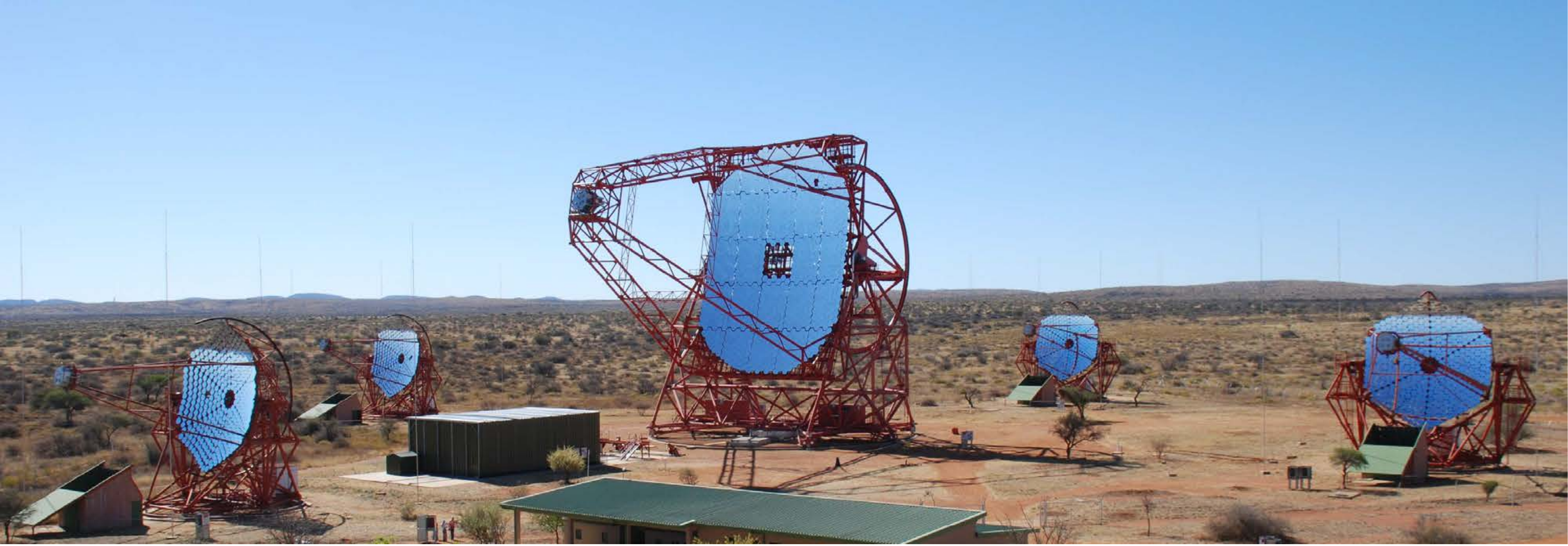
H.E.S.S. - status & recent results

Olaf Reimer for the H.E.S.S. collaboration

universität innsbruck

Roma International Conference on AstroParticle Physics 2024



High Energy Stereoscopic System

H.E.S.S.

- 4 x ∅12m in operation since 2003, 1 x ∅ 28m since 2012
- 4 x camera upgrade 2017 (*HESS1U*), 1 x 2019 (*NamCam* aka CTA-MST *FlashCam* prototype)
- presently operated in 2^{nd} extension phase
- focus in extension phases: high efficiency (last 5 years > 97%, resulting in > 1400h/a)
  legacy program + time domain opportunities

Performance boosted through extensive developments in principal H.E.S.S. simulation & analysis chains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A Monte Carlo template based analysis for air-Cherenkov arrays

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A run-wise simulation and analysis framework for Imaging Atmospheric Cherenkov Telescope arrays

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ABSTRACT

We introduce a new simulation and analysis paradigm for Imaging Atmospheric Cherenkov Telescope (IACT) arrays, simulating the actual observation conditions as well as individual telescope configuration for each observation unit. Compared to existing frameworks, where simulations are usually generated using pre-defined settings, this run-wise simulation approach implies more realistic simulations and hence reduced systematic uncertainties. The computational effort of this dedicated simulation concept is notably independent of the amount of different observation configurations but just scales linearly with observation time. This corresponds to a large advantage for increasingly complex current and future IACT arrays where the size of the phase space makes it computationally unfeasible to generate simulations that reach the requirements regarding systematics using the classical simulation scheme.

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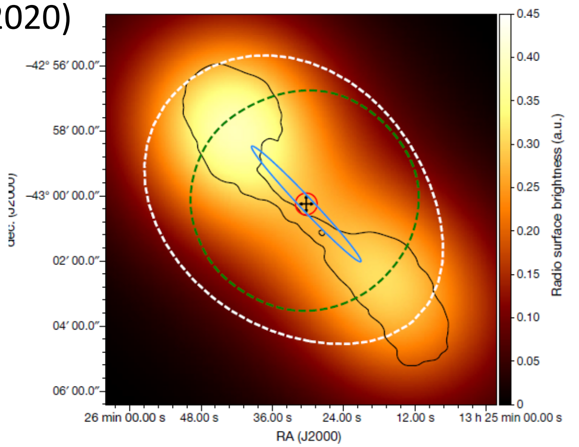
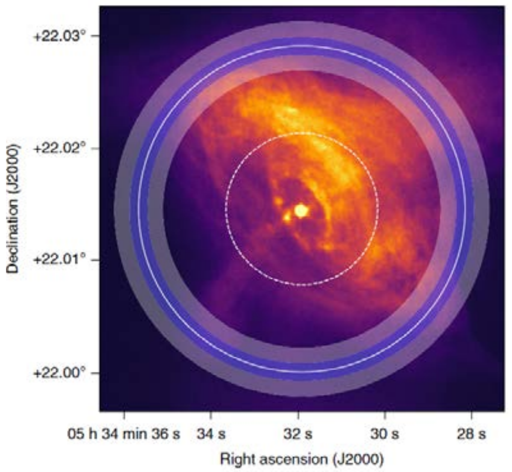
H.E.S.S.

allowed for reconstruction & analysis of H.E.S.S. obs data in a new-quality, e.g.

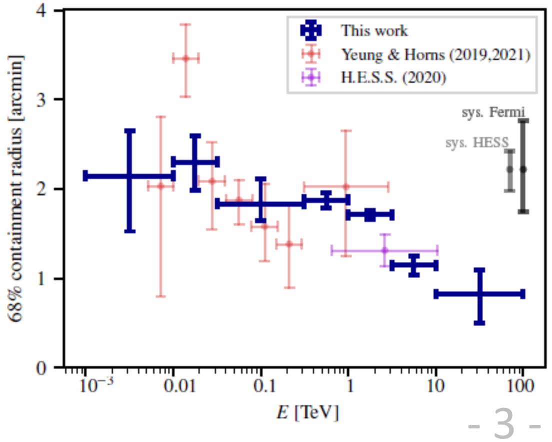
Resolving acceleration to very high energies along the jet of Centaurus A (*Nature* 582, 2020)





Resolving the Crab pulsar wind nebula at teraelectronvolt energies (*Nature Astronomy* 4, 2020)

Spectrum and extension of the inverse-Compton emission of the Crab Nebula from a combined Fermi-LAT and H.E.S.S. analysis (*A&A* 686, 2024)

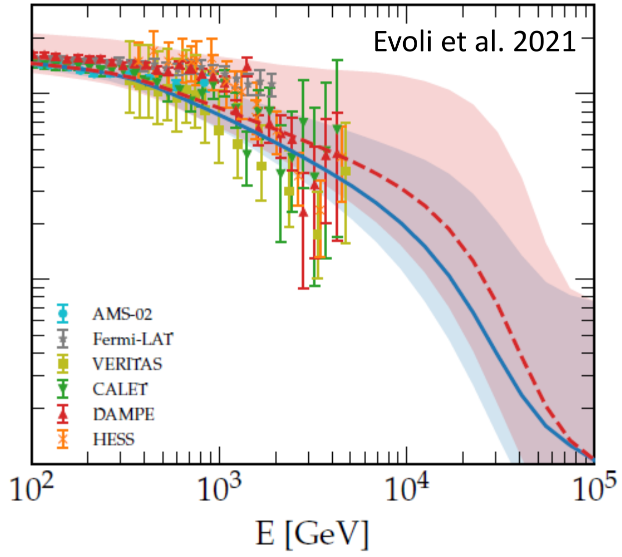


Cosmic Ray Electron (+ Positron) Measurements

…it has been quiet from H.E.S.S. since preliminary results as of ICRC'17. Until last year (de Naurois @ ICRC'23).

Depending on your perspective:
CR $e^{\pm}$ are an unavoidable contamination but constitute science case itself

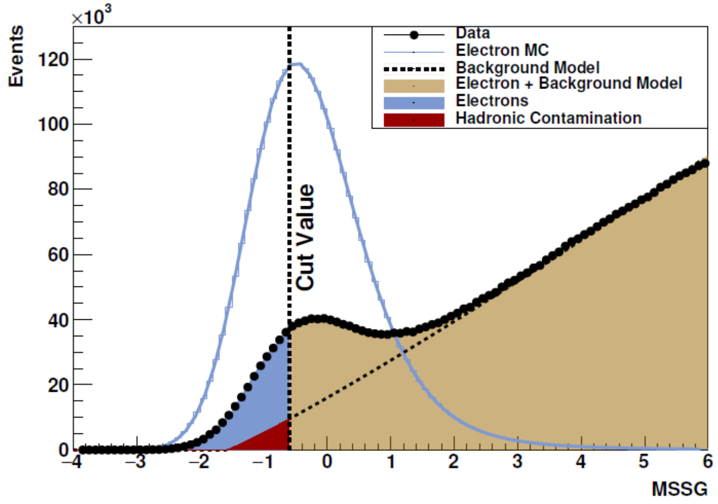
H.E.S.S. (2008 & 2009): $e^{\pm}$ spectra < 4 TeV ; spectral break at ~ 1TeV, confirmed by MAGIC, VERITAS, AMS-02, DAMPE, CALET.



New study by HESS towards higher energies (presently concluding journal review) .

Analysis involves **'run-wise' simulations** where each 28 min data-set ('run') is simulated with actual pointing, specific NSB, telescope multiplicity, wobble offsets, transparency coefficients, dead-times etc., involving ~200 000 $e^{\pm}$ showers.

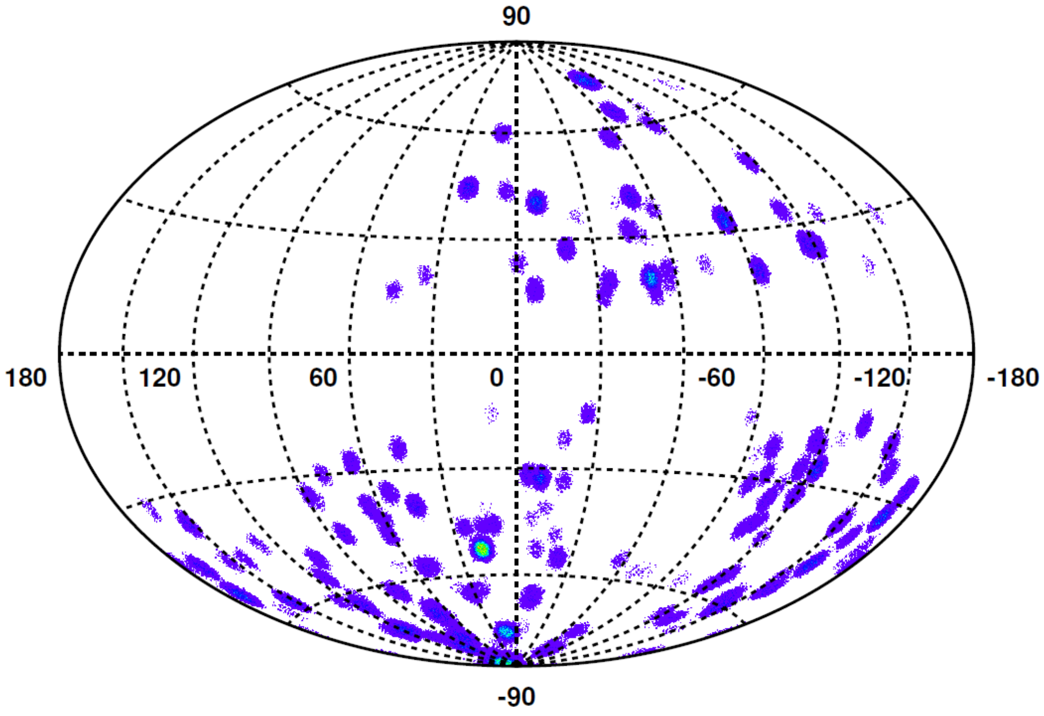
H.E.S.S.



- Particle ID derived using quality of the fit (MSSG).
- Electron candidates are cut at MSSG < -0.6.
- Contamination by hadrons is derived from an analytic approximation to the MSSG distribution at each energy.

CR e± Data Selection Summary

- Only CT1-CT4 (CT5 has small fov)
- Only 2003-2015 (homogeneity)
- Standard quality cuts
- ZA < 45° (threshold)
- |b| > 15° (avoid Galactic Plane)
- Four telescope events
- Central 4° of fov (reconstruction)
- d (sources) > 0.25° (PSF: 0.06°)
- d (LMC, SMC) > 5°



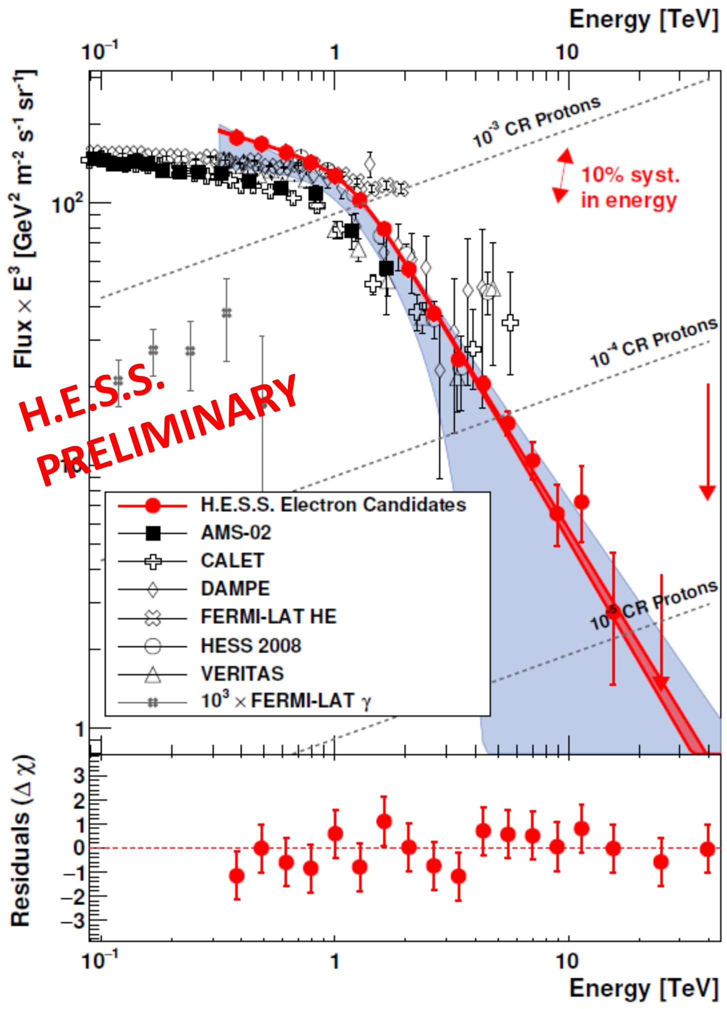
A lot of data…

6830 runs corresponding ~ 2800h (> HGPS!)

…allowing for conservative selection

H.E.S.S.

CR e± Spectrum



$$F(E) = F_0 \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-\Gamma_1} \left(1 + \left(\frac{E}{E_b}\right)^{\frac{1}{\alpha}}\right)^{-(\Gamma_2 - \Gamma_1)\alpha}$$

flux normalisation

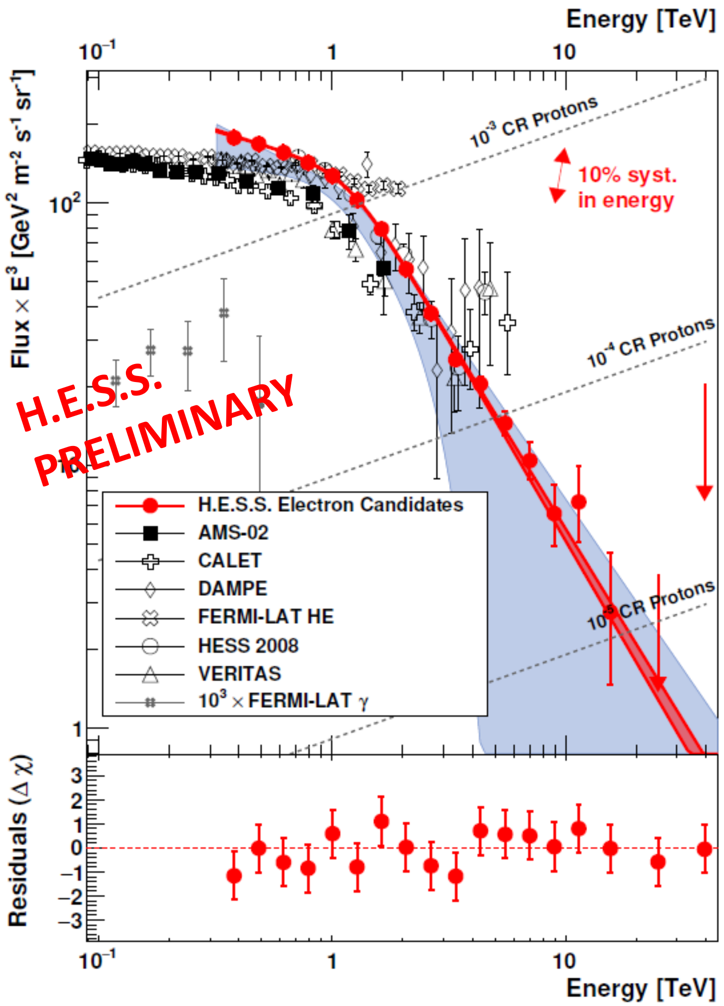
$$F_0 = (126.1 \pm 0.5_{\mathrm{stat}} \pm 13_{\mathrm{sys}})\,\mathrm{GeV}^2\,\mathrm{m}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$$

No significant deviations from broken PL

No confirmation of 1.4 TeV excess/feature
No spectral hardening above 5 TeV

∅ potential DM signal (many!)
∅ PSR J0855-4644 (Bao et al.).

CR e± Spectrum



$$F(E) = F_0 \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-\Gamma_1} \left(1 + \left(\frac{E}{E_b}\right)^{\frac{1}{\alpha}}\right)^{-(\Gamma_2 - \Gamma_1)\alpha}$$

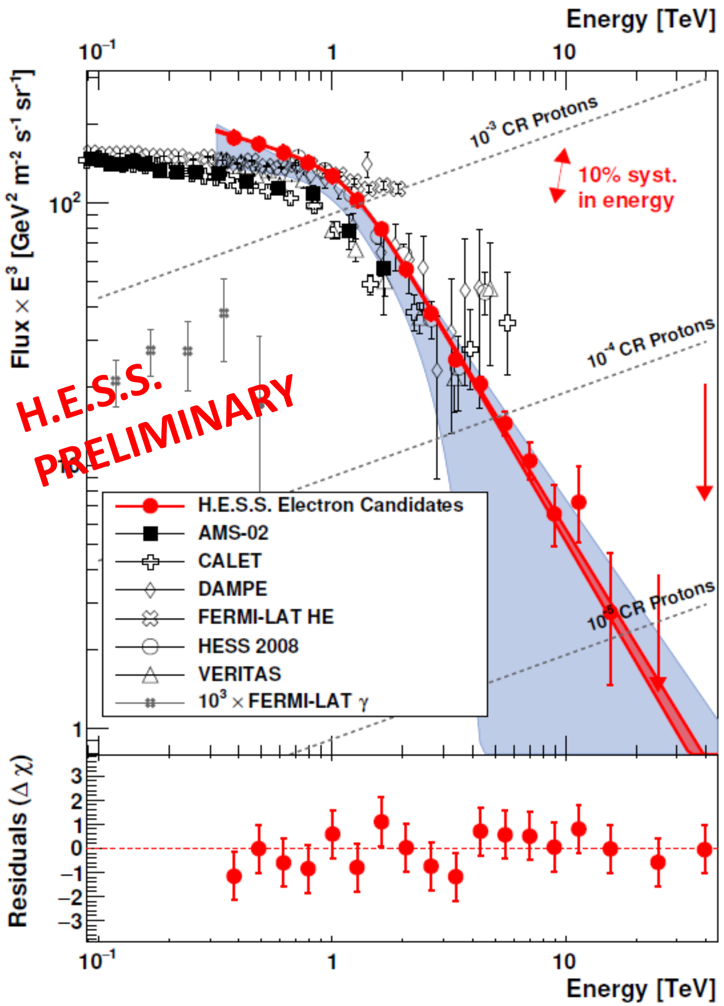
spectral shape

$$\Gamma_1 = 3.25 \pm 0.02_{\,\mathrm{stat}} \pm 0.2_{\,\mathrm{sys}}$$
$$\Gamma_2 = 4.49 \pm 0.04_{\,\mathrm{stat}} \pm 0.2_{\,\mathrm{sys}}$$

E_{low} softer but compatible with 3.2 (AMS-02/CALET) & 3.1 (DAMPE/Fermi-LAT)

E_{high} softer than DAMPE & VERITAS

CR e± Spectrum



$$F(E) = F_0 \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-\Gamma_1} \left(1 + \left(\frac{E}{E_b}\right)^{\frac{1}{\alpha}}\right)^{-(\Gamma_2-\Gamma_1)\alpha}$$

flux normalisation

$$F_0 = (126.1 \pm 0.5_{\mathrm{stat}} \pm 13_{\mathrm{sys}})\ \mathrm{GeV}^2\,\mathrm{m}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$$

E_{low} 30% higher than other measurements

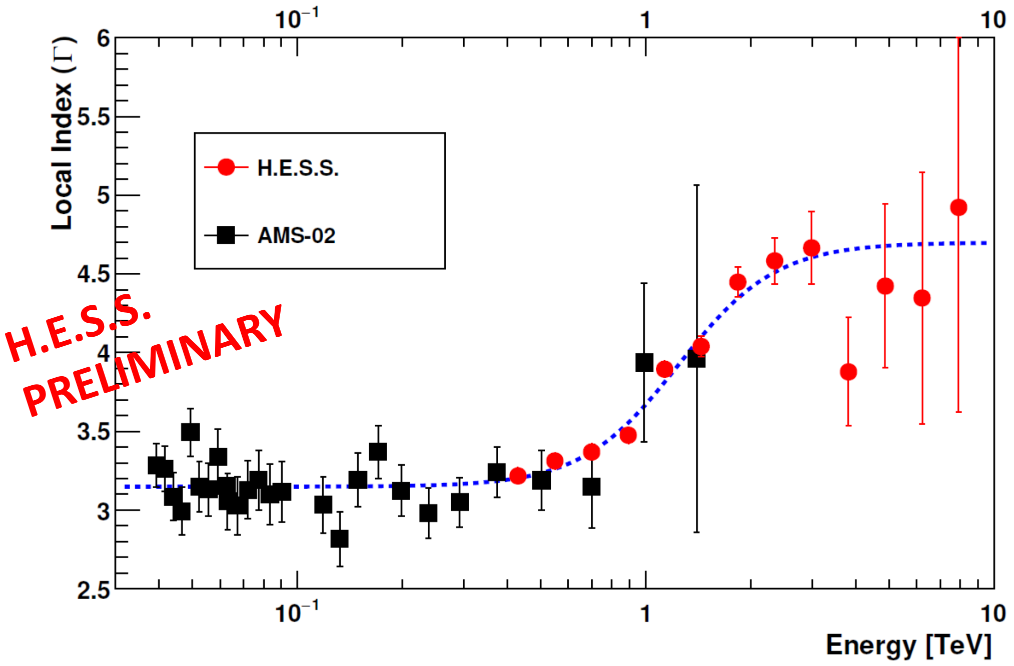
- systematic uncertainties
- < 15% (<3 TeV) due to residual hadronic contamination
- compatible, no preference to discrepancy between AMS-02/CALET and Fermi-LAT/DAMPE

break energy

$$E_b = (1.17 \pm 0.04_{\mathrm{stat}} \pm 0.12_{\mathrm{sys}})\ \mathrm{TeV}$$

- marginally compatible with DAMPE & CALET
- significantly higher than VERITAS
- incompatible with 95% lower limit (Fermi-LAT)

CR e± Spectrum



$$F(E) = F_0 \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-\Gamma_1} \left(1 + \left(\frac{E}{E_b}\right)^{\frac{1}{\alpha}}\right)^{-(\Gamma_2-\Gamma_1)\alpha}$$

break energy

$$E_b = (1.17 \pm 0.04_{\,\mathrm{stat}} \pm 0.12_{\,\mathrm{sys}})\ \mathrm{TeV}$$

sharpness of spectral break

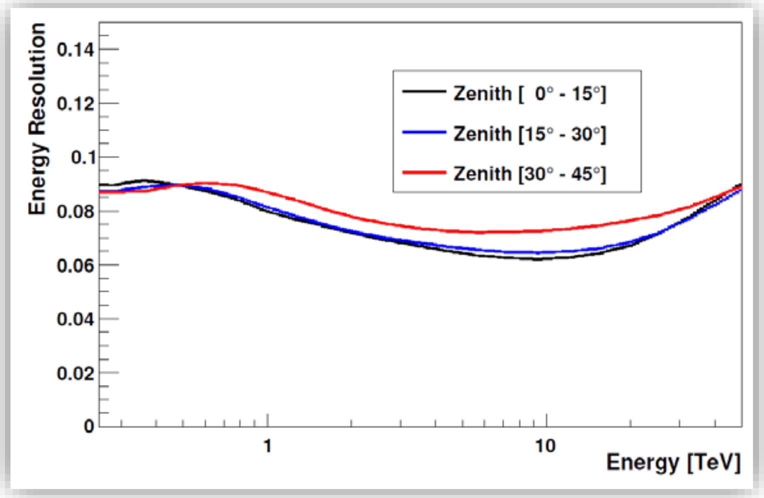
$$\alpha = 0.21 \pm 0.02_{\,\mathrm{stat}}\ {}^{+0.10_{\mathrm{sys}}}_{-0.06_{\mathrm{sys}}}$$

Not sharp!

α = 0 ruled out

ΔΓ/(ΔE/E) ~ 1/3

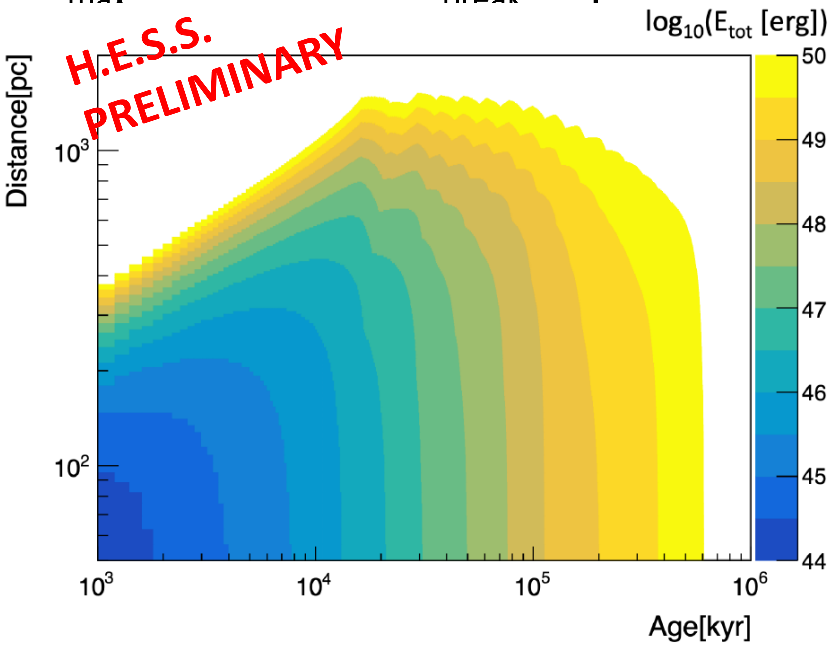
with ΔE ~ 9%



H.E.S.S.

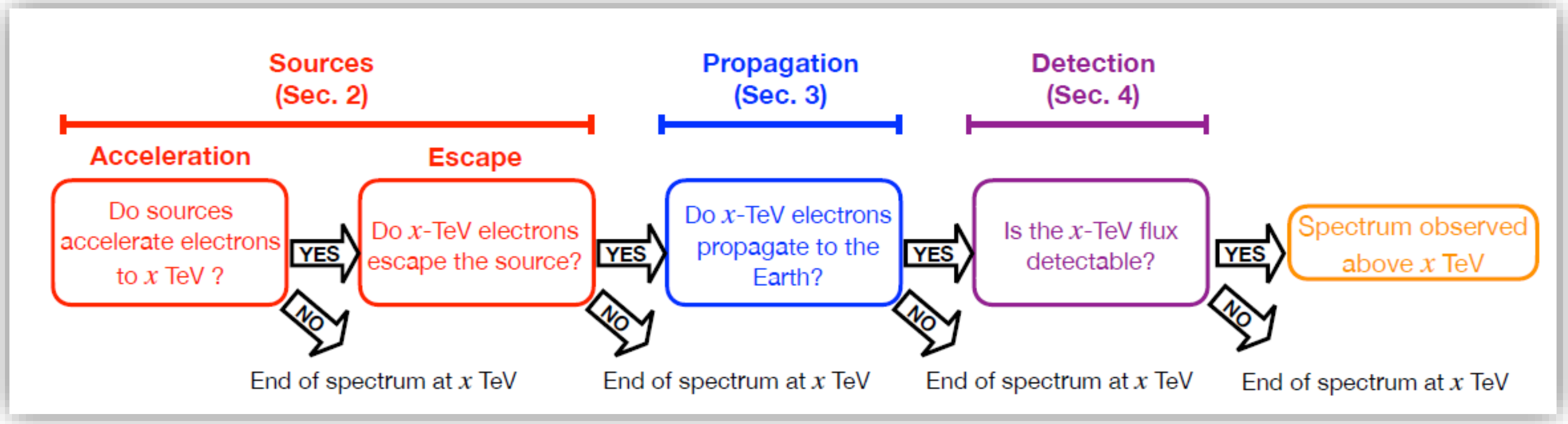
CR e± Spectrum

E_{max} >10 TeV and E_{break} impose limitations on cooling time (~ 100 kyr) and propagation (~ few 100 pc).



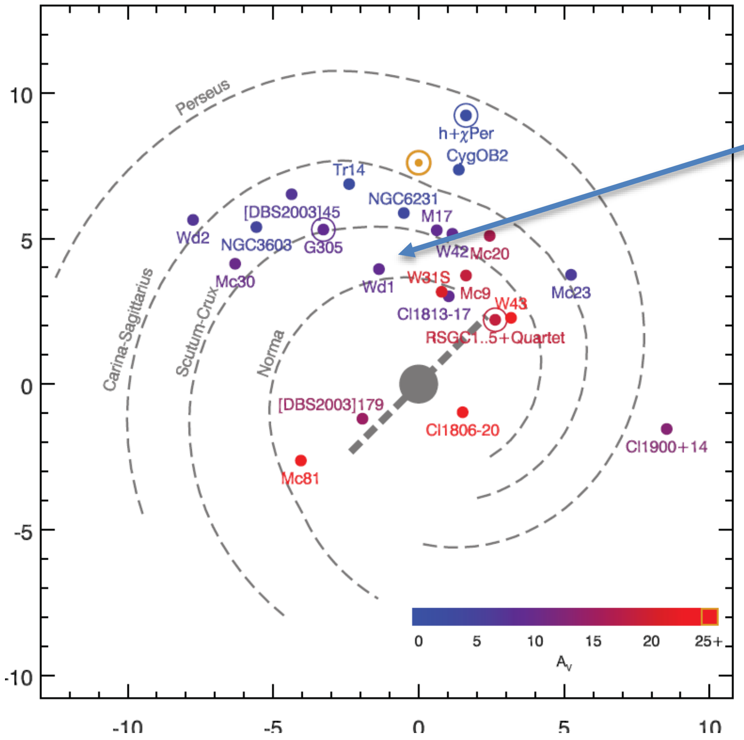
- No strong local source
- burst-like scenario (Vela-type 300 pc, 11 kyr → E < $2x10^{46}$ erg)
- fairly sharp break disfavors a distributed ensemble of sources with spectrum of propagation times (e.g. Mauro et al. 2014, Recchia et al. 2019, Drury 2011) ↔ prospects for anisotropy studies?
- Steeply falling multi-TeV CR electron spectra extremely challenging for space-based instruments

Sudoh & Beacom 2023



H.E.S.S.

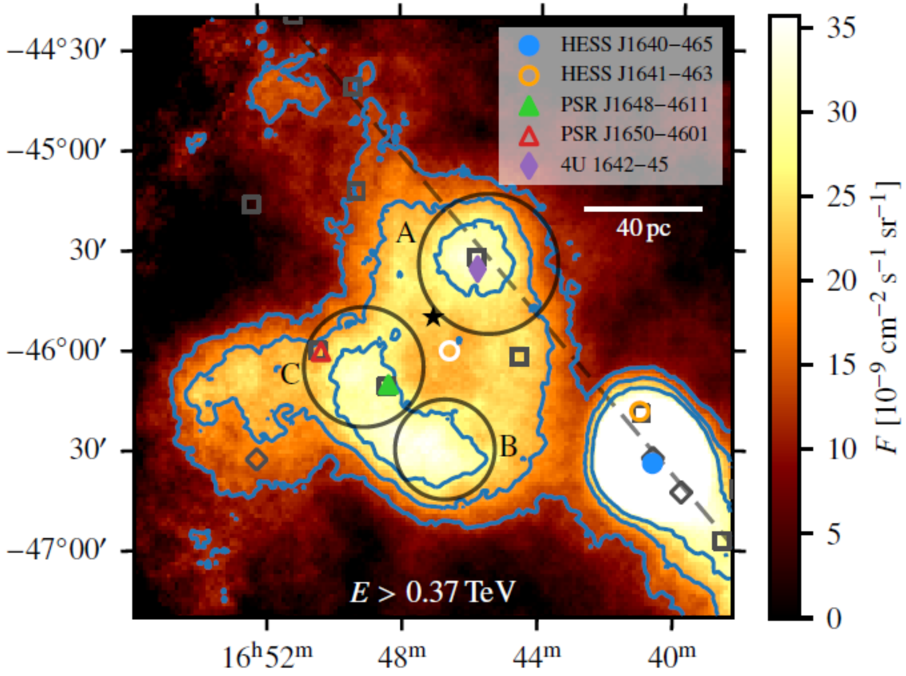
Young Massive Stellar Clusters

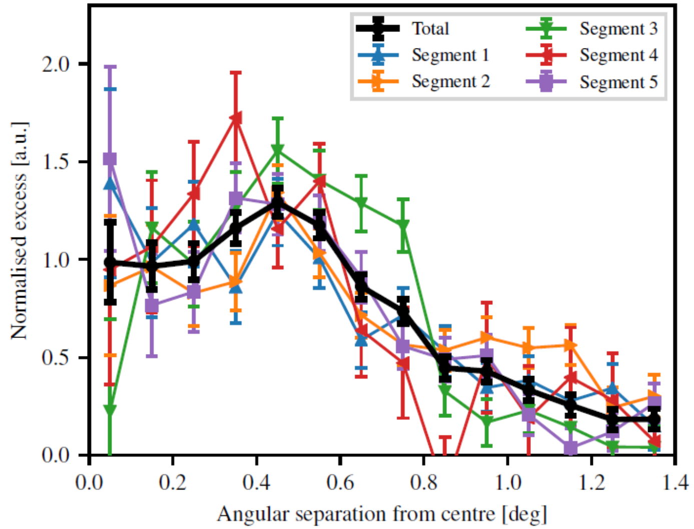


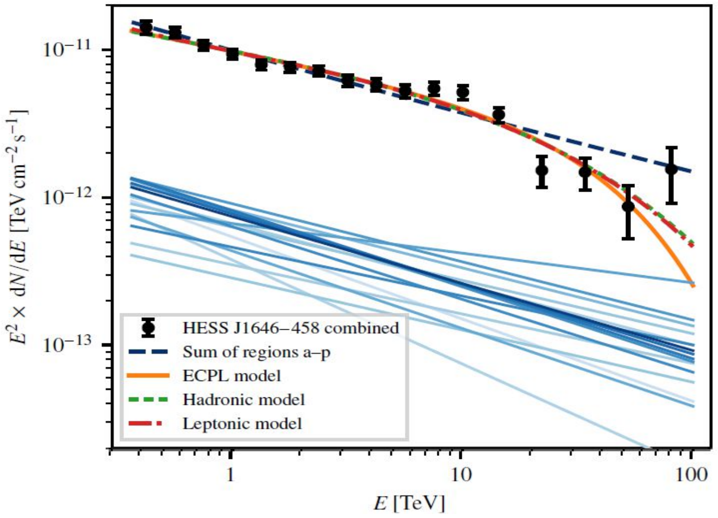
Davies et al. 2012

The most massive stellar cluster Westerlund 1

(H.E.S.S., *A&A* 666, 2022)







complex, shell like morphology, with Wd1 at its center

Pevatron candidate, but spectrum steepens above ~10 TeV

$W_e \sim 7.2 \times 10^{48}\,(d/3.9\,\mathrm{kpc})^2\,\mathrm{erg}$ vs $W_p \sim 6 \times 10^{51}\,(n/1\,\mathrm{cm}^{-3})^{-1}\,\mathrm{erg}$

H.E.S.S.

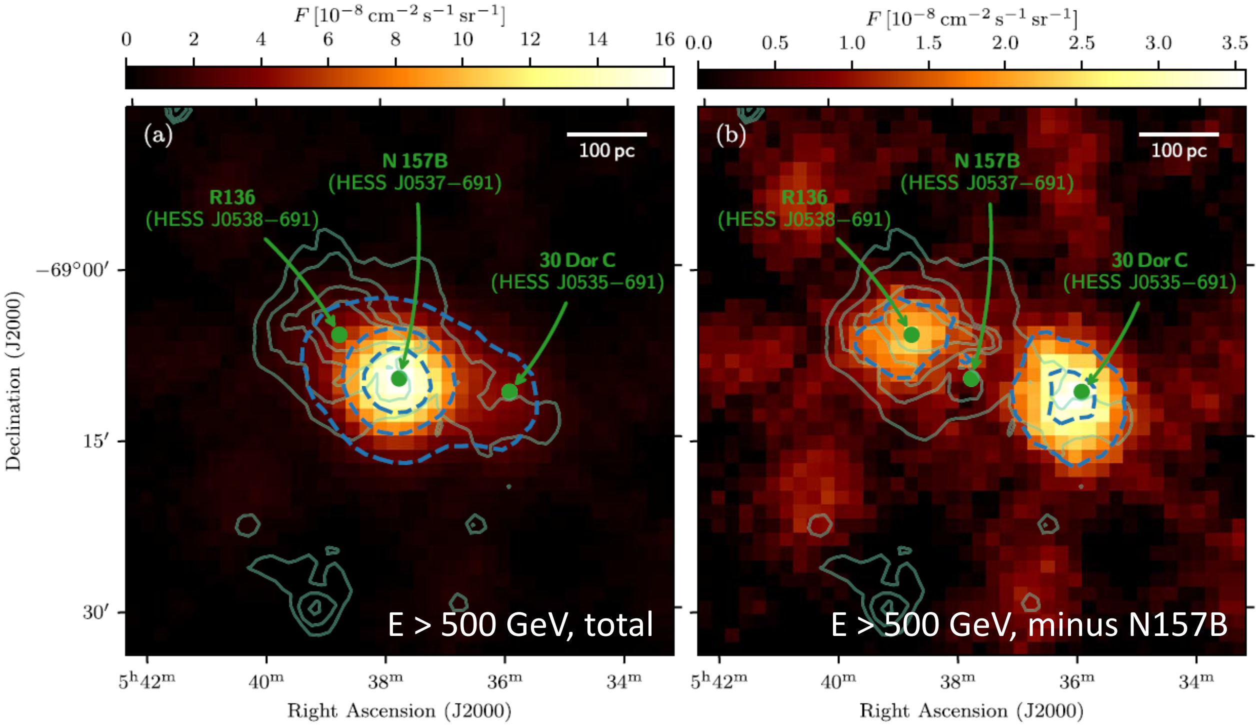
(H.E.S.S., *ApJ* 970, 2024)

Young Massive Stellar Clusters

New: R136 (close to 30 Dor C) in LMC

NASA, ESA, CSA, STScI, Webb ERO Production Team

H.E.S.S.



Open cluster?
Superbubble?
OB association LH90?

Vieu & Reville 2023

- Star Cluster
- Massive star cluster
- Young massive star cluster
- Evolved massive star cluster
- Extended massive star cluster
- Wind-blowing cluster
- Loose cluster

A young MSC (YMSC) is an MSC that still contains stars expected to undergo a transition to the WR phase in the end of their life. Assuming roughly that stars with ZAMS mass larger than $20M_\odot$ are expected to become WR stars (Crowther 2007; Sander, Hamann & Todt 2012), young clusters are clusters that are less than about 10 Myr old, assuming coeval star formation.

Young Massive Stellar Clusters

(H.E.S.S., *ApJ* 970, 2024)

New: R136 (close to 30 Dor C) in LMC

NASA, ESA, CSA, STScI, Webb ERO Production Team

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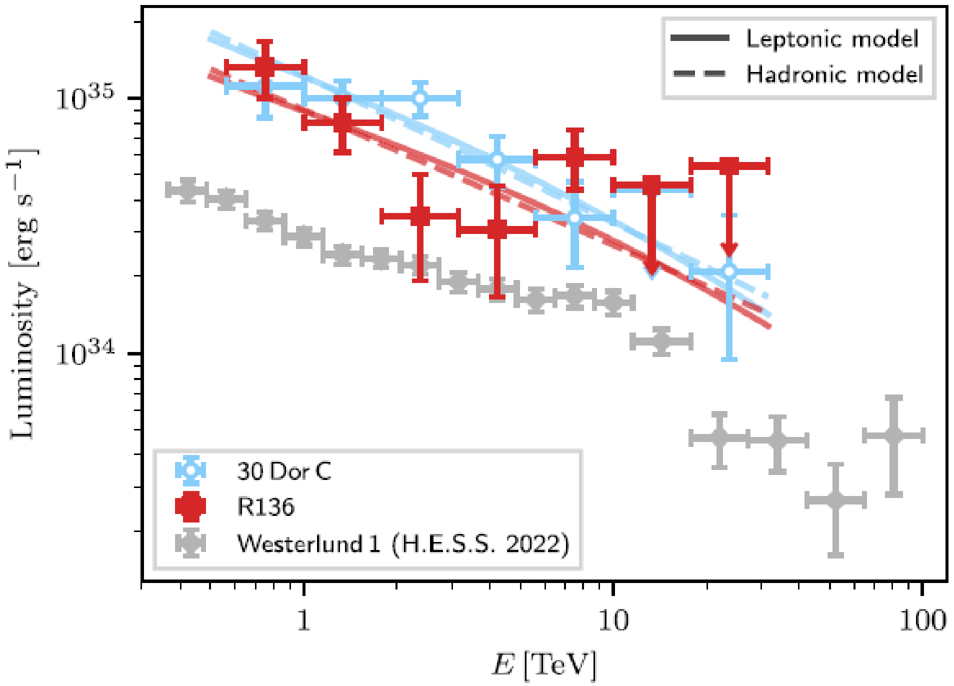


$$\Gamma_e^{30\,\mathrm{Dor\,C}} = -3.27 \pm 0.11_{\mathrm{stat}}$$
$$\Gamma_e^{\mathrm{R136}} = -3.19 \pm 0.17_{\mathrm{stat}}$$

IC + synch [5 μG LMC average]

$$L_e^{30\,\mathrm{Dor\,C}} \approx 8.5 \times 10^{36}\ \mathrm{erg\ s^{-1}}$$
$$L_e^{\mathrm{R136}} \approx 5.3 \times 10^{36}\ \mathrm{erg\ s^{-1}}$$

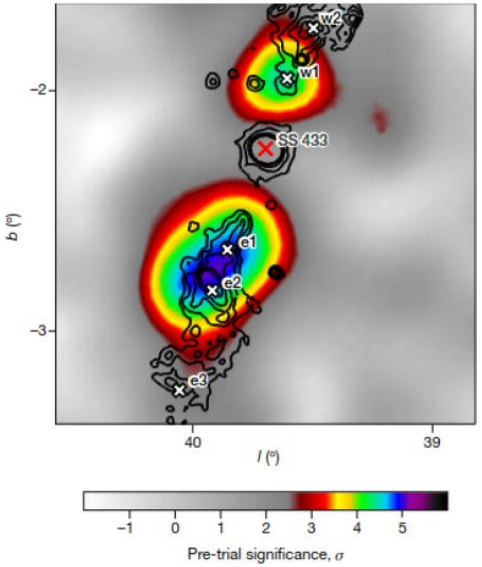
$$\Gamma_p^{30\,\mathrm{Dor\,C}} = -2.64 \pm 0.08_{\mathrm{stat}}$$
$$\Gamma_p^{\mathrm{R136}} = -2.59 \pm 0.13_{\mathrm{stat}}$$

*mind Fermi-LAT constraint

$$W_p^{30\,\mathrm{Dor\,C}} \approx 1.4 \times 10^{52} (n/1\ \mathrm{cm^{-3}})^{-1}\ \mathrm{erg}$$
$$W_p^{\mathrm{R136}} \approx 9.7 \times 10^{51} (n/1\ \mathrm{cm^{-3}})^{-1}\ \mathrm{erg}$$

Microquasar SS433

HAWC paved the way.



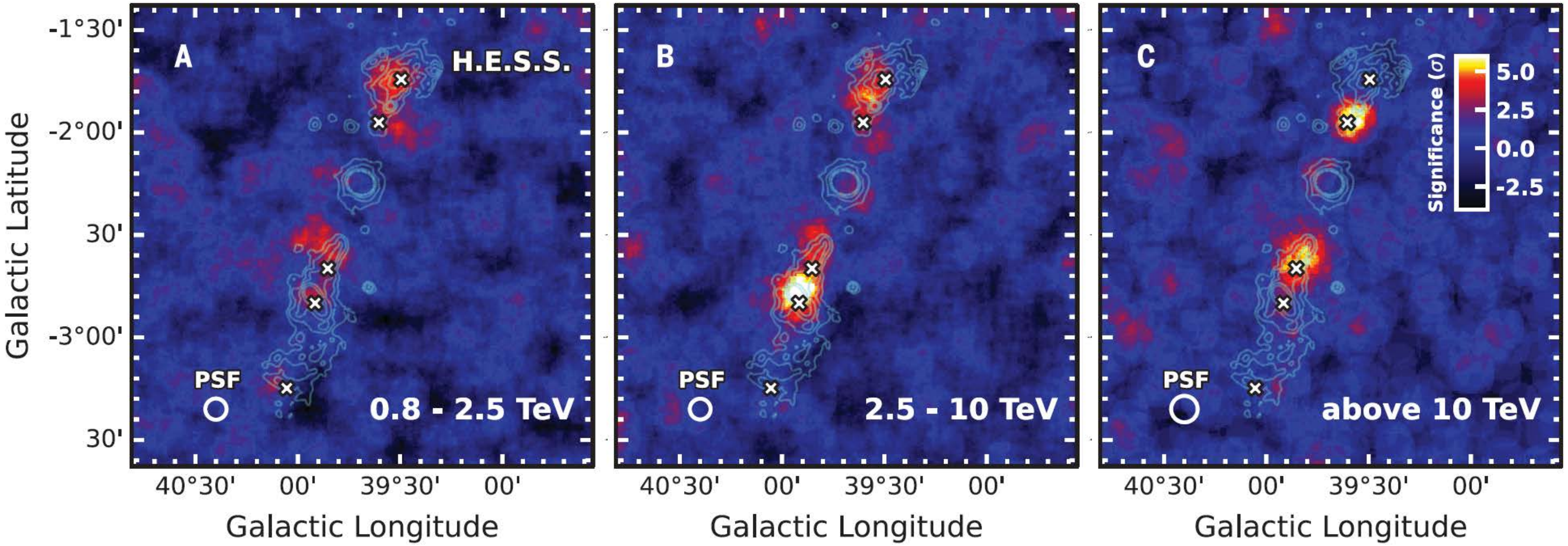
HAWC 2018

H.E.S.S.

spectro-morphological analysis with improved high-energy optimization

(ABRIR, Olivera-Nieto et al. 2022)

Resolved jets of microquasar SS433 (H.E.S.S., *Science* 383, 2024)



- now > 200h observation time (prev ~10h only u.l.)
- Multiple knots along jet on either side.
- **Energy dependent morphology.**
- Highest energies at e1/w1, lower energies at larger radii.

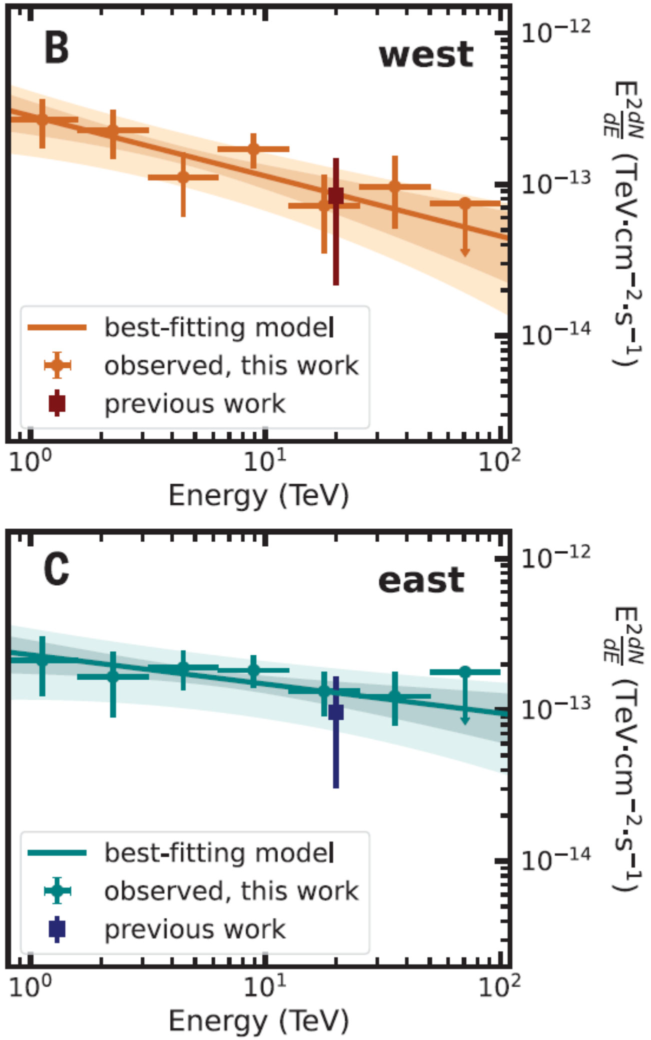
Microquasar SS433

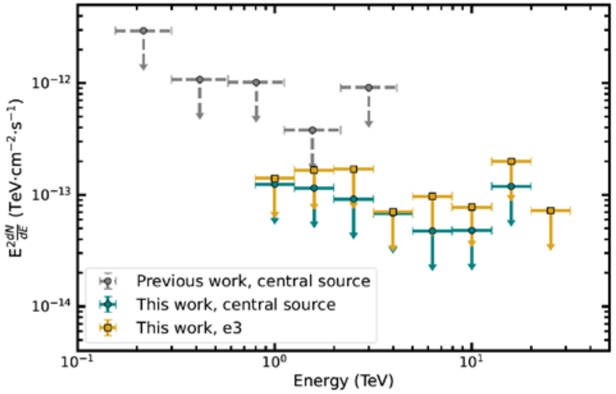
spectro-morphological analysis with improved high-energy optimization

(ABRIR, Olivera-Nieto et al. 2022)

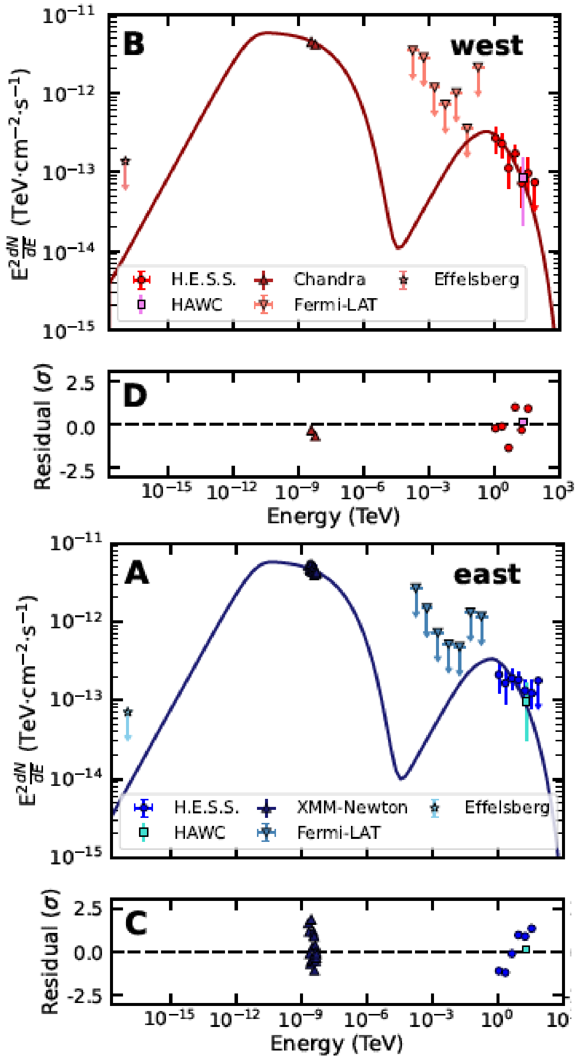
SS433 lobes spectra

Resolved jets of microquasar SS433 (H.E.S.S., *Science* 383, 2024)



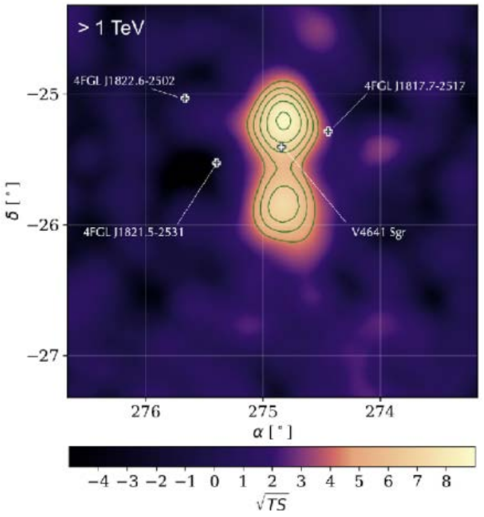


- Nothing from central sourc
- No significant variability.



Microquasar V4641 Sgr

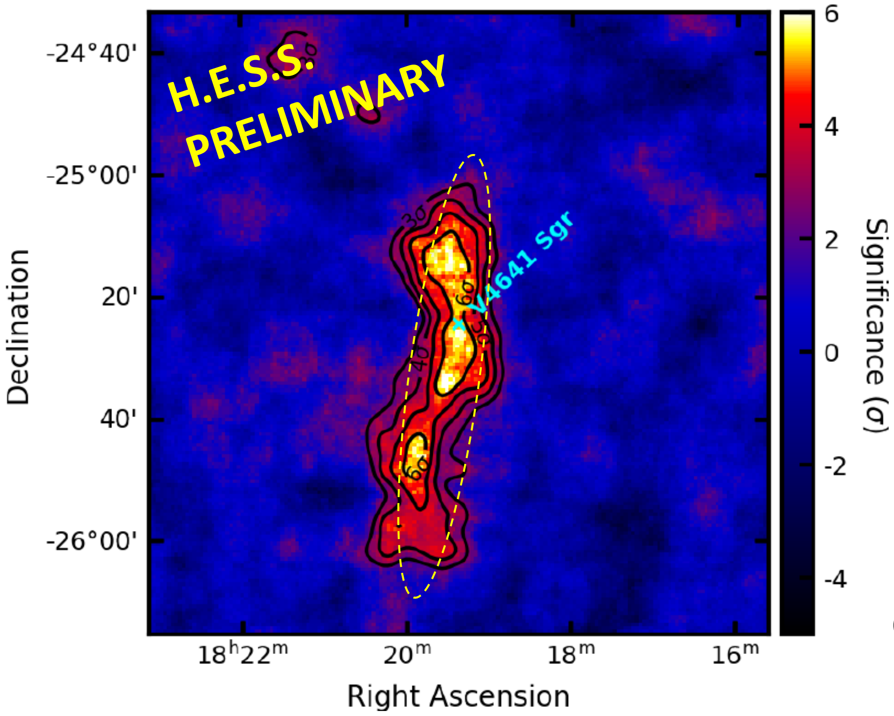
HAWC paved the way once.
So it could work again :)

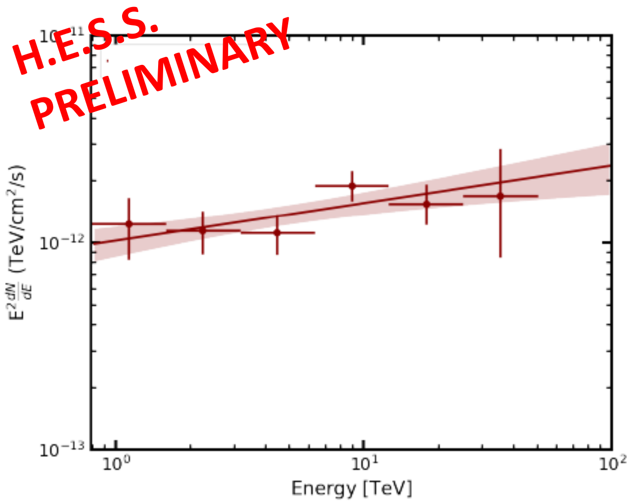


HAWC 2023

spectro-morphological analysis with improved high-energy optimization
(ABRIR, Olivera-Nieto et al. 2022)

- ~ 15 h archival data + ~ 100 h dedicated observations
- **Clearly detected, elongated and asymmetric**
- Bright, hard (<2) spectrum



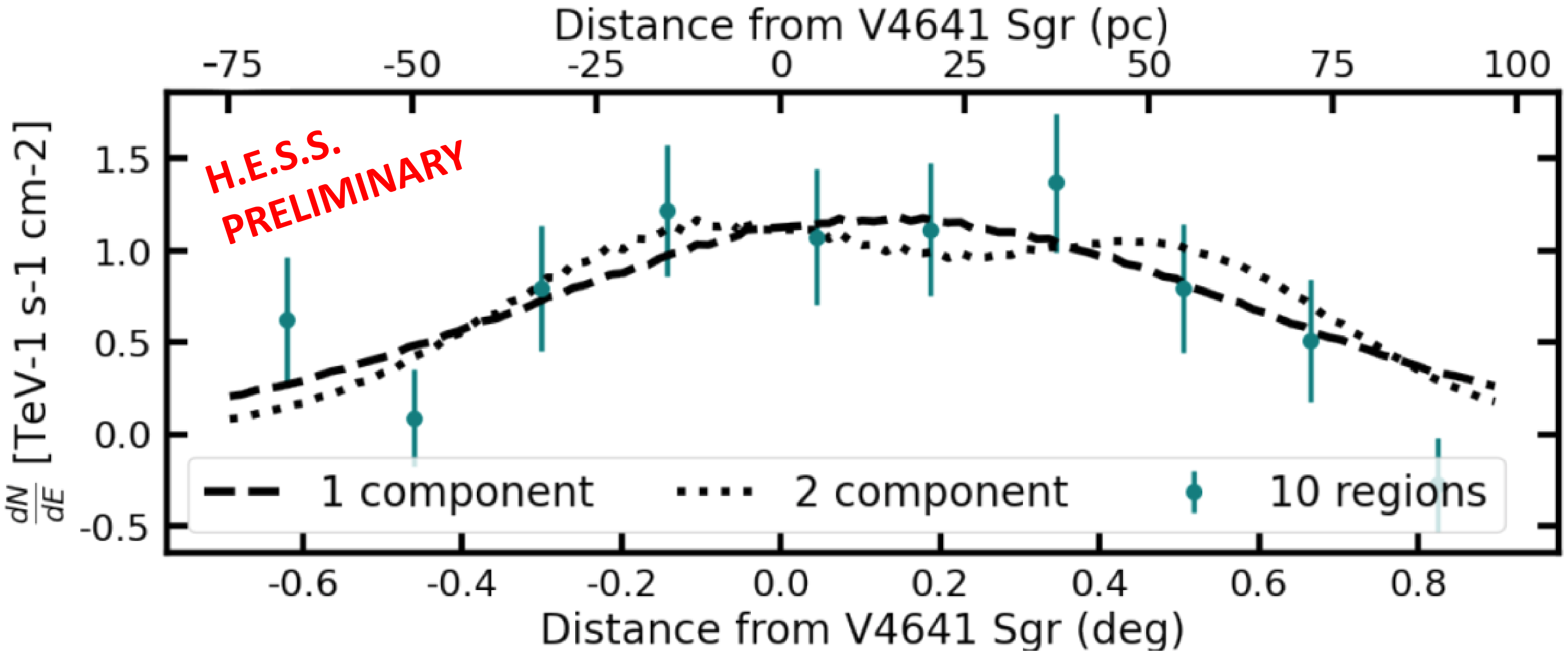


Olivera-Nieto @ γ2024

Microquasar V4641 Sgr

spectro-morphological analysis with improved high-energy optimization
(ABRIR, Olivera-Nieto et al. 2022)

- V4641 not in the center of emission
- **best described as a single component**
- **asymmetric: 0.45° major vs 0.07° minor axis**



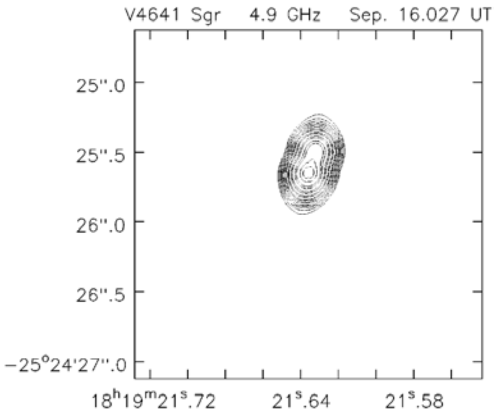
Olivera-Nieto @ γ2024

H.E.S.S.

Microquasar V4641 Sgr

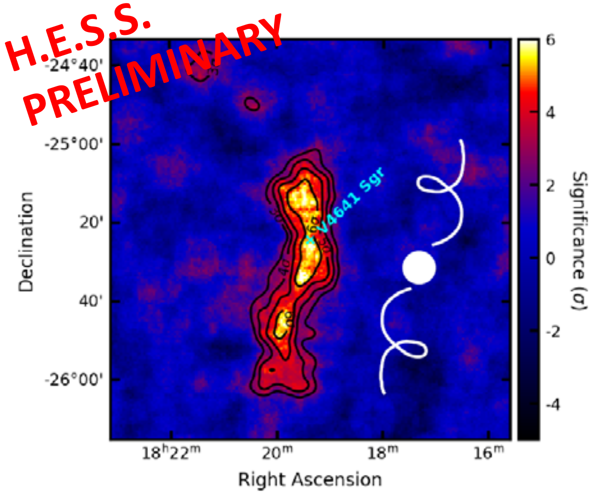
spectro-morphological analysis with improved high-energy optimization
(ABRIR, Olivera-Nieto et al. 2022)

Hjellming et al. 2000



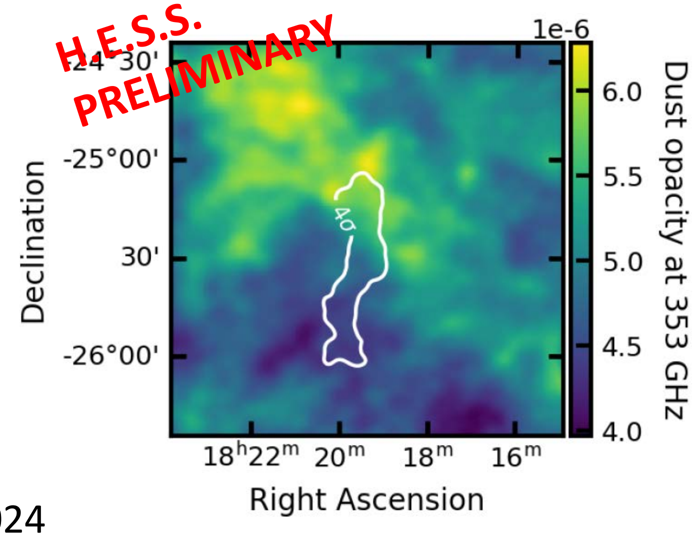
Imprint of jets?

Very different from radio.
System orientation unclear/discrepant



Imprint of escaped particle interactions?

ISM data sparse → radio obs
IGMF → X-ray obs



Olivera-Nieto @ γ2024

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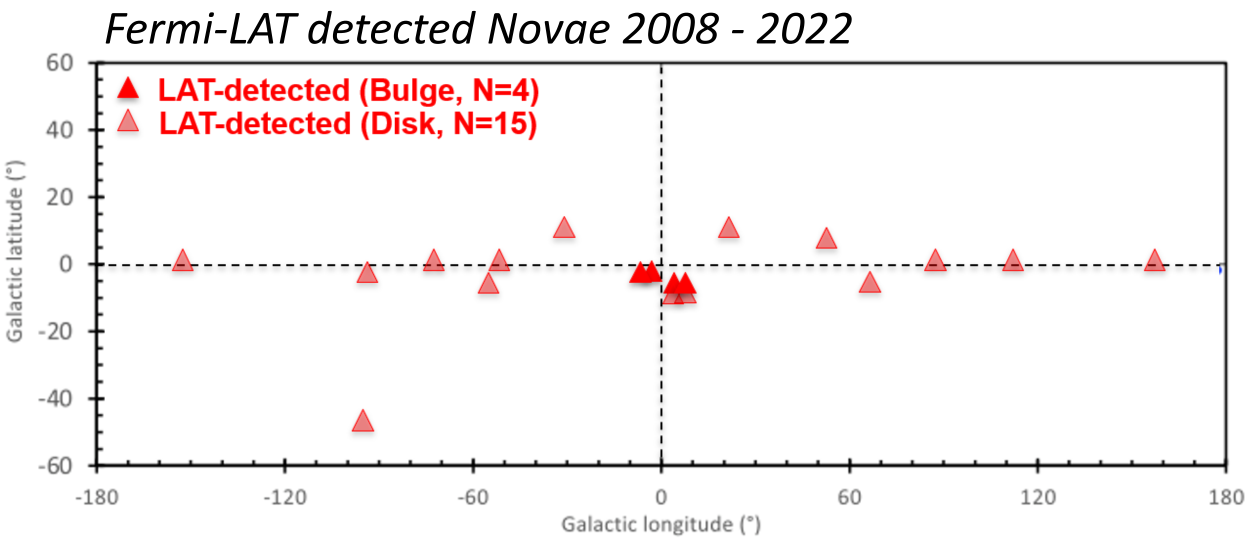
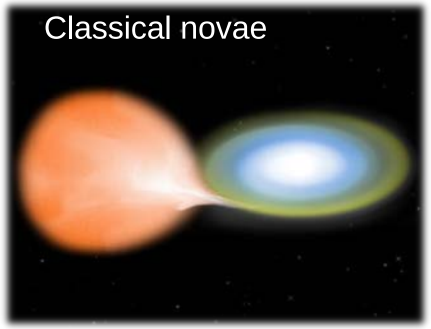
Novae



Compact cataclysmic variable:

WD + main sequence star

Roche lobe overflow



- V1324 Sco 2012, V959 Mon 2012, V339 Del 2013 (Ackermann+14)
- V1369 Cen 2013, V5668 Sgr 2015 (Cheung+16)

…

Symbiotic system:

WD + Red Giant

accretion from red giant wind

Credit: David Hardy

- Symbiotic V407 Cyg 2010 (Abdo+10)
- Symb.-rec. V745 Sco 2014 (Cheung+14)
- Symb. V1535 Sco 2015 (Franckowiak+18)

…

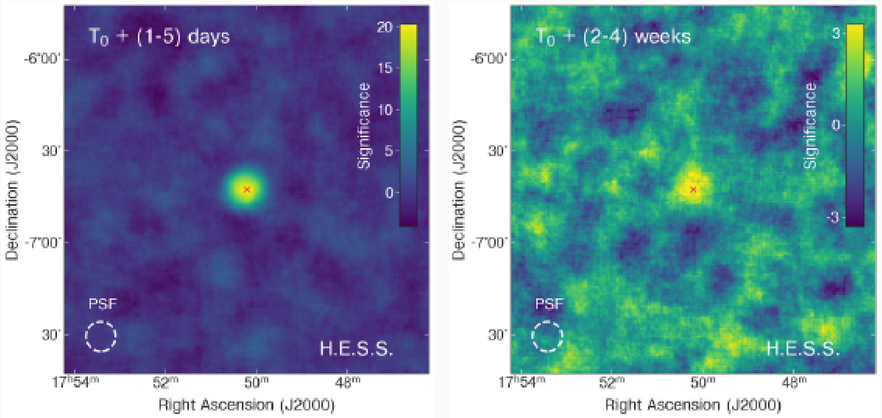
- Recurrent **RS Oph** (Cheung+22)

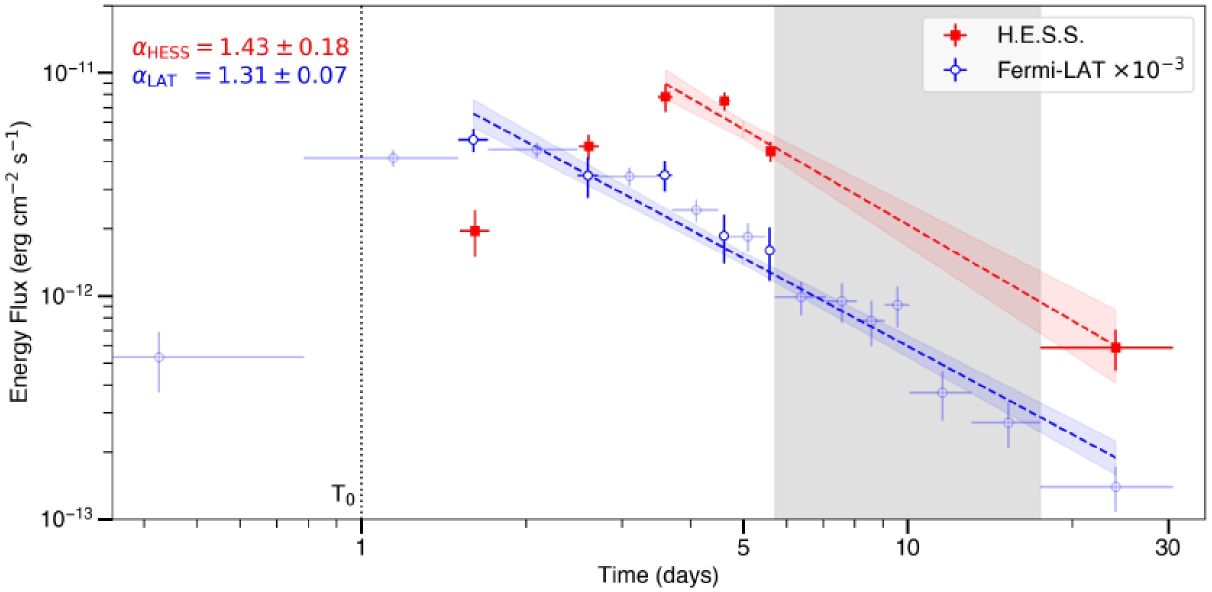
H.E.S.S.

RS Oph

RS Oph outburst reported on 8th Aug 2021, 22:20 UTC (AAVSO)

Night	T_{obs} (UTC)	Livetime (hours)	Significance (σ)
09 Aug. 2021	18:17:40	3.2	5.8 (6.4)
10 Aug. 2021	17:53:46	3.7 (2.8)	9.0 (7.1)
11 Aug. 2021	17:44:08	3.7	9.8 (9.6)
12 Aug. 2021	18:17:12	2.3	13.6
13 Aug. 2021	17:44:43	2.8	10.5 (9.4)
25 Aug. – 07 Sep. 2021	17:48:03; 19:47:31	14.6 (13.4)	3.3 (2.3)

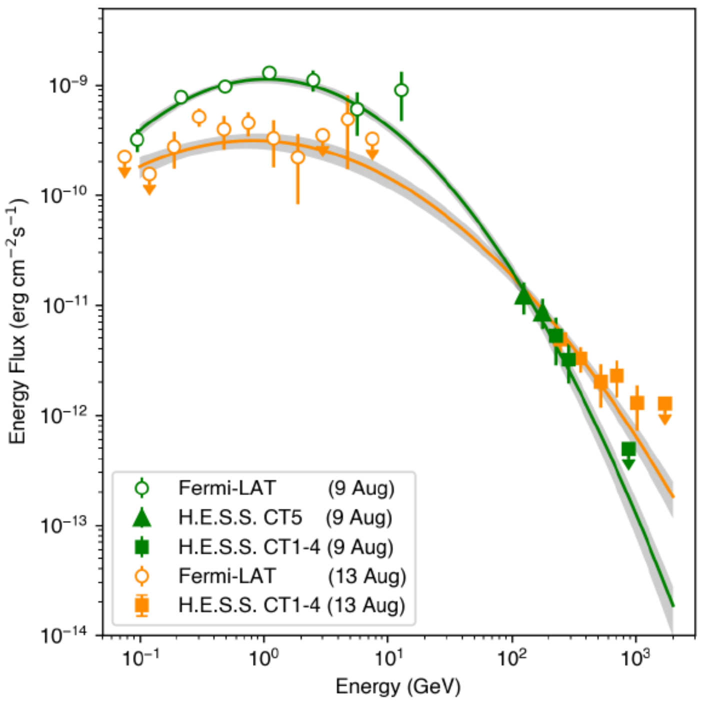




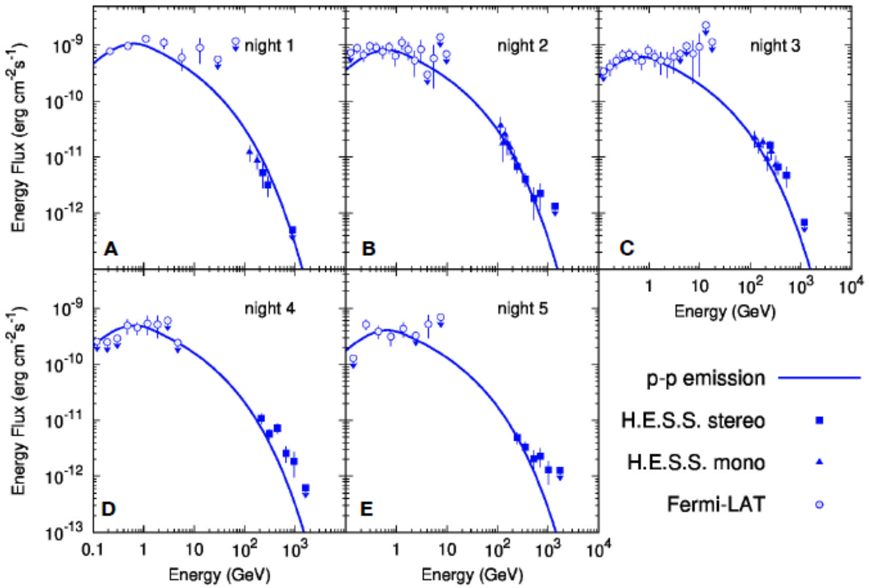
- H.E.S.S. flux between 250 GeV and 2.5 TeV
- Fermi flux between 60 MeV and 500 GeV
- Peak H.E.S.S. flux 3 days after optical peak (T_0)
- 2 days after Fermi LAT maximum
- Comparable decay slope
- γ-ray emission still visible after ~ 20 days

RS Oph

Time-resolved hadronic particle acceleration in the recurrent nova RS Ophiuchi
(H.E.S.S. , *Science* 376, 2022)

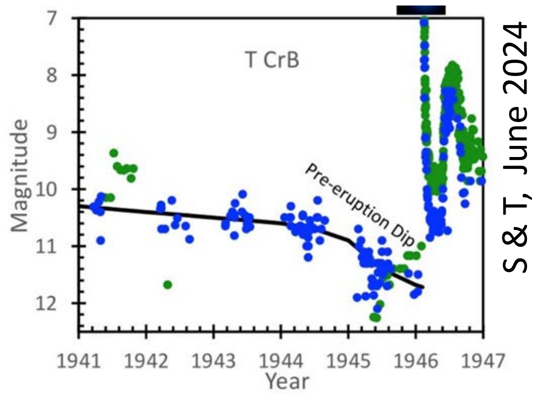


→ nightly spectra modelled in hadronic emission scenario



- Confinement limit is the dominant constraint for protons
- Measured fluxes imply > 10% of internal energy to accelerate protons
- Delay in Fermi vs. H.E.S.S. peak = finite acceleration time
- Hadronic model consistent with observed spectral evolution
- Leptonic model extremely stretched by required > 1% acceleration efficiency; incompatible to prediction of injection at high-Mach number shocks e.g. Malkov & Drury, 2001)

T CrB ?

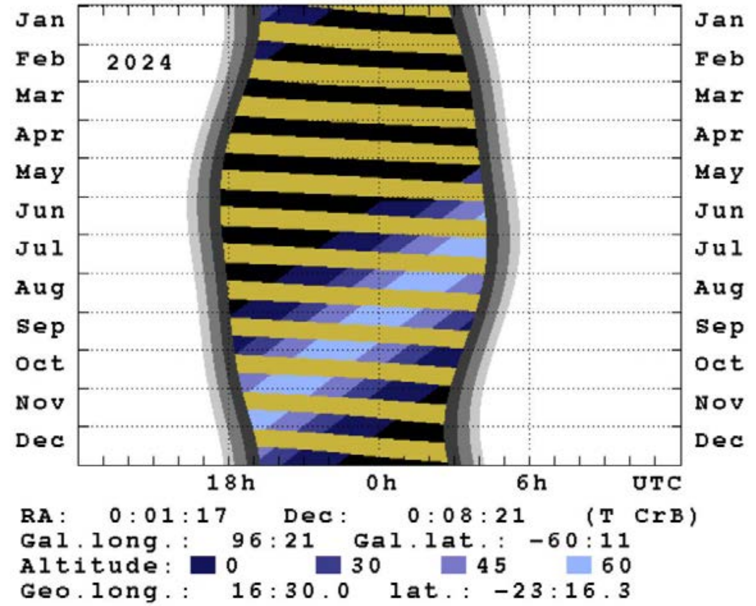


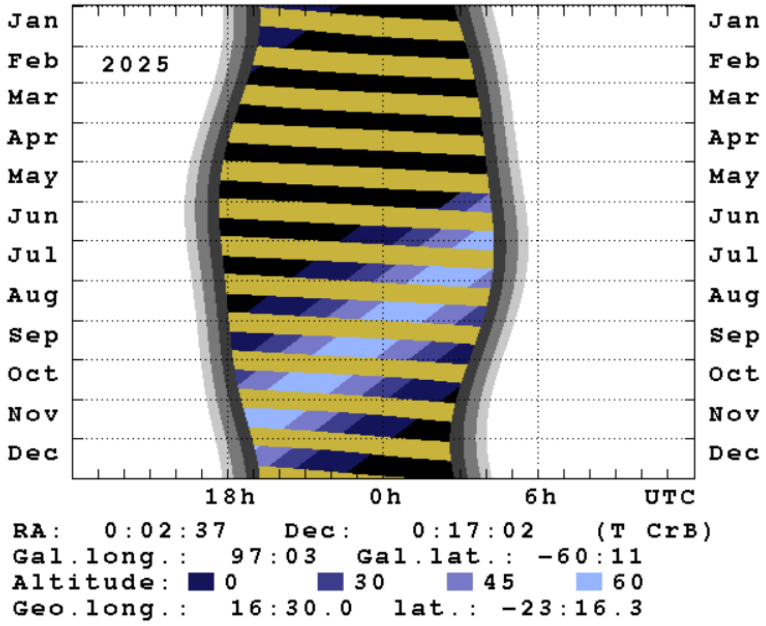
- Recurrent nova, every ~ 80 yr
- Distance 0.9 kpc (RS Oph: 1.4 kpc)

→ might appear very much brighter in LAT than RS Oph
→ might remain detectable a substantially later times

- Fermi-LAT provides daily monitoring through the FSSC

H.E.S.S. visibility





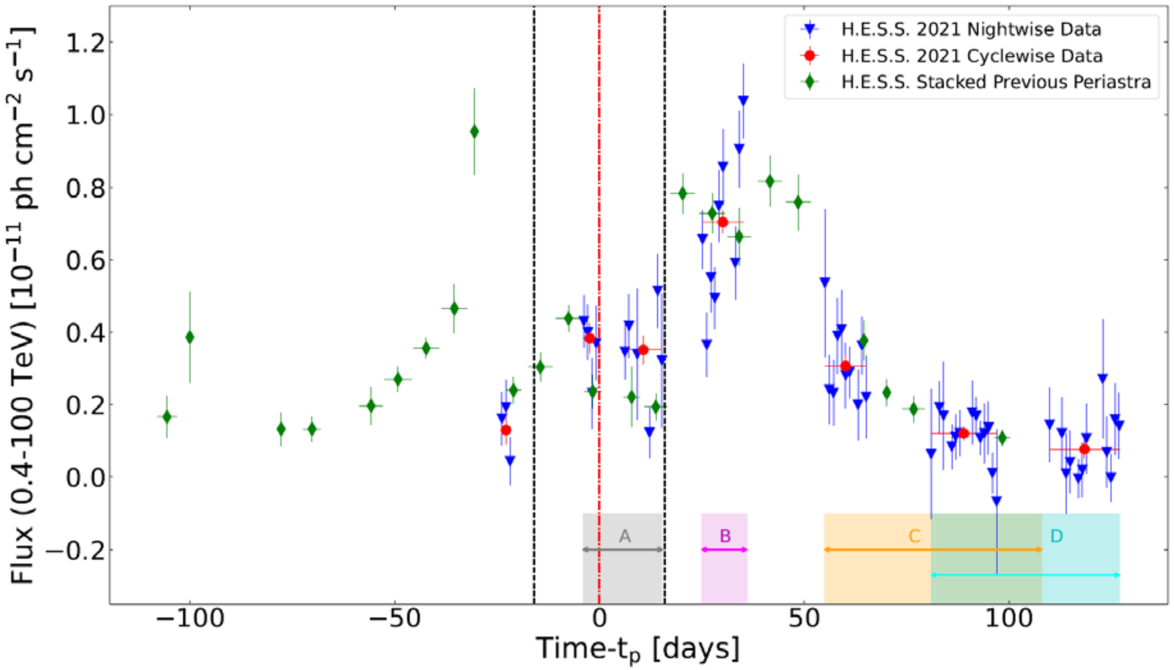
H.E.S.S.

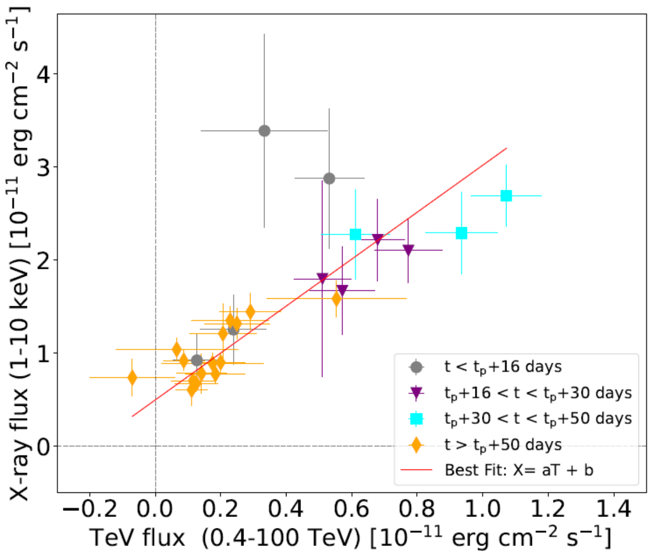
Binaries

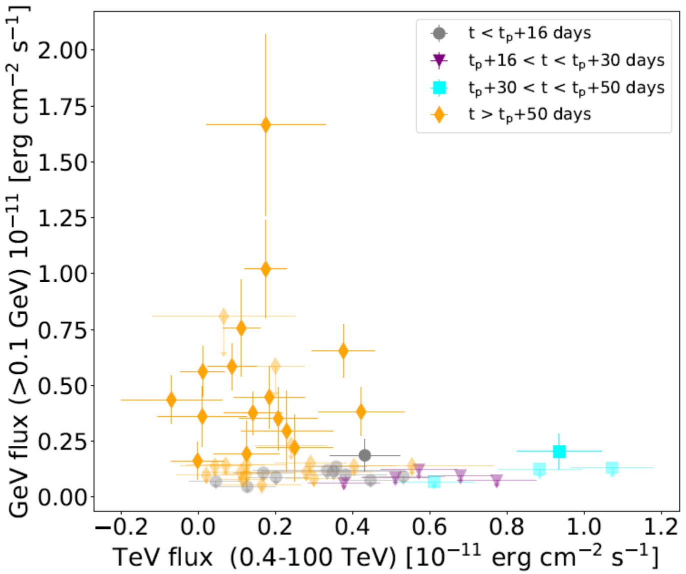
(H.E.S.S., *A&A 687*, 2024)

Monitoring the Periastron passages

- PSR B1259/LS 2883 (2021)







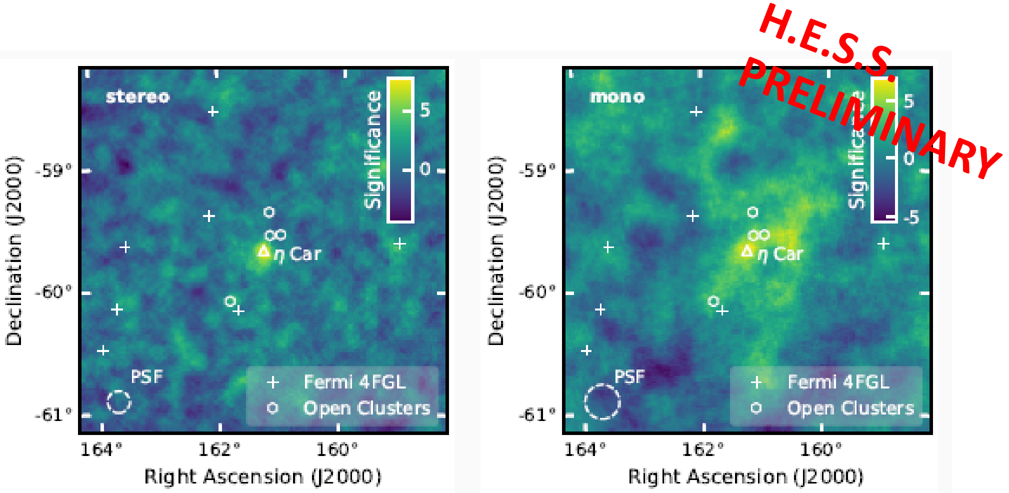
H.E.S.S.

- particular dense *after-Periastron* data set
- good overall match VHEγ - X-ray
- no correspondence to 2021 GeV flare (t_p +55 … +108)
- no obvious correlation VHEγ - GeVγ
- significant spectral evolution GeV/TeV (~ $\Delta\Gamma$ = 0.56)

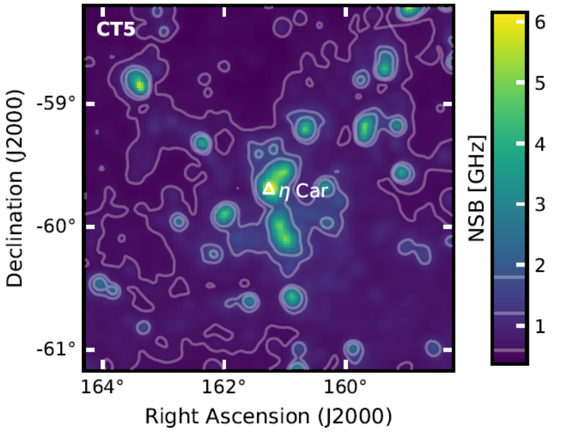
Binaries

Monitoring the Periastron passages

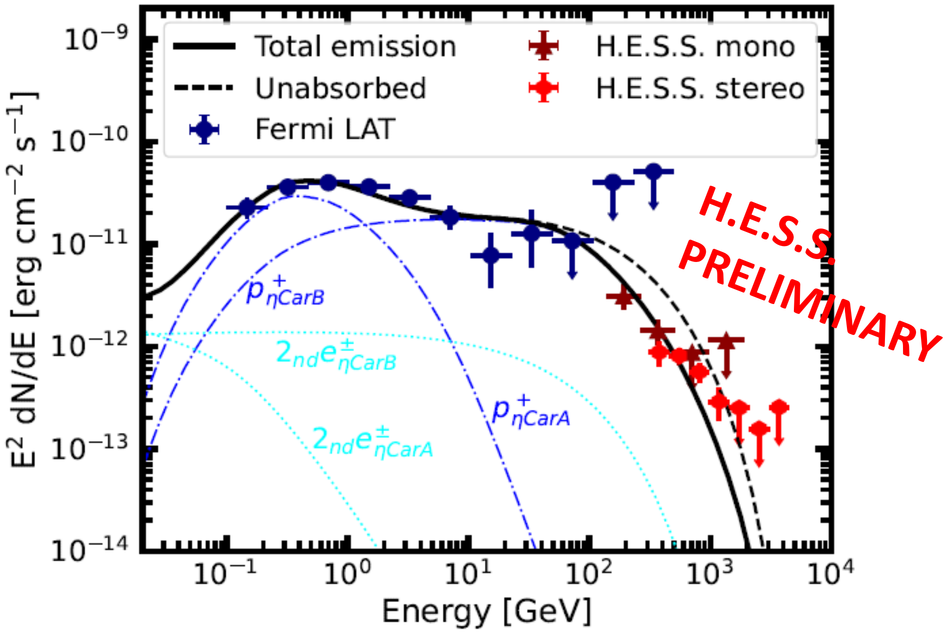
- PSR B1259/LS 2883 (2021)
- eta Carinae (2020)



Steinmaßl @ ICRC'23



$\Phi = 0.97 \ldots 1.05$



- detected from 140 GeV … ~ 1 TeV
- completion of all-phase orbit sampling
- soft spectrum with $\Gamma = 3.3 \pm 0.4$
- continuation of high energy (> 10 GeV) Fermi-LAT periastron emission
- hadronic emission scenario incl. p-cutoff & $\gamma\gamma$

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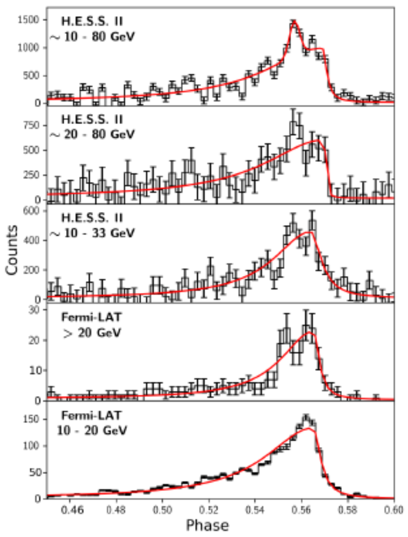
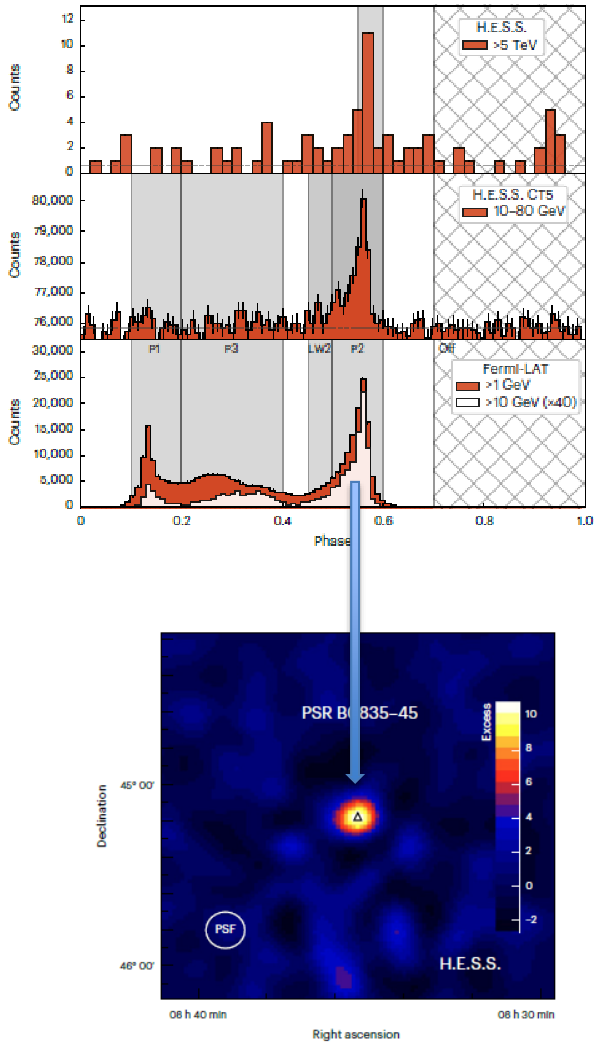
Pulsar B0833-45 (Vela)

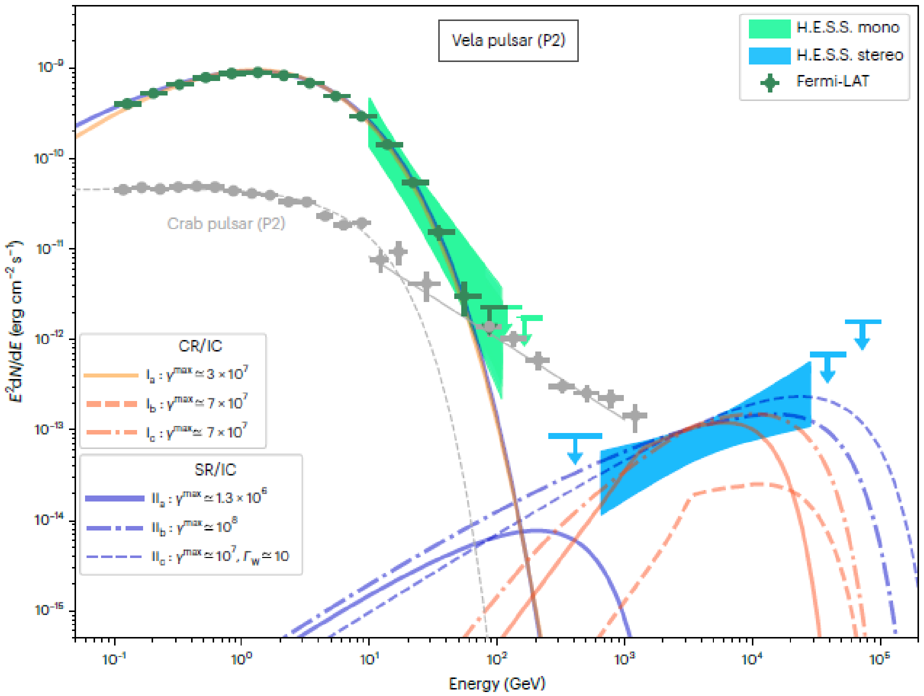


H.E.S.S., *A&A 620*, 2018



- Pulsed emission > 5 TeV
- P2: 20 – 100 GeV spectrum ≠ 1 – 20 TeV spectrum

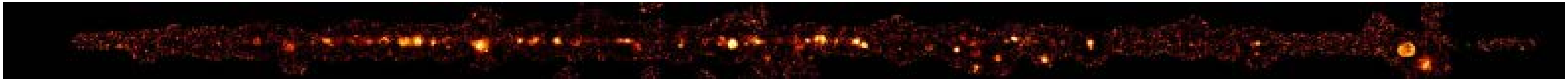
H.E.S.S., *Nature Astronomy 7, 2023*



Surveys

A major emphasis of HESS has been on surveys in various domains:
The HESS Galactic Plane Survey (2018) has been a key enterprise during the first decade of HESS.

- **HGPS 2.0 is in preparation**
- will approx. double # of sources
  → source morphology assessments
  → source extension assessments
  → diffuse emission assessment



- **HESS Extragalactic Gamma-ray Survey (HEGS)**
- **Inner Galaxy Survey (Galactic Bulge)**
- **HESS LMC Survey**

H.E.S.S.

Summary

HESS continues at high efficiency and is engaged in a broad science bouquet:

- New studies of CR e± up to 40 TeV
- New accelerators: Young Stellar Clusters
- New diagnostics (Vela, Crab, μQSO)
- Monitoring (B1259-63, η Car)

Further results I had not had the time to present….

- New studies on diffusion (PWN halos)
- New constraints on AGN: M87 spectrum A&A 685, 2024;
  EHT 2018 campaign: https://doi.org/10.1051/0004-6361/202450497
- New surveys → towards a H.E.S.S. legacy
- New constraints on DM from Inner Galaxy Survey: Strongest limits on DM in this energy range
  https://doi.org/10.1103/PhysRevLett.129.111101

- 3rd extension period: 2025 – 2028
- New legacy program to be implemented

Thank you for your attention!

H.E.S.S. - status & recent results

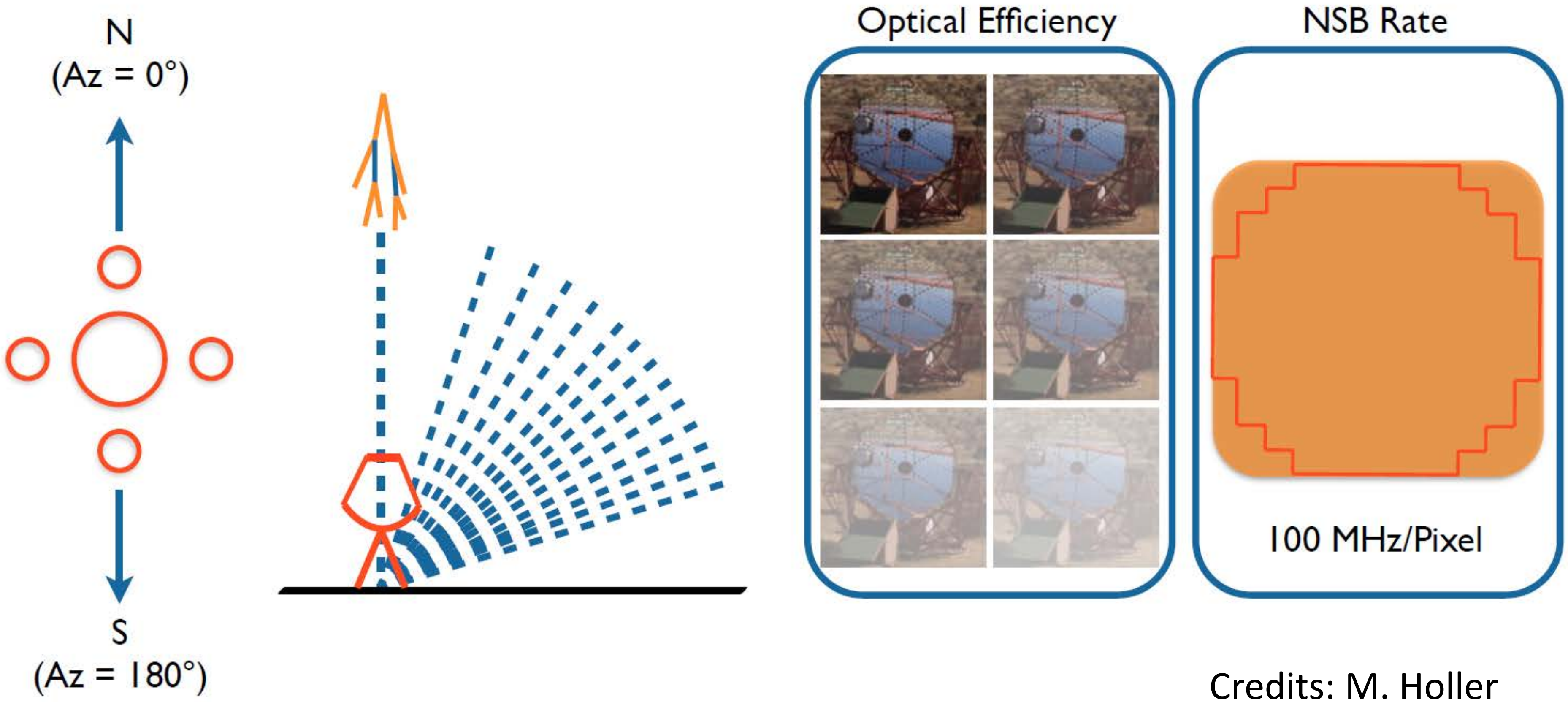
Olaf Reimer for the H.E.S.S. collaboration

H.E.S.S.

Roma International Conference on AstroParticle Physics 2024

Backup

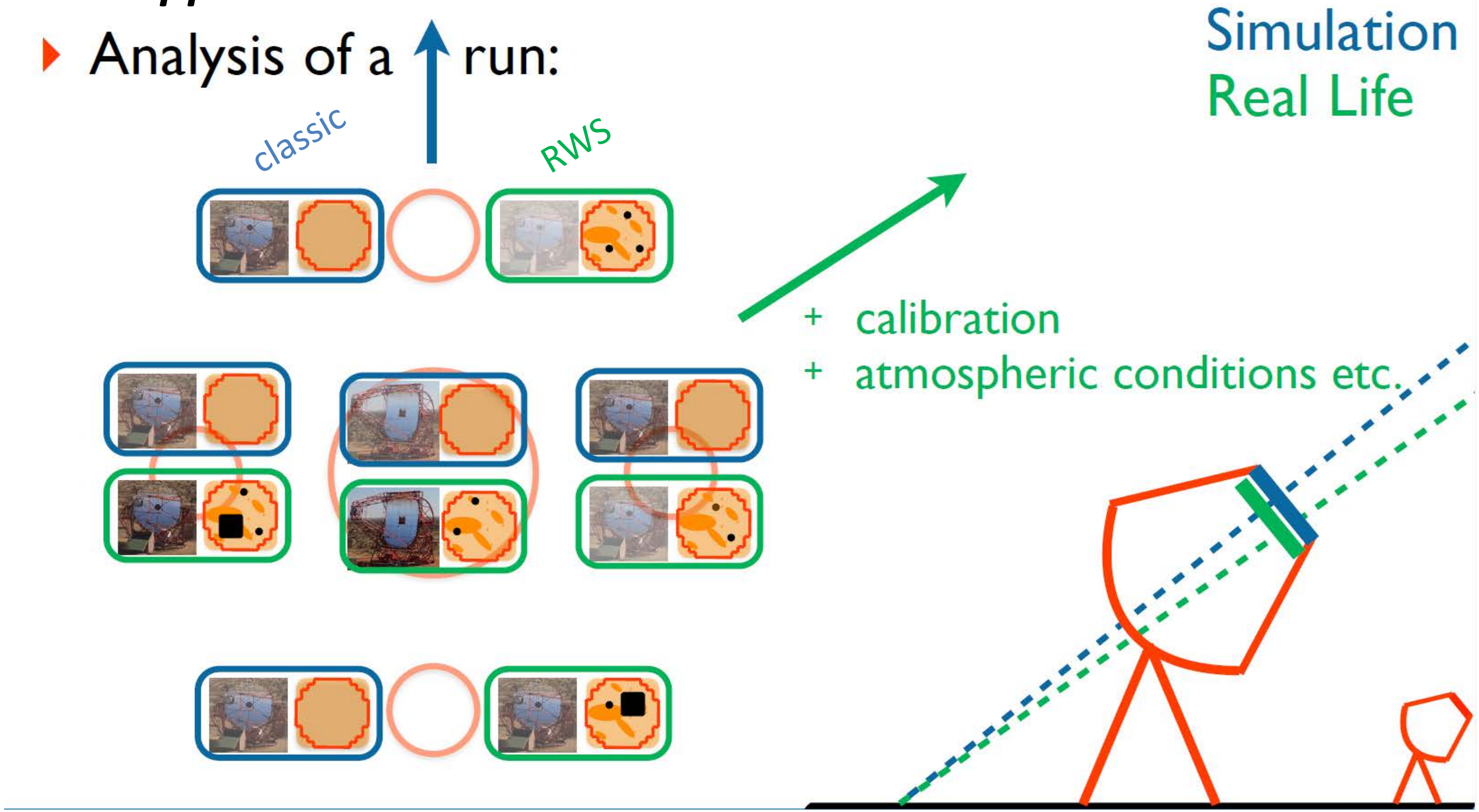
Common (conventional) approach



Credits: M. Holler

Backup

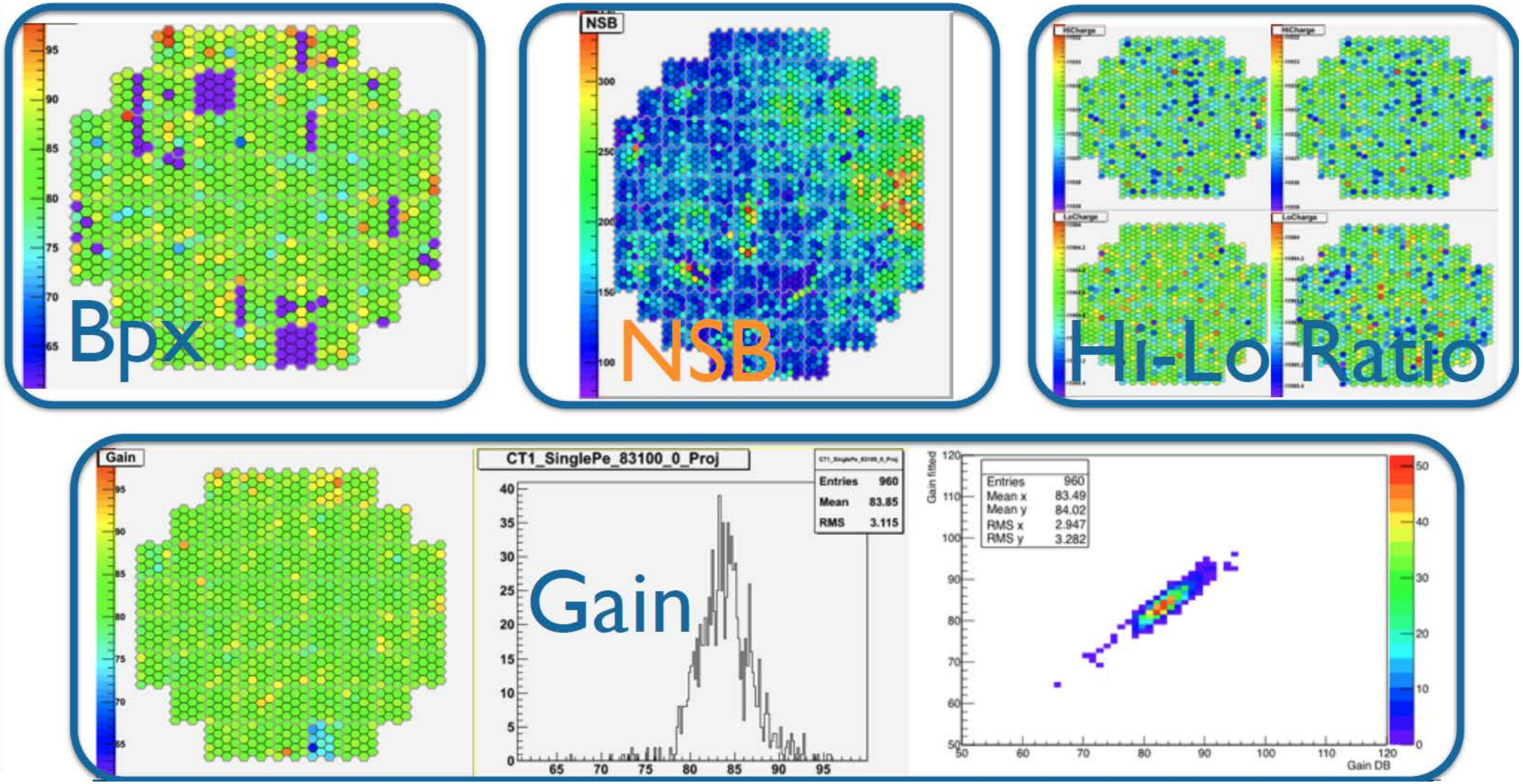
RWS approach



Credits: M. Holler

Backup

RWS approach



Credits: M. Holler