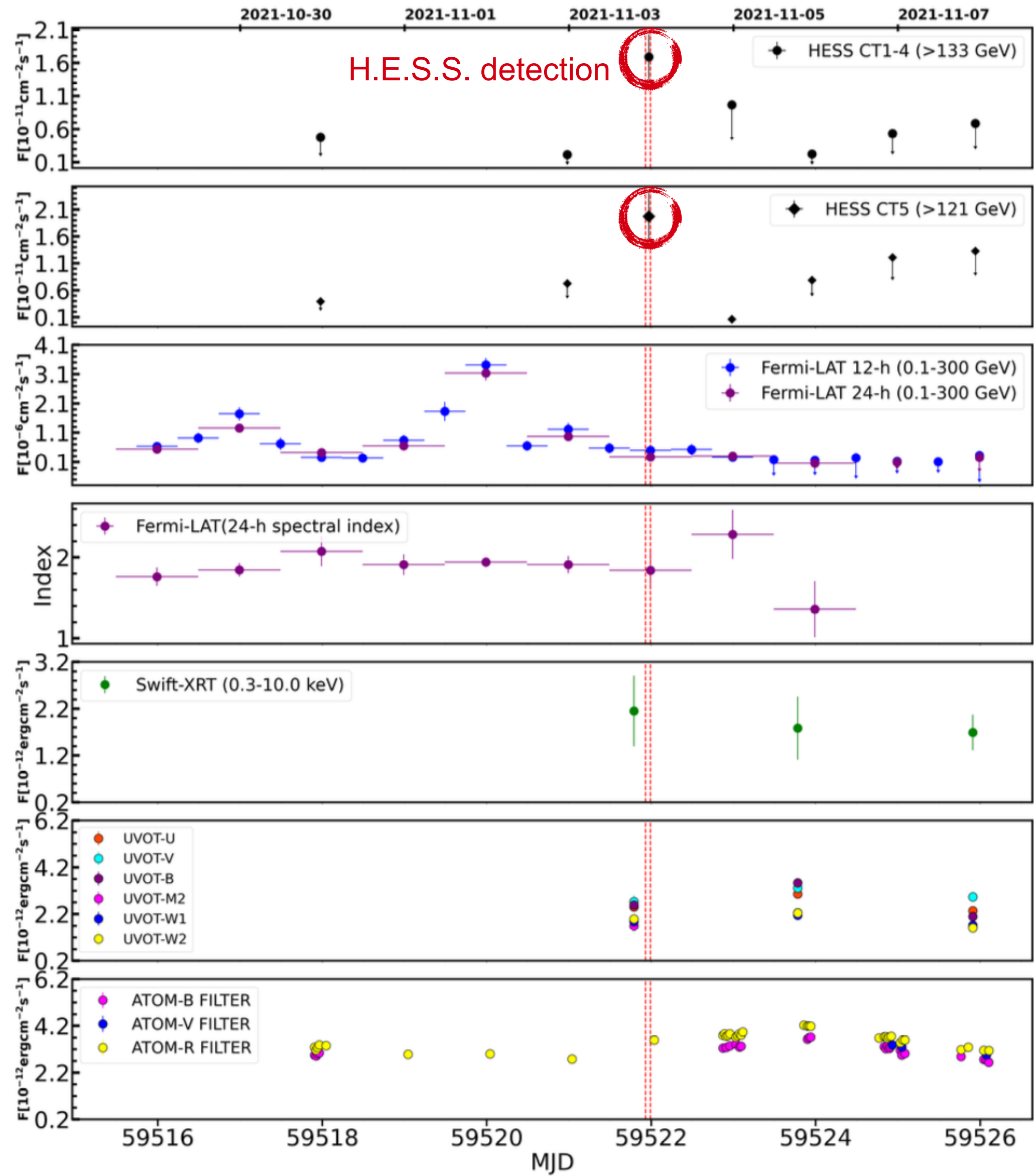
- <https://hess-experiment.eu/science/hess-grb-obs/interactive-tool/>
- Public list of all GRB follow-up observations by H.E.S.S.
- Can explore dataset interactively



PKS 0346–27 — H.E.S.S.’ most distant blazar

- Flare in November 2021
 - detected in one night with H.E.S.S.
 - delay of two days w.r.t. GeV flare

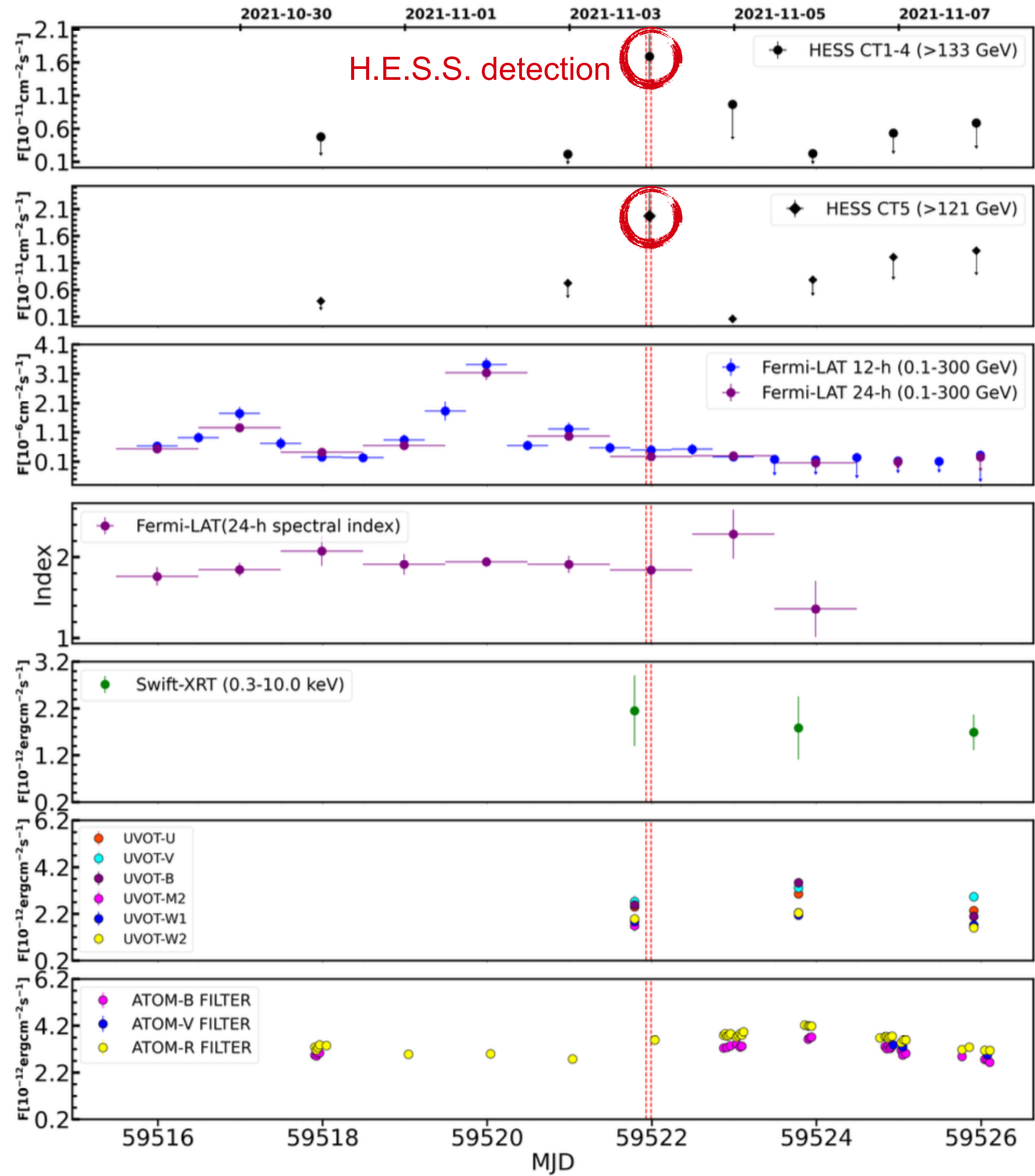
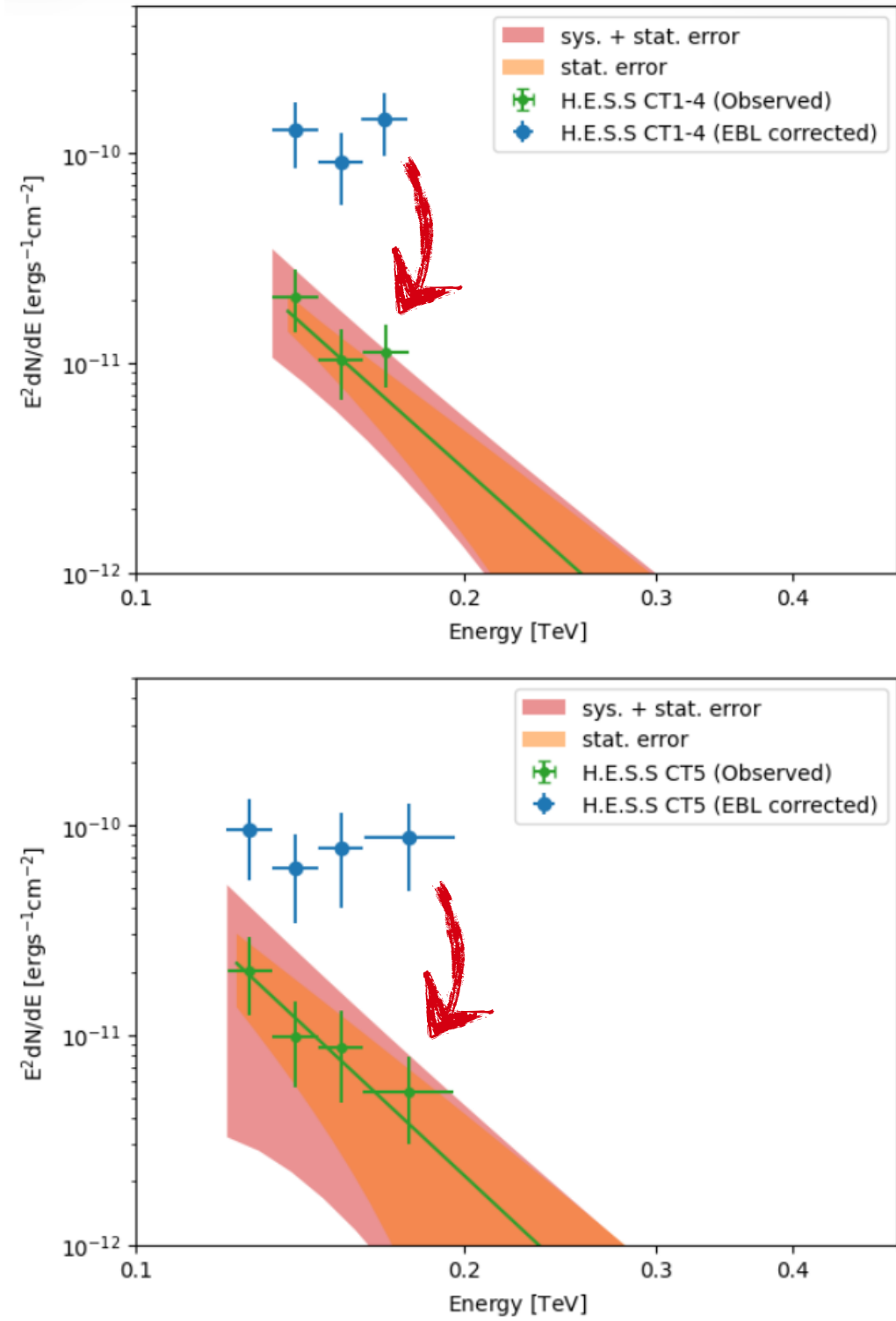
H.E.S.S. 2026
A&A 706, A246



PKS 0346–27 — H.E.S.S.’ most distant blazar

- **Flare in November 2021**
 - detected in one night with H.E.S.S.
 - delay of two days w.r.t. GeV flare
- **Redshift $z = 0.991$ — a new distance record for H.E.S.S.!**
 - severe EBL absorption

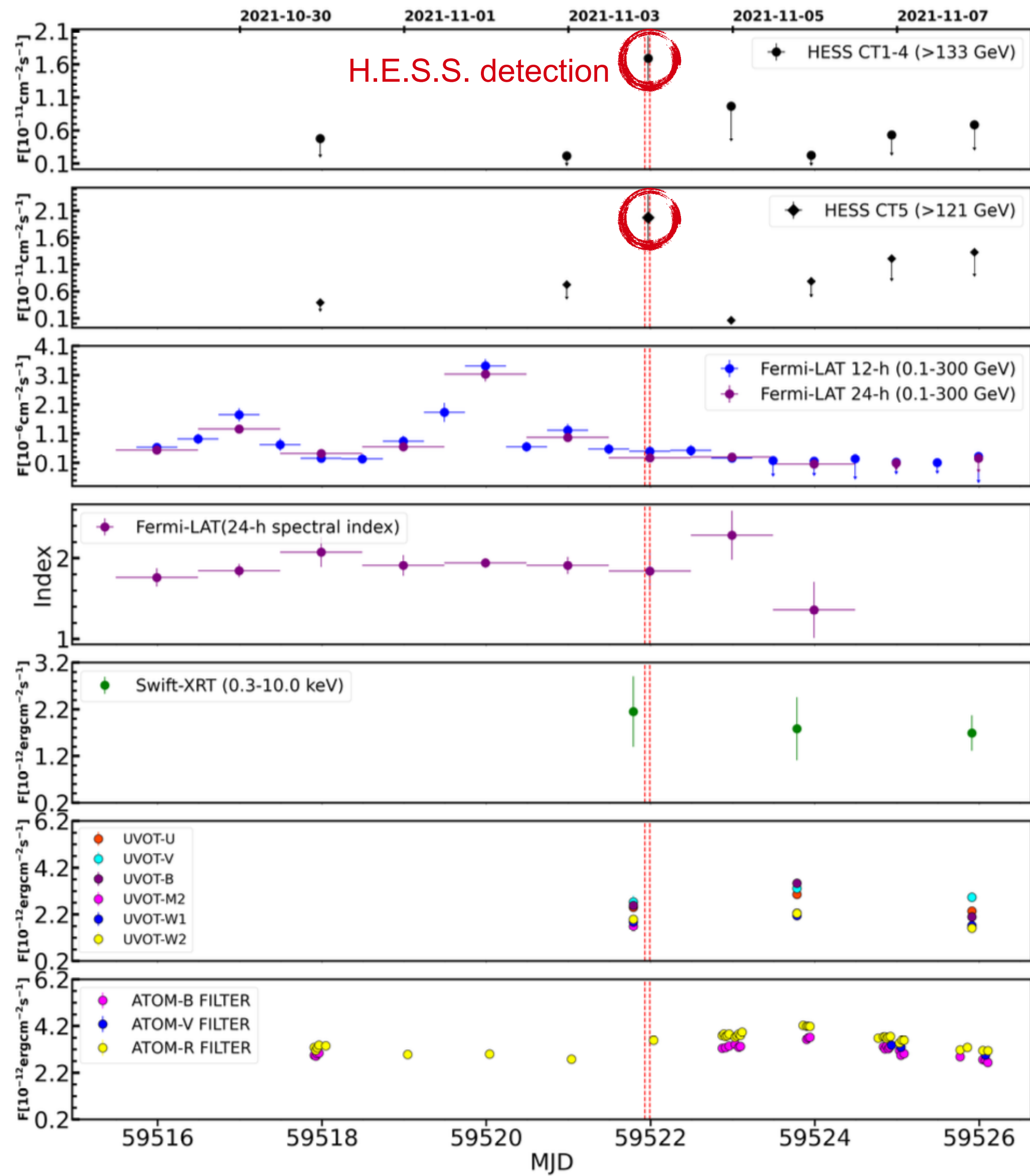
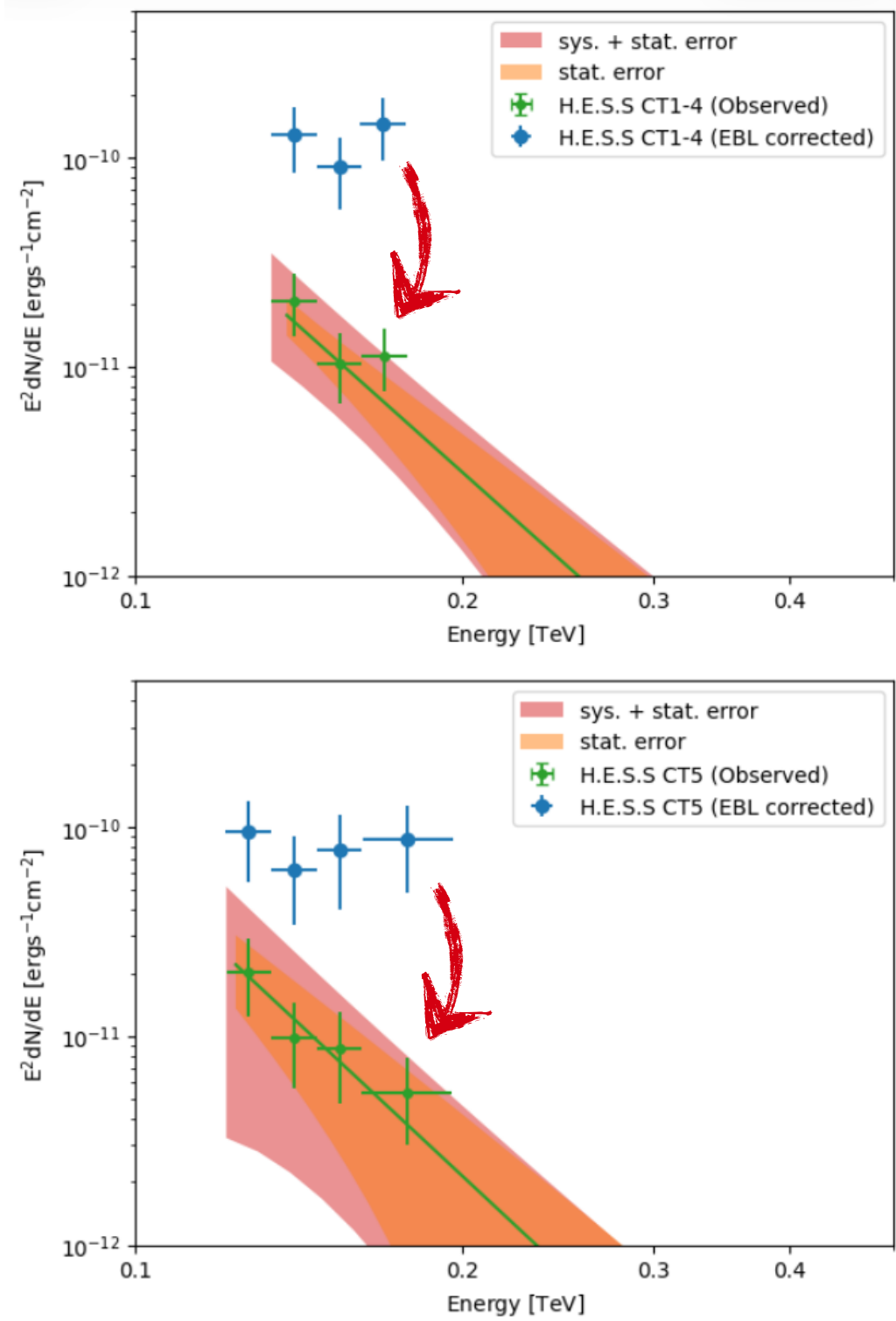
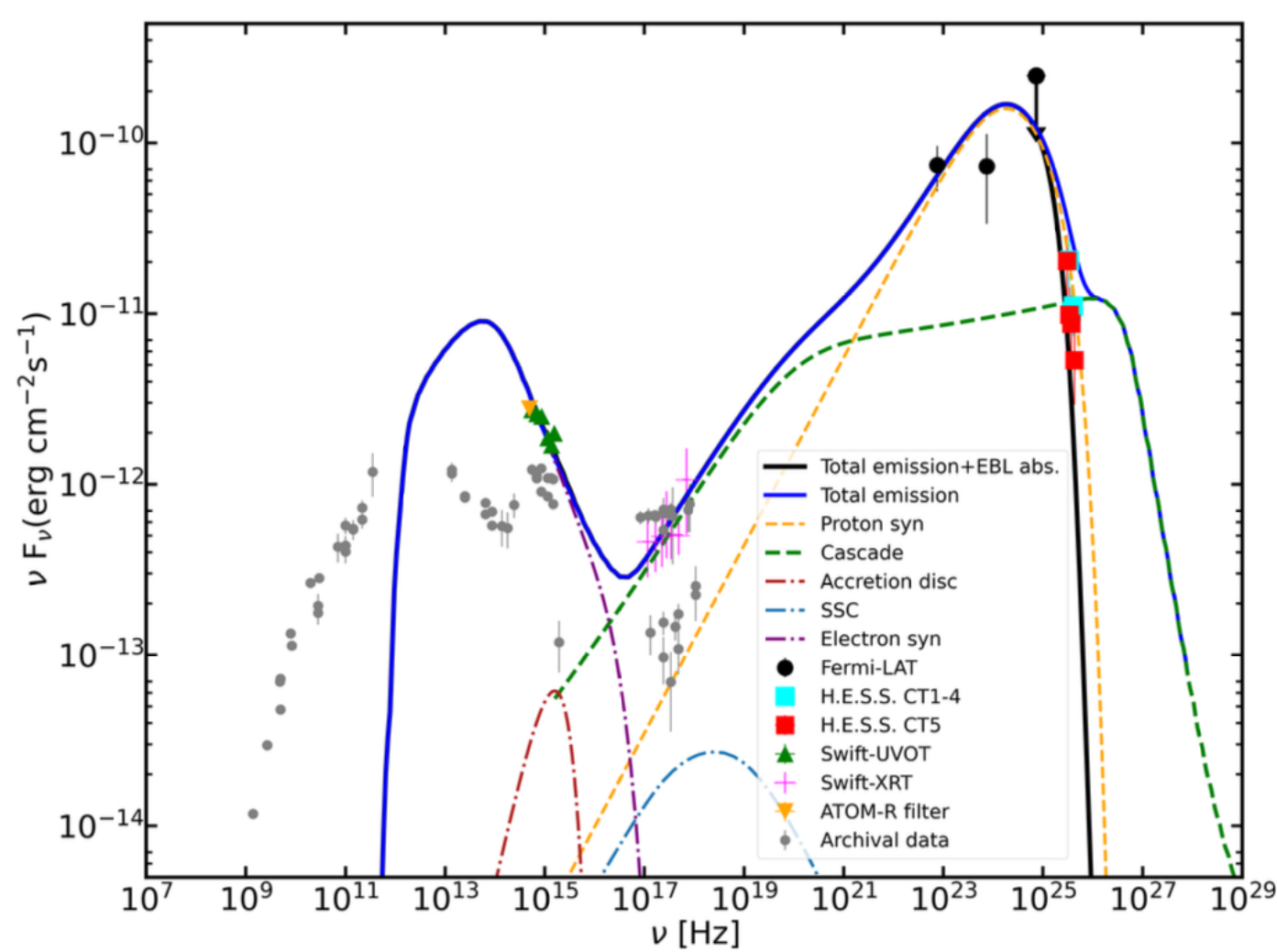
H.E.S.S. 2026
A&A 706, A246



PKS 0346–27 — H.E.S.S.’ most distant blazar

- **Flare in November 2021**
 - detected in one night with H.E.S.S.
 - delay of two days w.r.t. GeV flare
- **Redshift $z = 0.991$ — a new distance record for H.E.S.S.!**
 - severe EBL absorption
- **Broadband SED fit**
 - hadronic model favoured
 - delay w.r.t. GeV emission an open question

H.E.S.S. 2026
A&A 706, A246

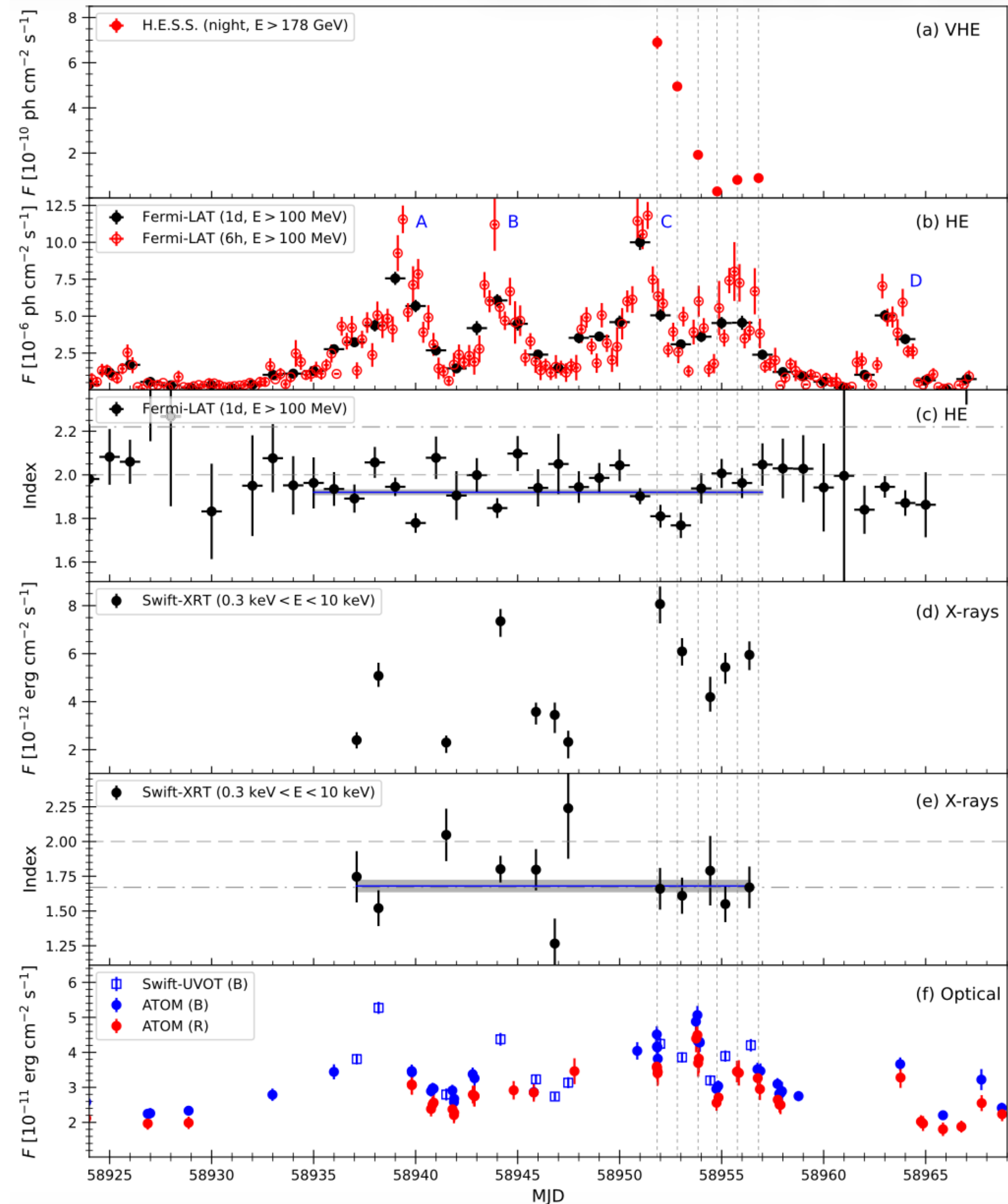
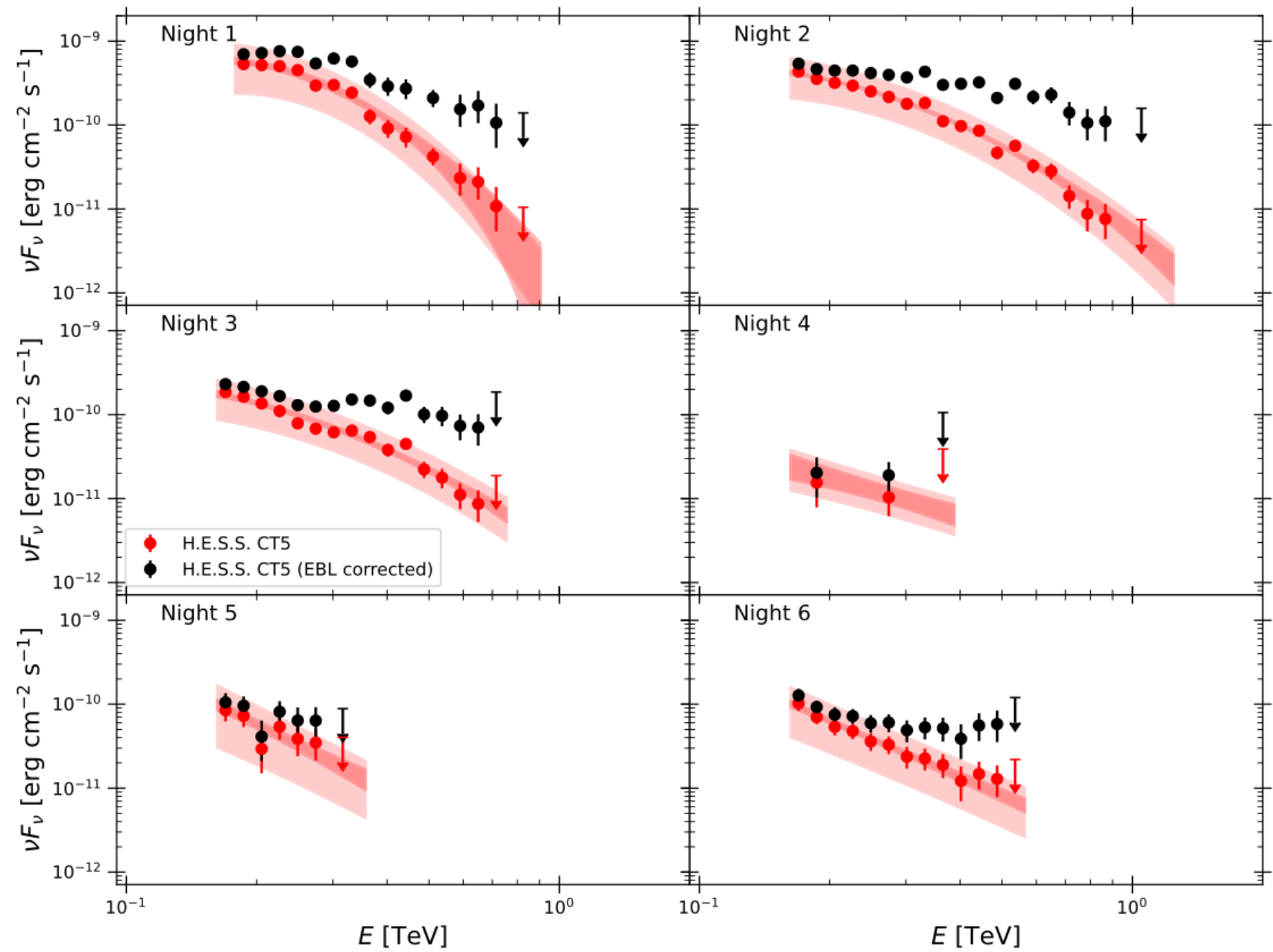


PKS 0903–57 — the “lockdown flare”

H.E.S.S. 2026
JHEAp 53, 100599

- **Flare in April 2020**
 - ▶ shortly after CT5 camera upgrade (end of 2019)
 - ▶ detected in six consecutive nights
 - ▶ variability time scale ~ 5 h
 - ▶ coincident with GeV flare
- **Led to classification of blazar as FSRQ** (Goldoni et al. 2024)
 - ▶ $z = 0.2621 \rightarrow$ second-closest VHE-detected FSRQ

- **Modelling**
 - ▶ broad-line region (BLR) opaque to gamma rays
 - ▶ emission region outside of BLR



Search for dark-matter annihilation lines toward the Galactic Centre

■ H.E.S.S. Inner Galaxy Survey

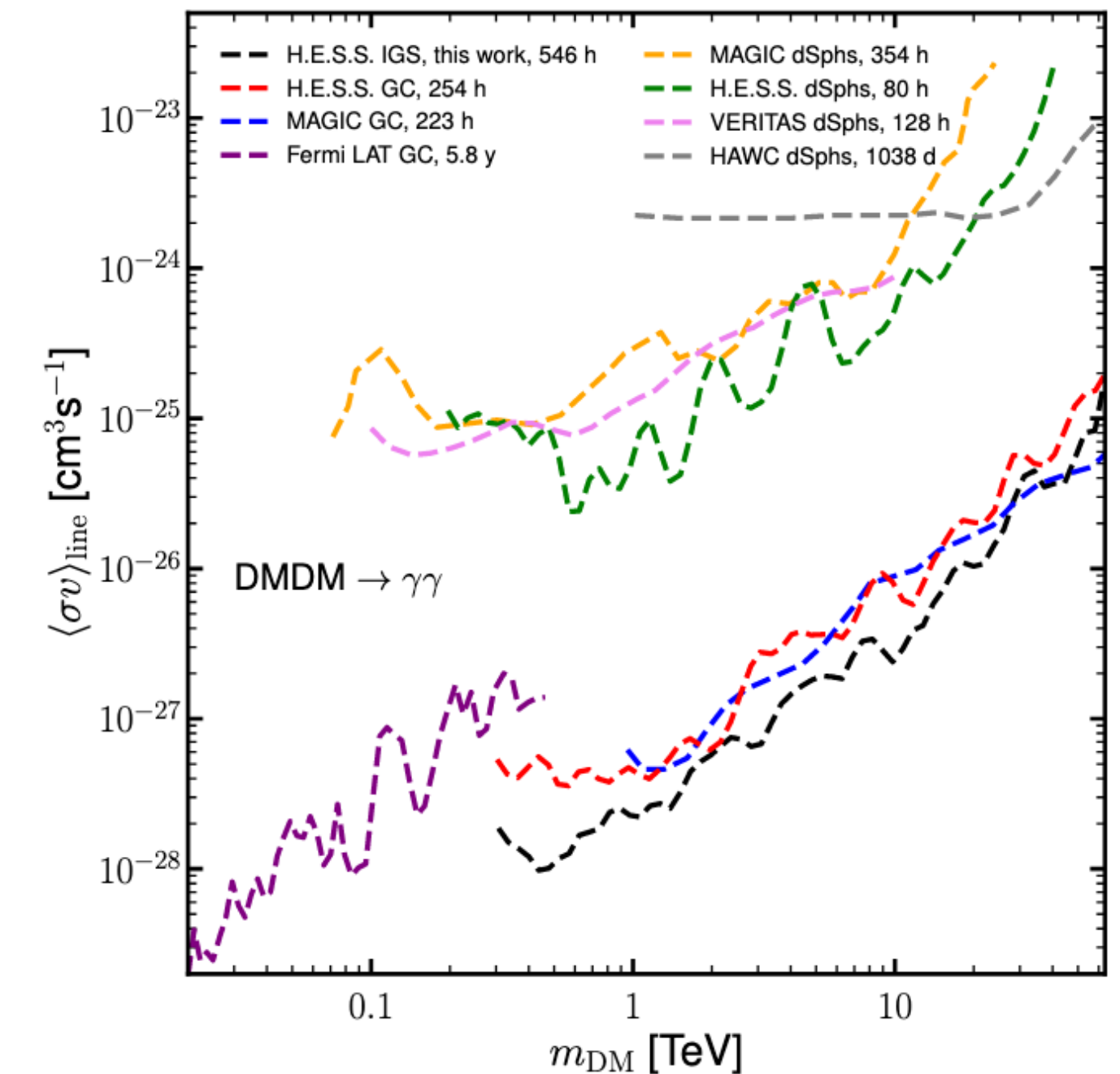
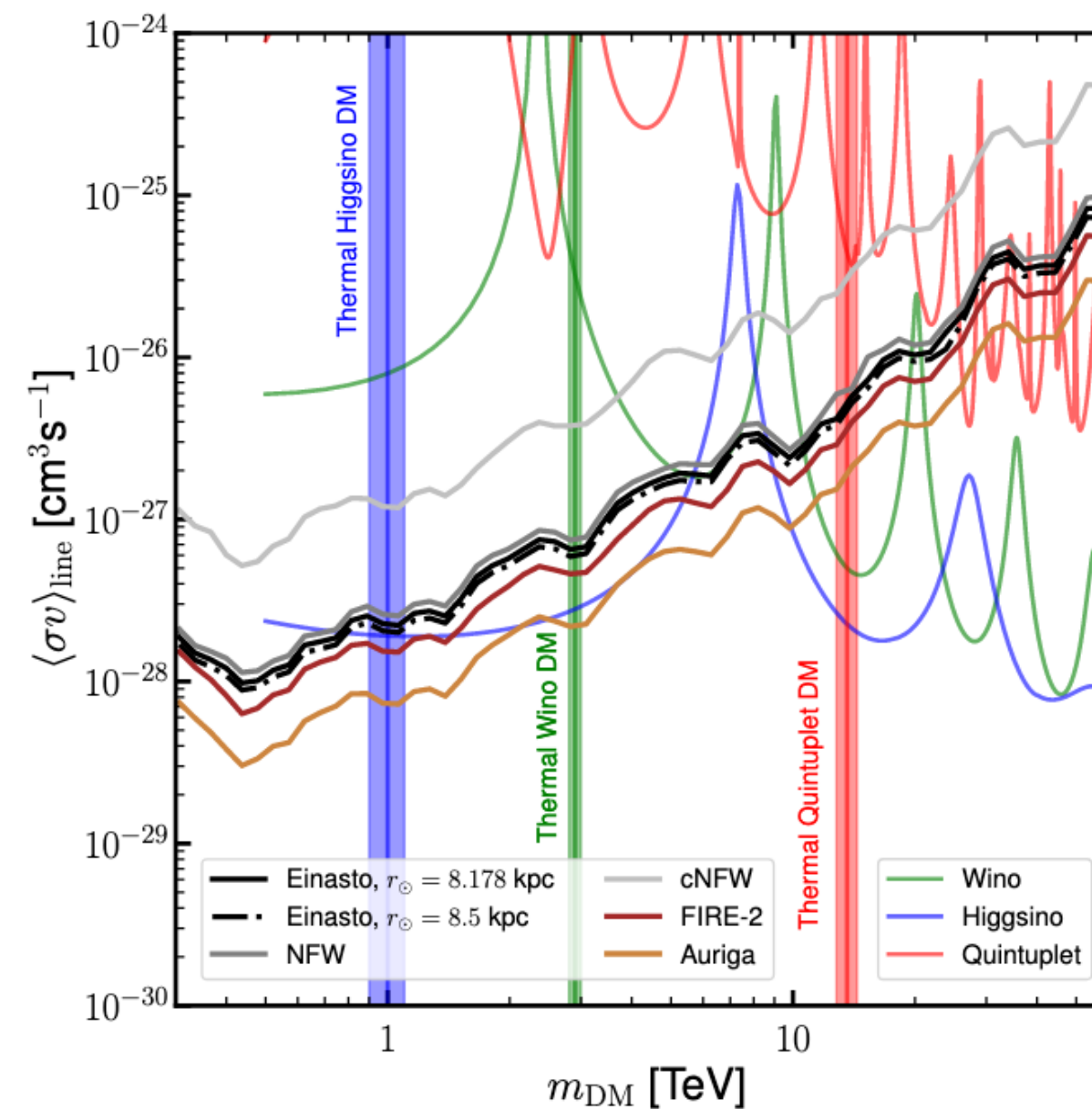
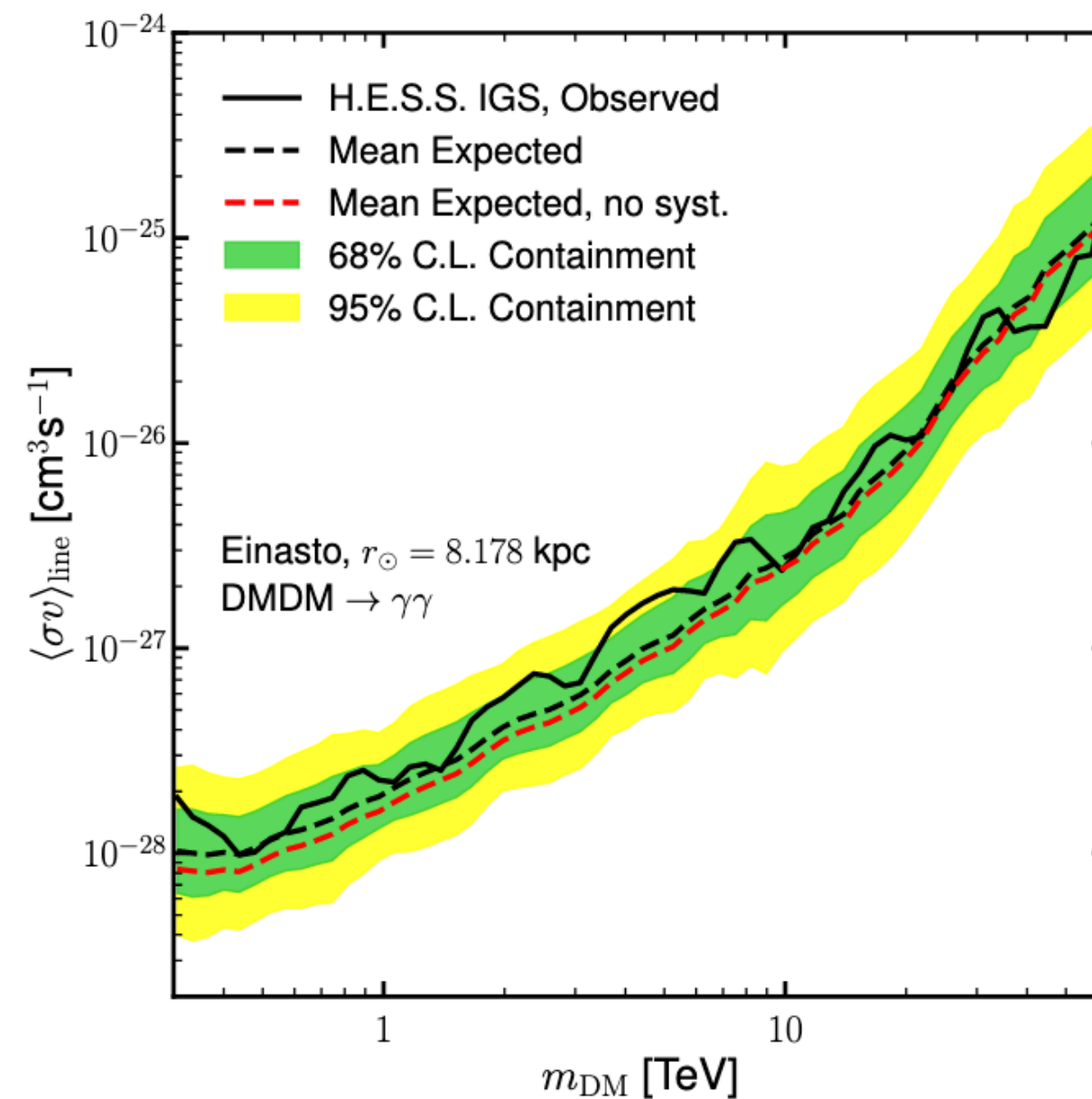
- ▶ extremely deep dataset (546 hours of observation)

■ World-leading limits on $\text{DM DM} \rightarrow \gamma\gamma$ channel

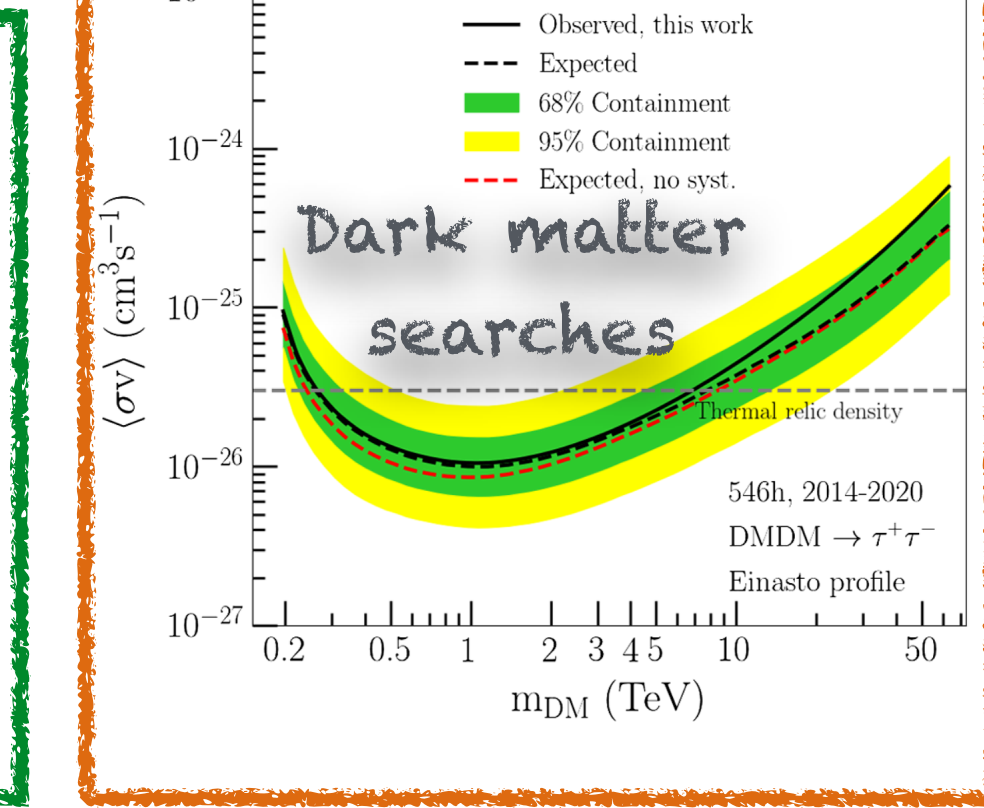
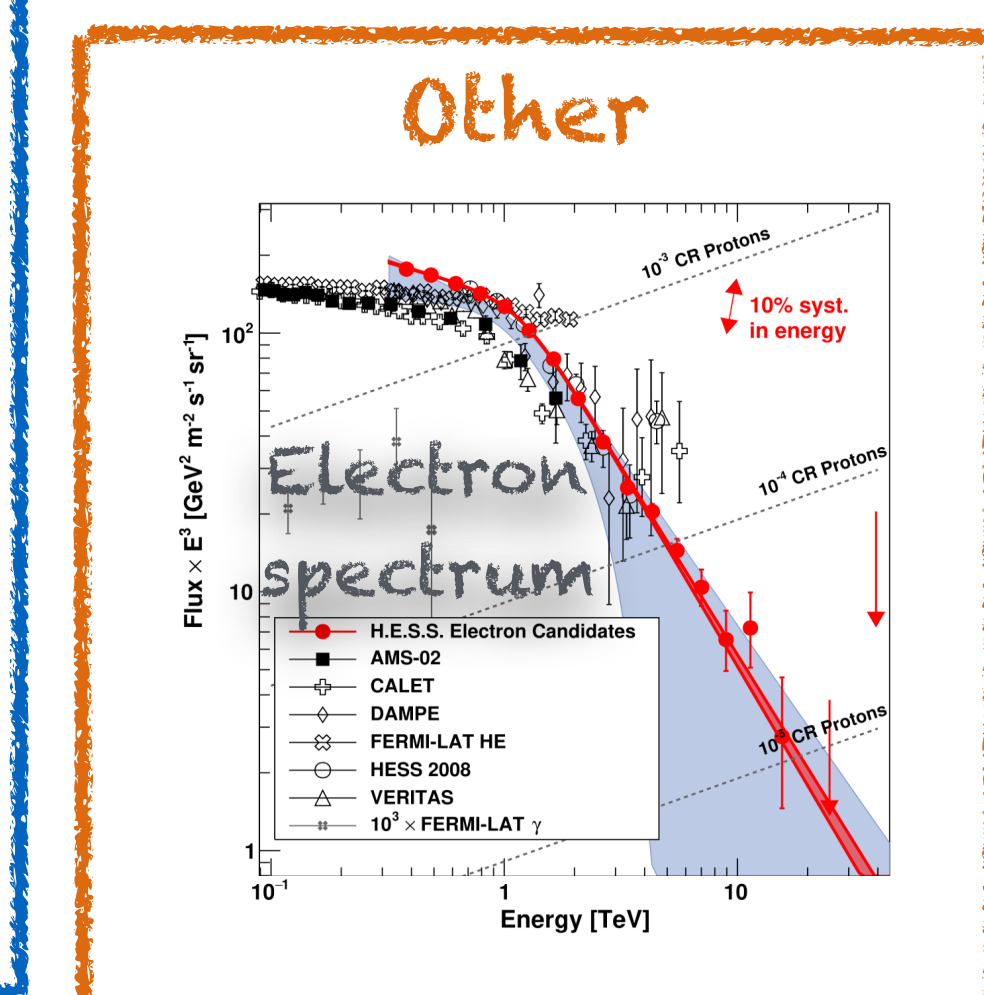
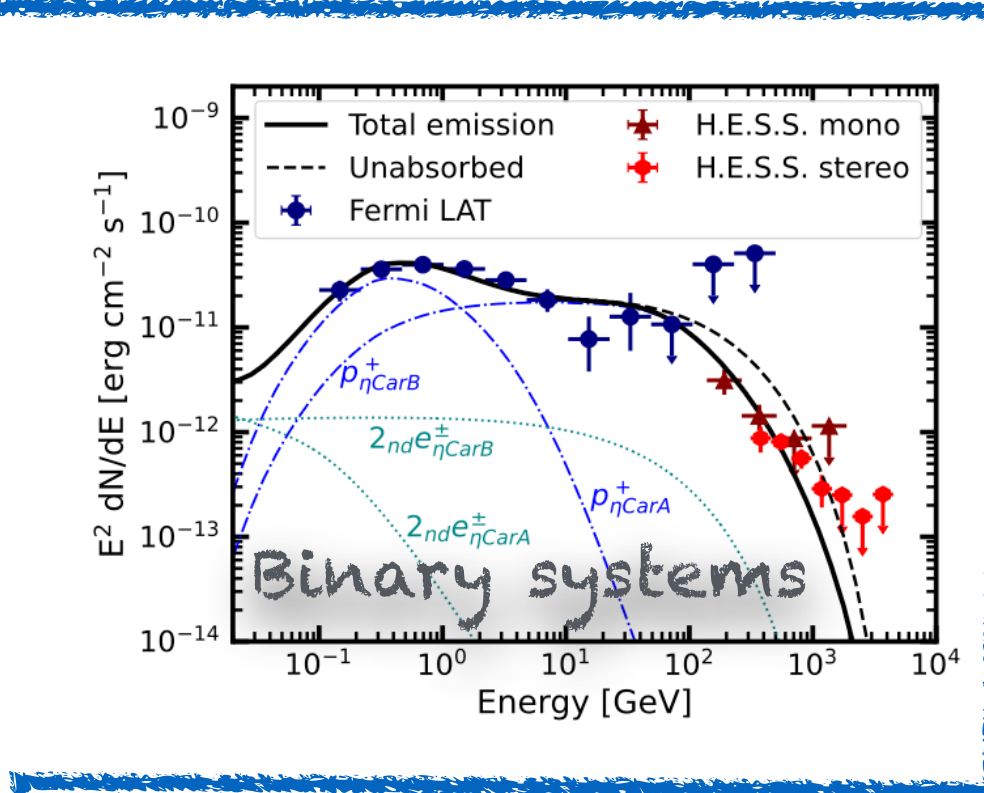
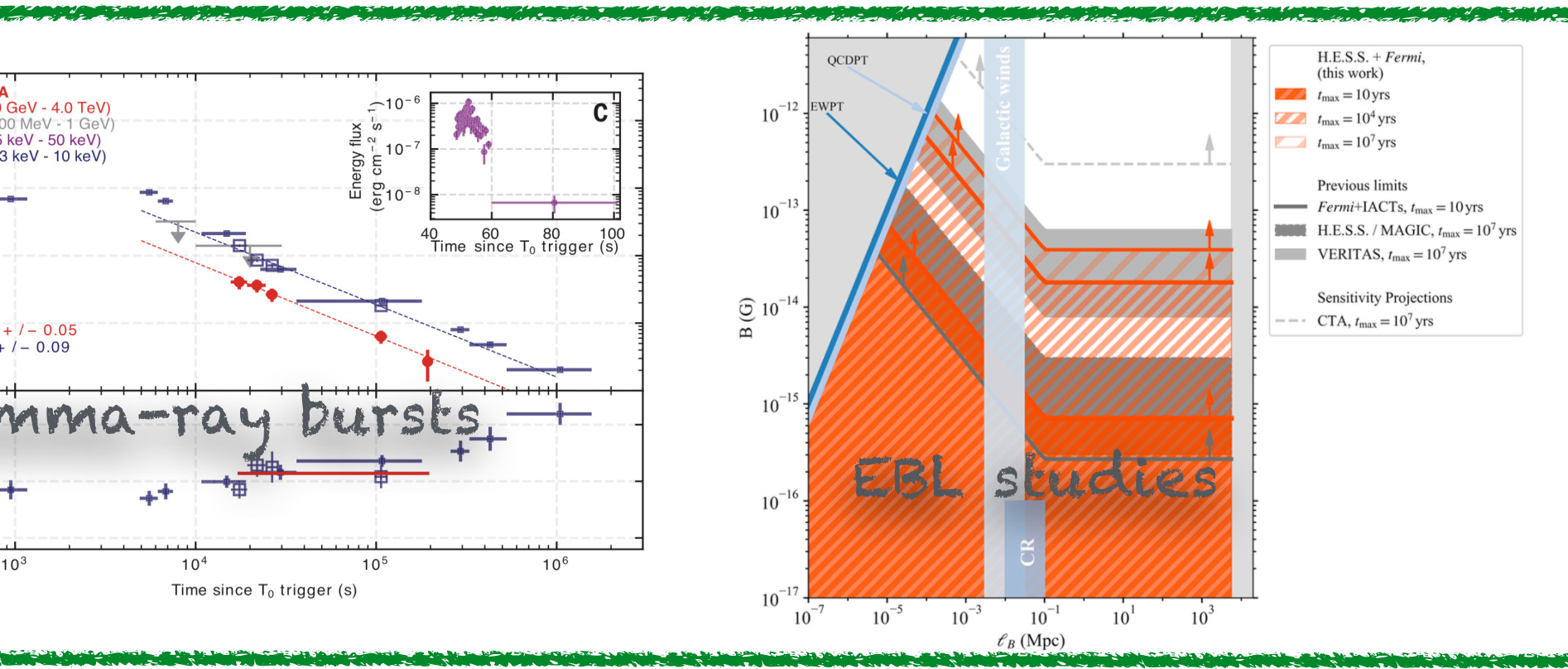
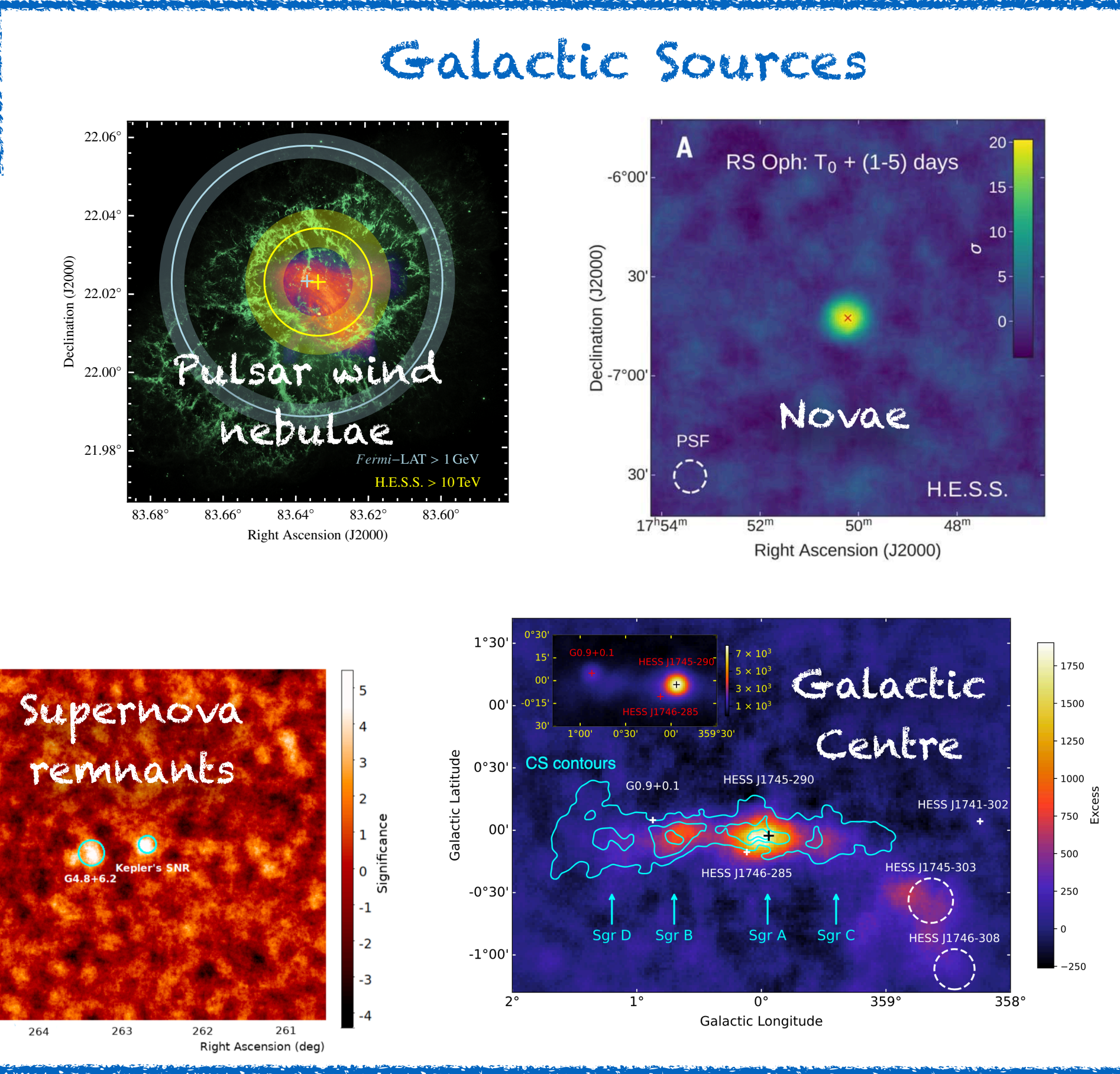
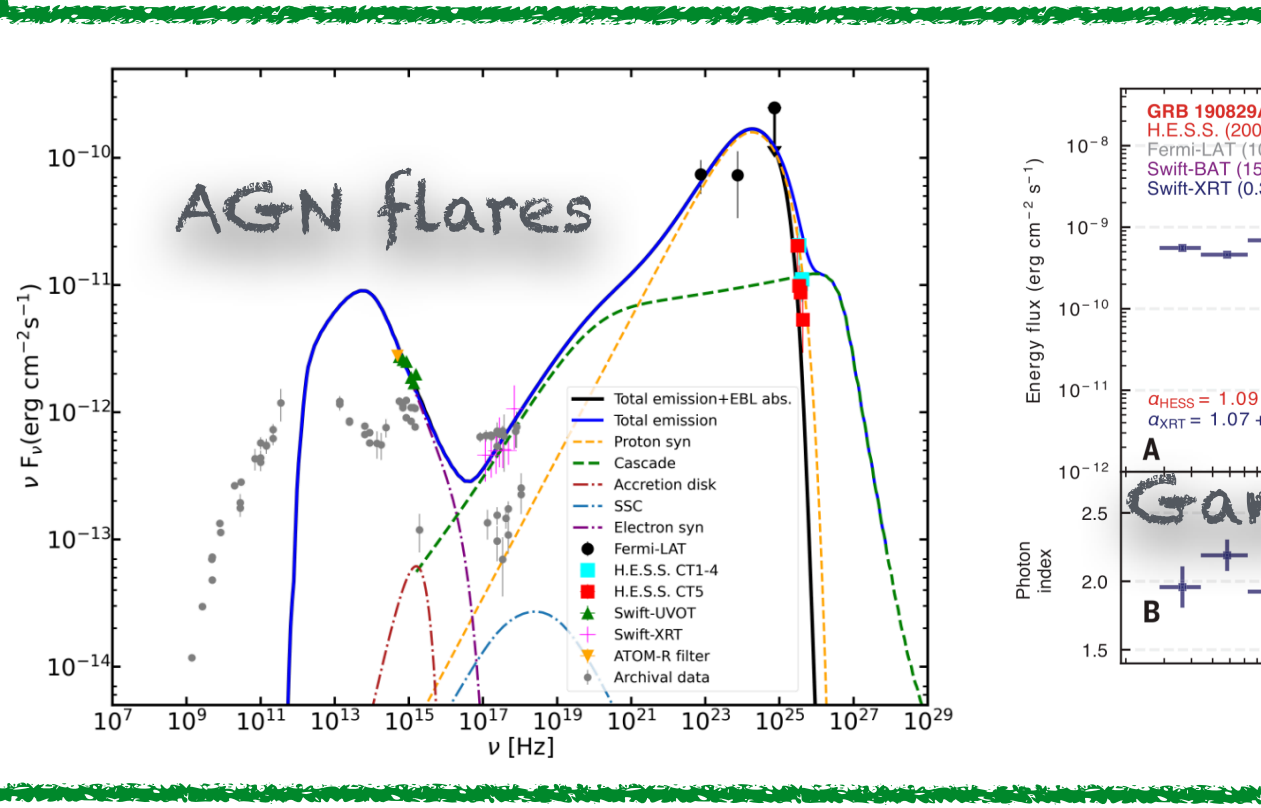
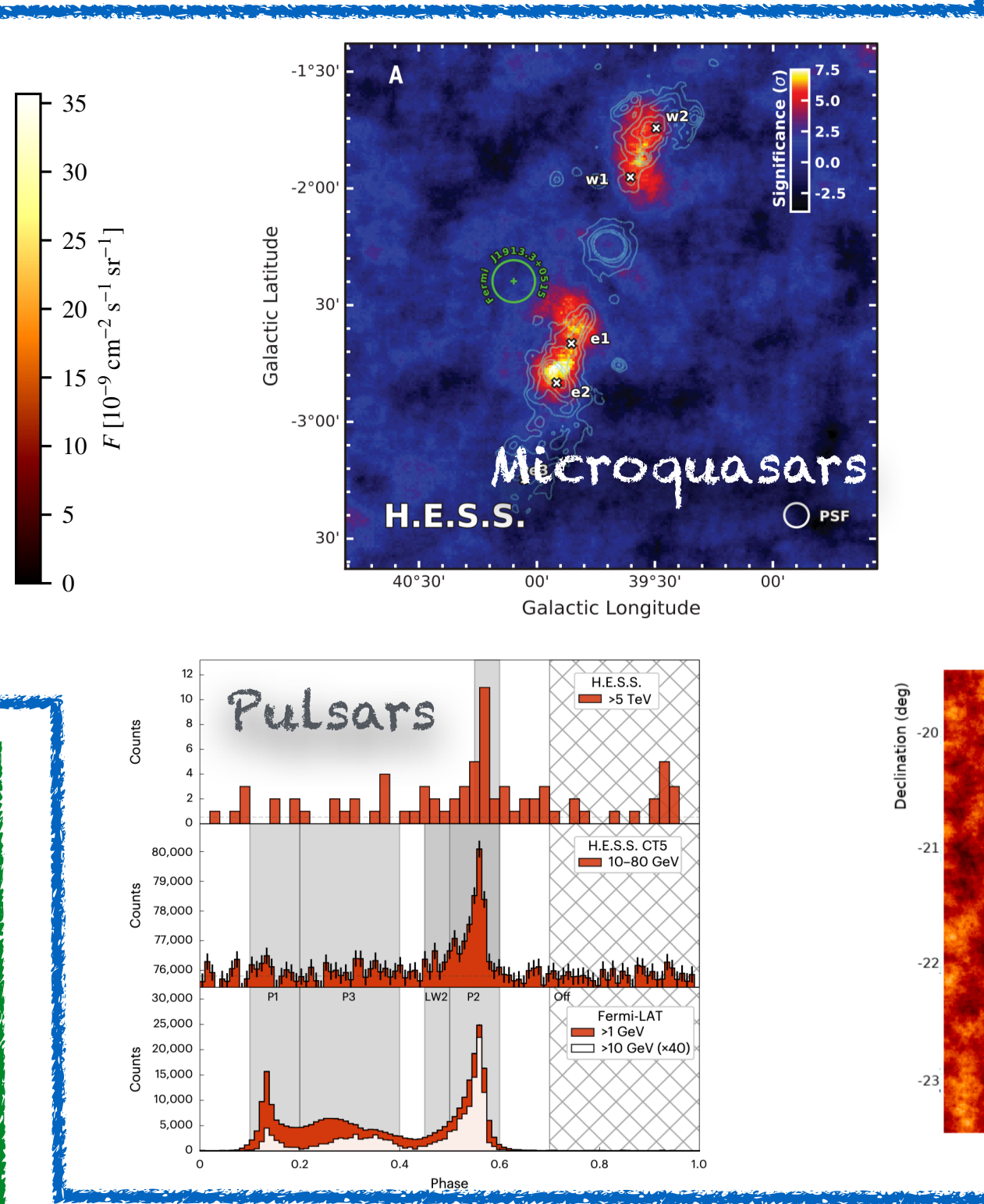
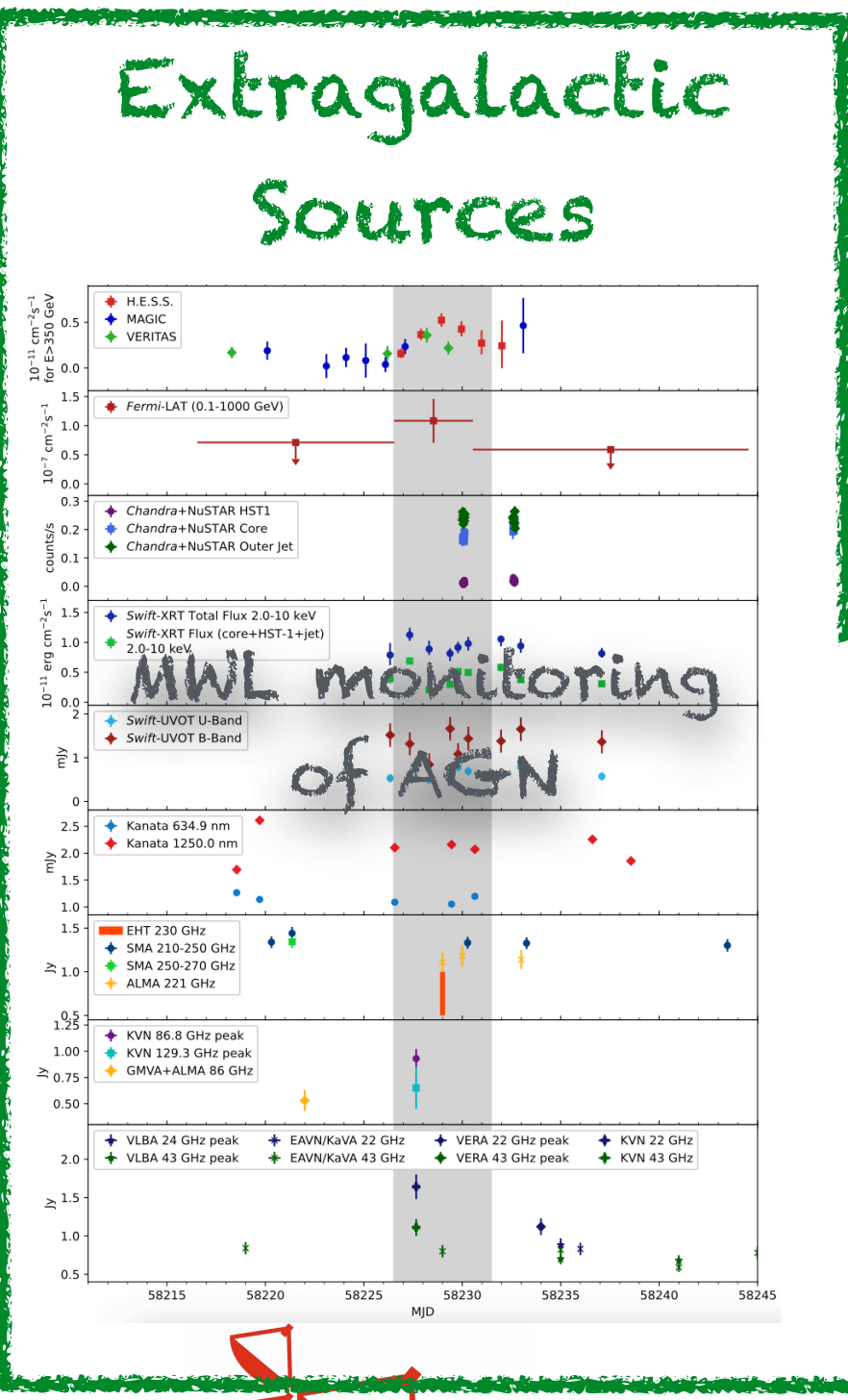
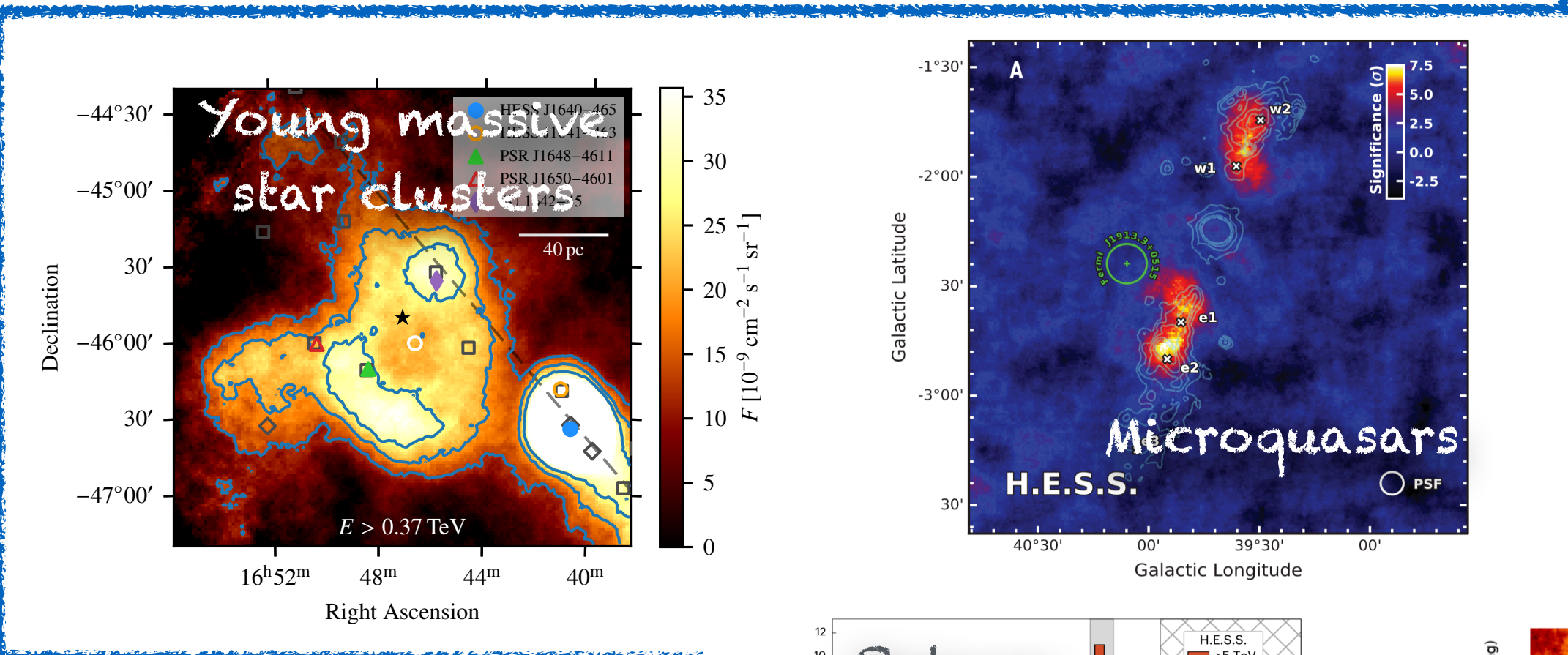
■ Constraints on SU(2) supersymmetry models

- ▶ thermal Wino and Quintuplet models already previously excluded
- ▶ reaching thermal mass for Higgsino model for the first time

H.E.S.S. 2026
PRL, accepted



H.E.S.S. Science Panorama





Exploring the origin of cosmic rays with high-energy gamma rays using H.E.S.S.

<https://hess-experiment.eu>

Lars Mohrmann (for the H.E.S.S. Collaboration)

46th COSPAR Scientific Assembly, Session E1.1
Florence, August 4, 2026



MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

