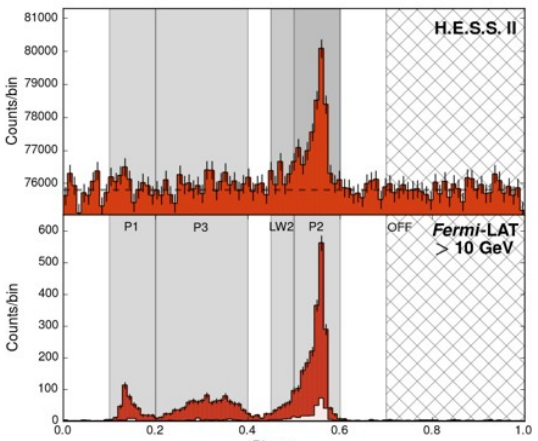
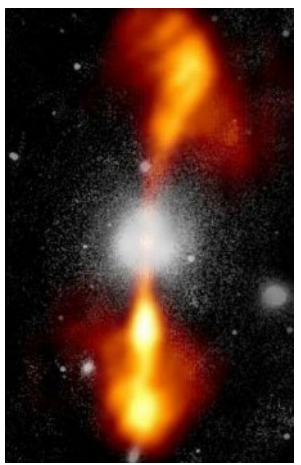
20 years on the austral sky with H.E.S.S.

M. de Naurois for the H.E.S.S. collaboration



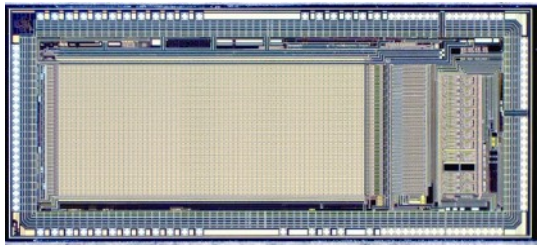


High Energy Stereoscopic System (H.E.S.S.)

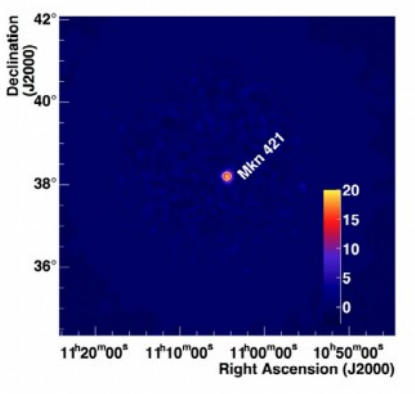
- Array of 4+1 Cherenkov telescopes located on Khomas Highland, Namibia (1800 m)
  - H.E.S.S. phase 1 (09-2002):
  - 4 telescopes: Ø 12 m,107 m^2
  - Stereoscopic reconstruction
  - 960 PMTs/camera, Field of view : 5°
  - Observations : ~1000h/year
  - Source position : ~ 10”
  - H.E.S.S. phase 2 (09-2012):
  - 5th telescope, Ø 28 m, 600 m^2 (largest IACT in the world)
  - 2048 PMTs, Field of view : 3.5°
    → Energy threshold (zenith) ~ 30 GeV

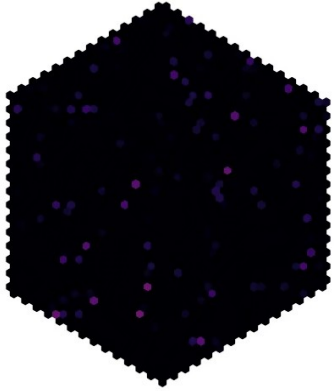
H.E.S.S. as test-bed for CTA

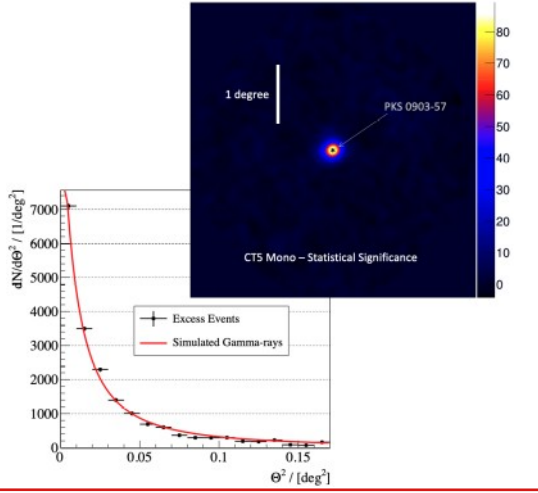
- NECTAr-based Camera in CT1 to CT4 (01/2017)
- Sampling capabilities, ...



- FlashCam Camera in CT5 (10/2019)
- High performance, high reliability camera
- Sampling capabilities
- ...



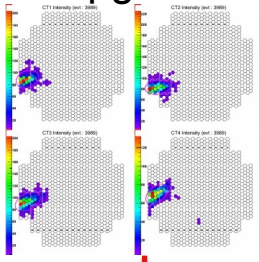




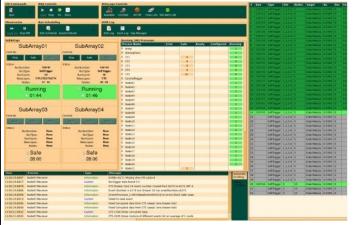
Evolution of H.E.S.S.

CT5 1st light

CT2-4 camera upgrade



DAQ & cluster upgrade



2002 2004 2008 2010 2012 2014 2016 2018 2020 2022

CT1-4 mirror refurbishment

CT1 camera upgrade

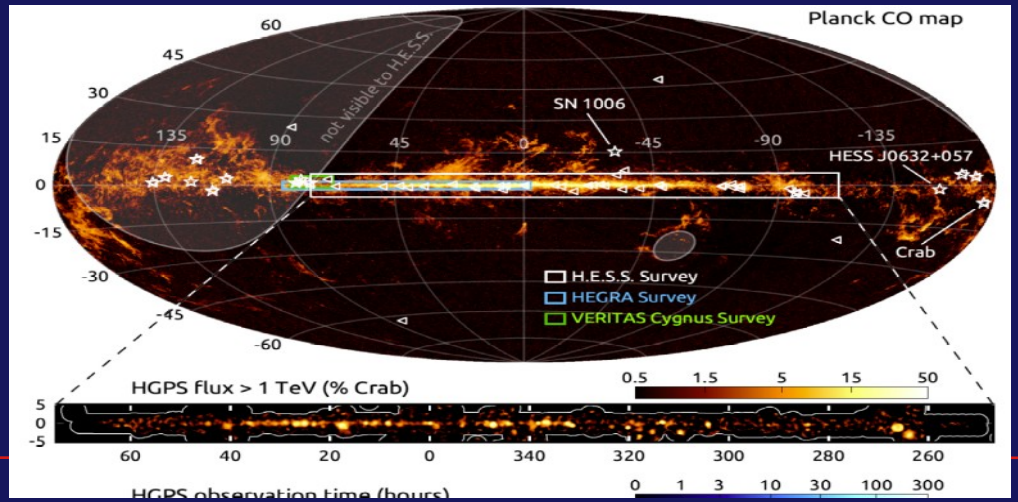
CT3 mirror refurbishment

CT5 camera upgrade

H.E.S.S. in a few numbers

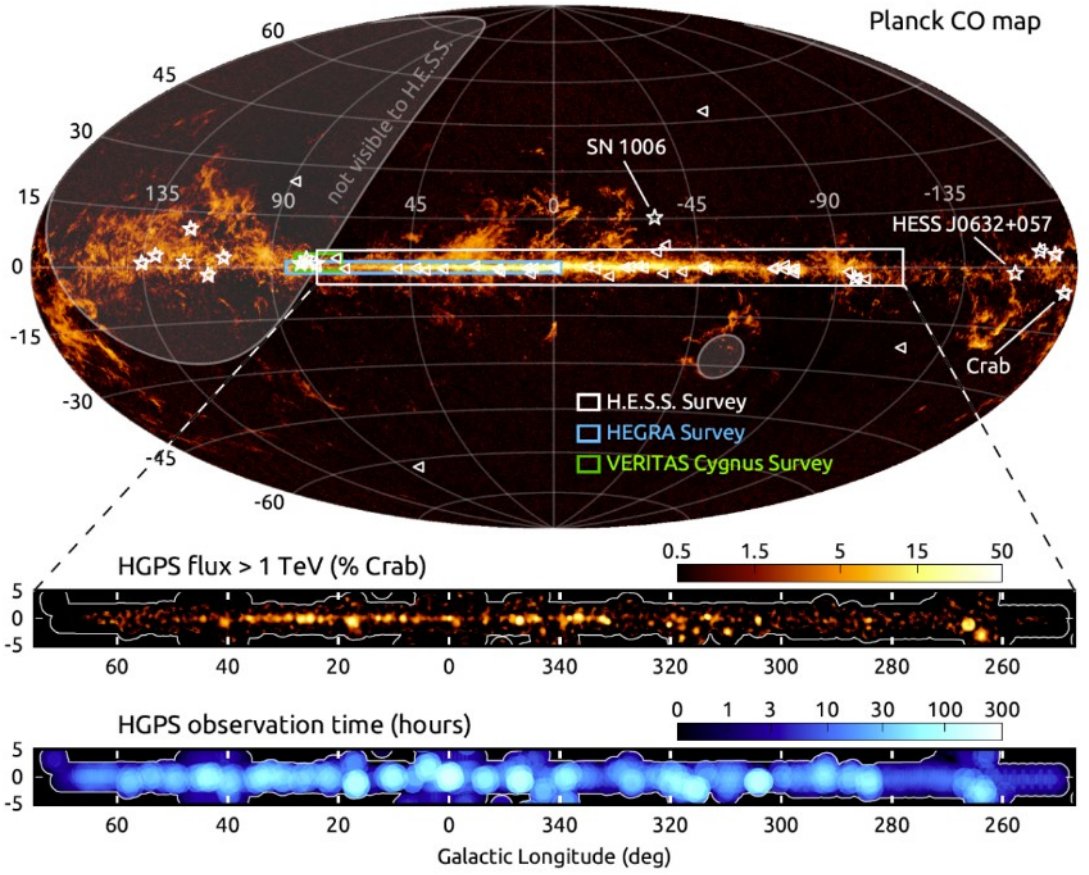
- 20 years of continuous operation (including COVID pandemics)
- 21 510 collected hours of data (> 6 PB of archive incl. Monte Carlo)
  - Current pace ~ 1400 hours/year (incl. Moonlight observations)
- 225 signing members from 14 countries
- ~ 230 publications in refereed journals, 7 Nature, 9 Science (more to come)
- 20th Birthday Celebration 18/10/2022

H.E.S.S. I Legacy
A new view on the Milky Way



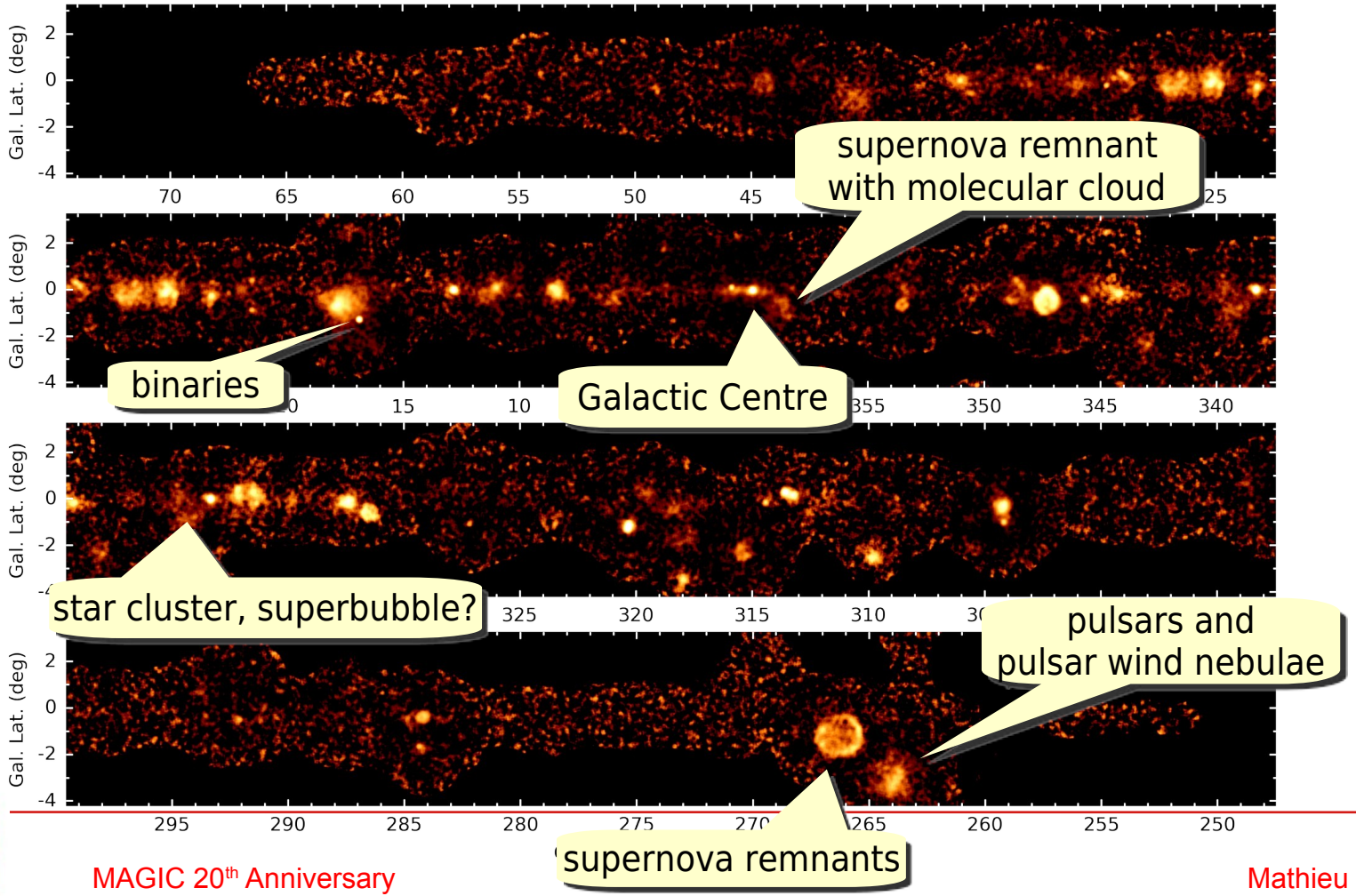
H.E.S.S Legacy Survey

- Major H.E.S.S. project
- Data collected 2004 – 2013
  - 2673 h after quality selection
  - l in [-110°, 70°]
  - b in [-5°, 5°]
  - Inhomogeneous exposure (sources of particular interest)
- Largest VHE survey so far done by IACTs
- Maps released in FITS format

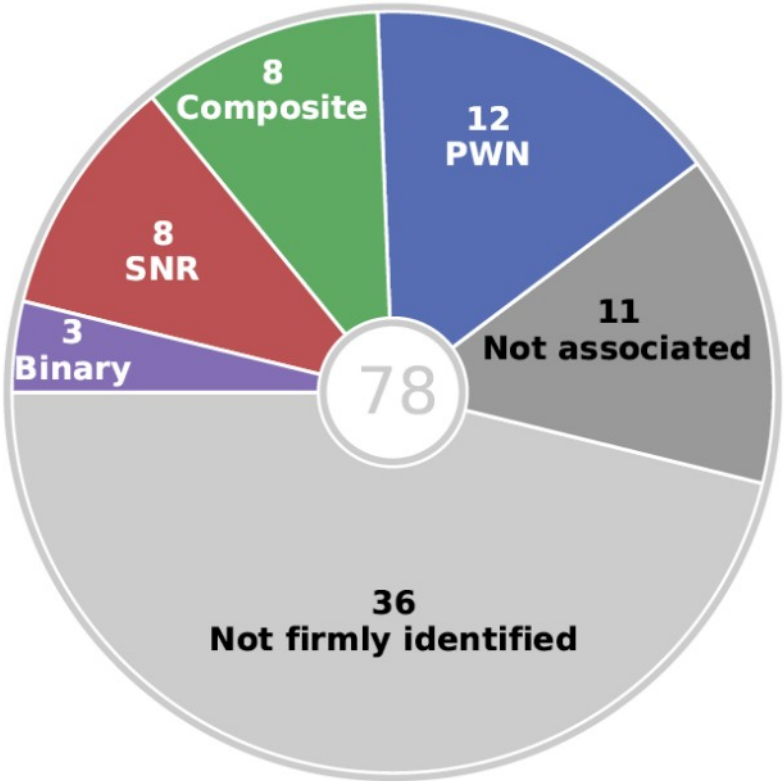


H.E.S.S. Collaboration - A&A 612 (2018)

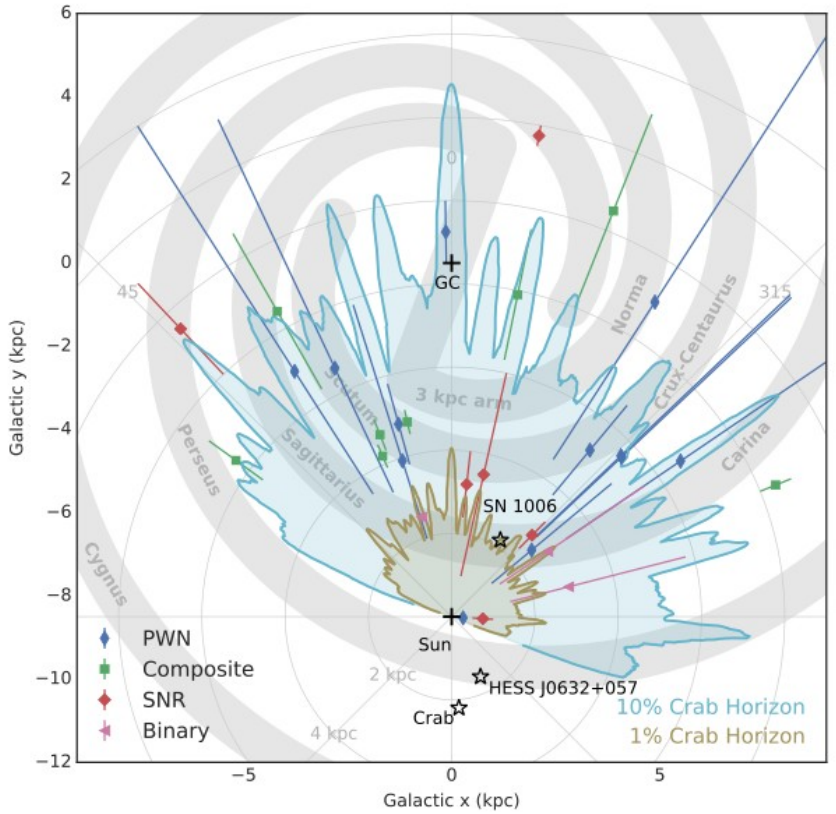
H.E.S.S Legacy Survey



Association and Identification



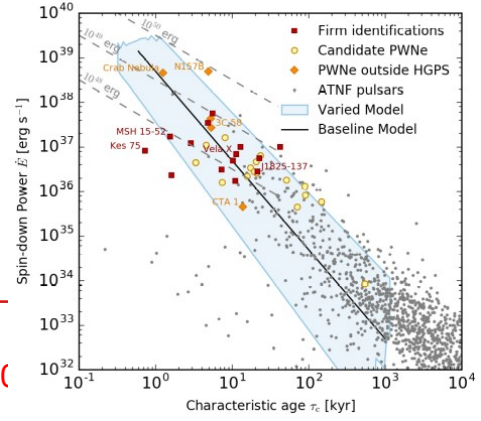
Horizon

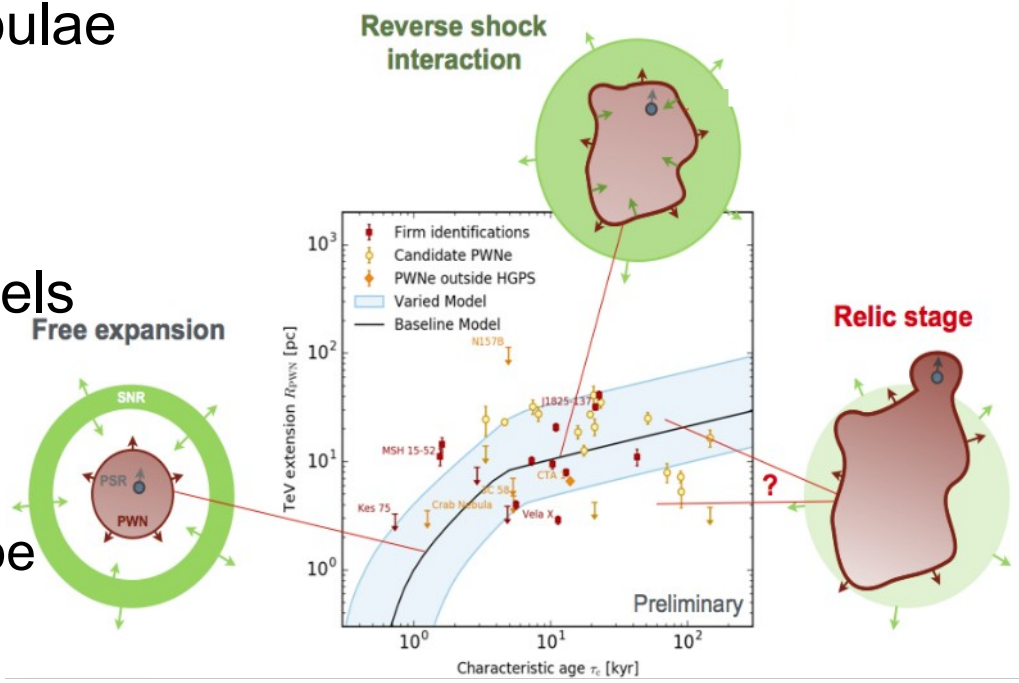


What surveys are good for?

- Population of TeV Pulsar Wind Nebulae in the H.E.S.S. HGPS
  - ~2/3 of pulsars with $\dot{E} > 10^{37}$ erg. s^{-1}
  - ~50% of pulsar with $\dot{E} > 10^{36}$ erg. s^{-1}
- Allows to build PWN evolution models
  - time-dependent $e^{\pm}$ injection
  - Analytical radius evolution
  - Cooling mechanisms: Synchrotron, Adiabatic, Inverse Compton & Escape

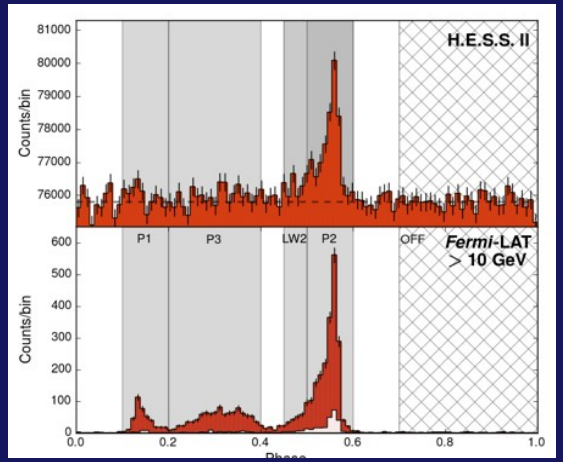
$$\dot{E}(t) = \frac{\dot{E}_0}{\left(1 + \frac{t}{\tau_0}\right)^2}$$

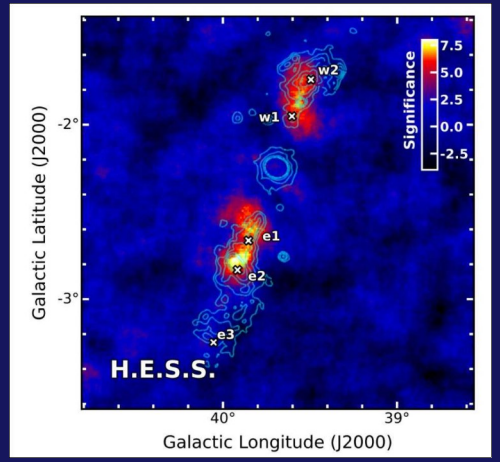




H.E.S.S. Collaboration - A&A. 612 (2018) A2)

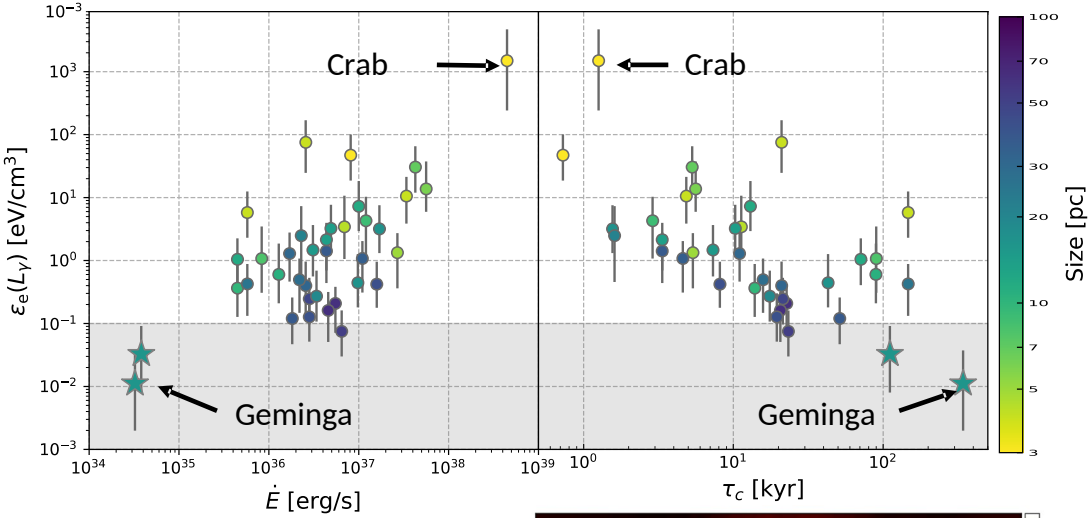
A few recent results - Galactic Sources

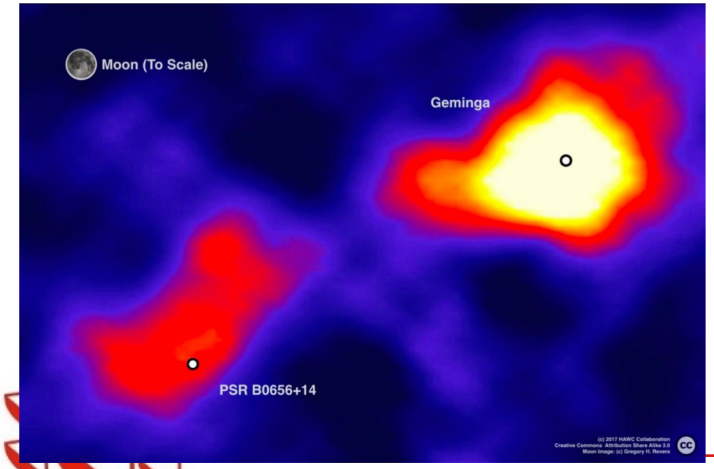




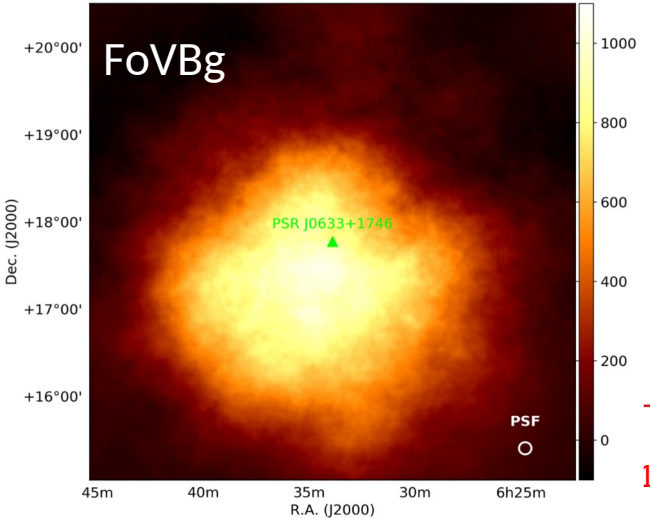
(very)–extended Source – Geminga

- Non Thermal Halo >> PWN size
- Geminga one of he largest known
- Age = 342 kyr, $\dot{E} = 10^{34.51}$ erg/s, Distance = 0.25 kpc
- R: radio = 0.01 pc, X-ray = 0.15 pc, TeV = 100 pc
- Could contribute to positron excess





- H.E.S.S. data
  - UsingFoV Background
  - True Extent > 1° radius
- Estimate of diffusion coefficient << average galactic value



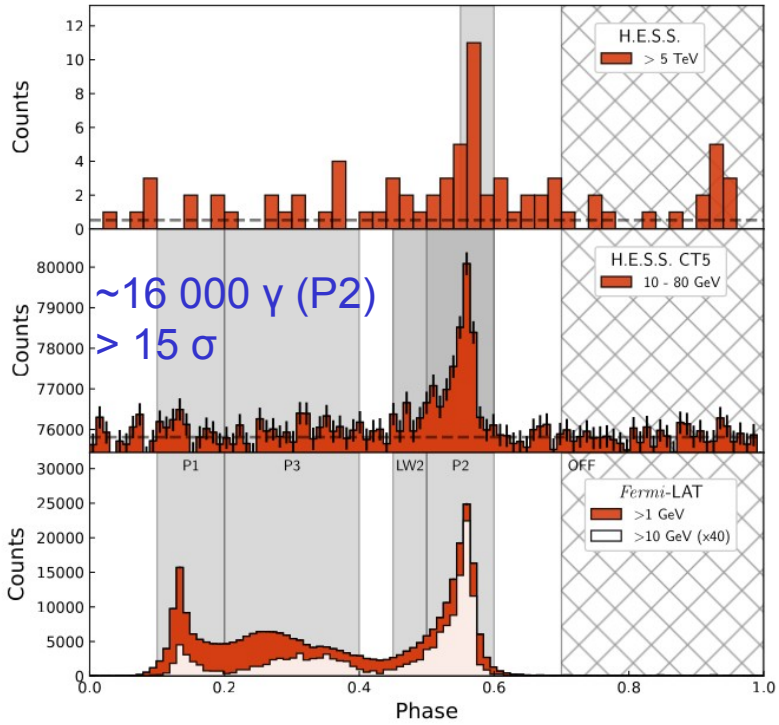
HAWC collaboration 2017

H.E.S.S. Collaboration - A&A in press

Vela Pulsar – H.E.S.S. II

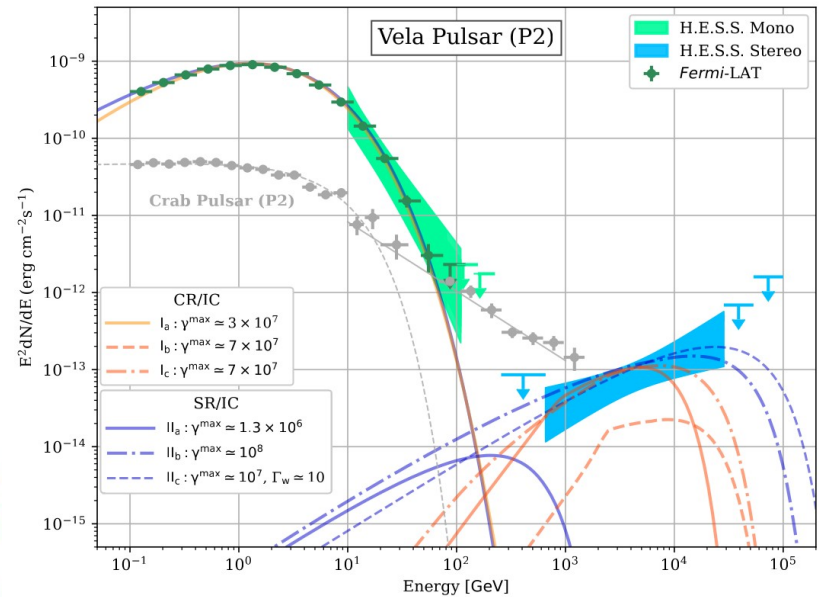
Nature Astronomy
October 5th 2023!

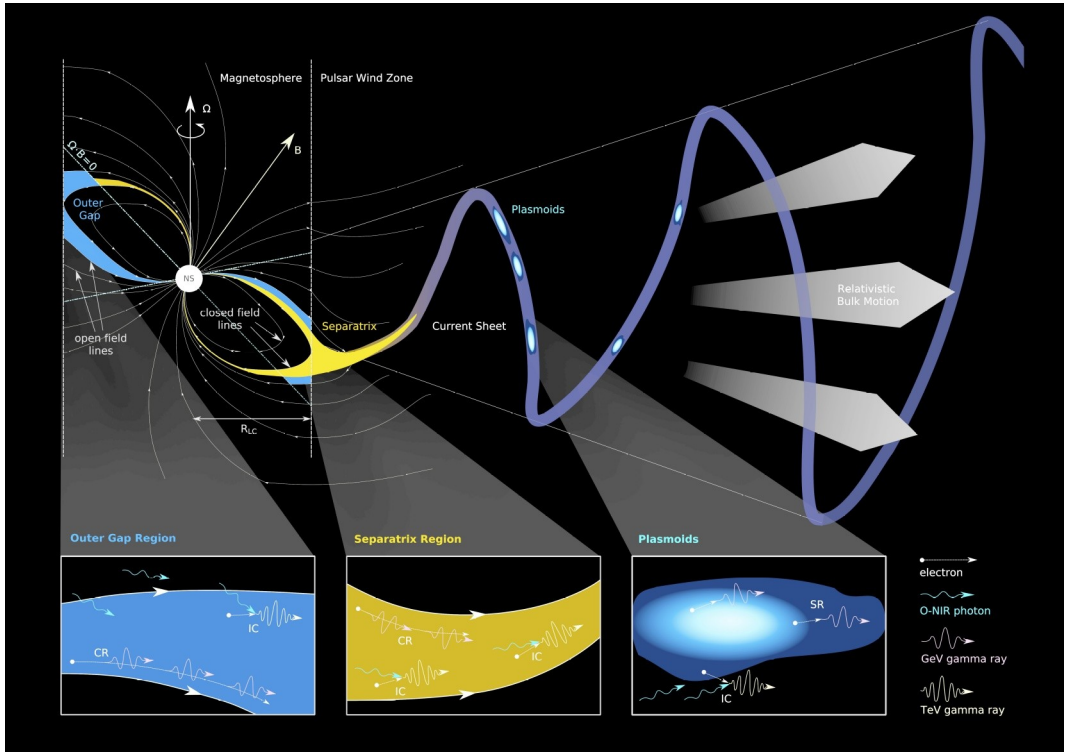
- Second VHE pulsar (H.E.S.S.)
  - At the threshold in standard observation mode
  - Deep observation campaign
  - VHE emission up to 20 TeV
    → new component?
- Crab vs Vela:
  - Crab:
    - P1 and P2 observed from the GeV to the TeV, bridge also detected from the ground (MAGIC)
    - Power-Law Spectrum from GeV to TeV
  - Vela:
    - P1/P2 changing a lot with energy, only P2 detected at TeV
    - Curvature / cutoff at few GeV with > 3σ for both Fermi and HESS
    - Very hard VHE spectrum: distinct spectral component



Interpretation

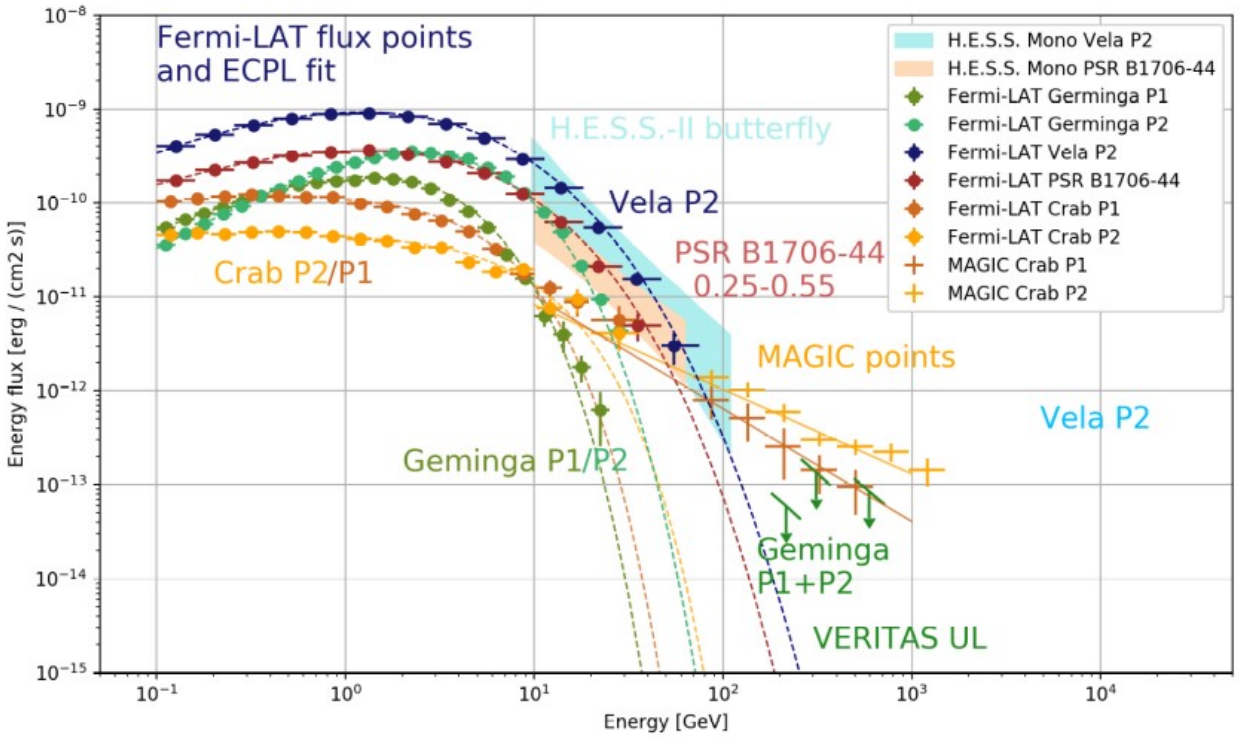
- TeV component most likely IC origin on IR photons
- Far from light cylinder
- Pulsars are efficient leptons accelerators





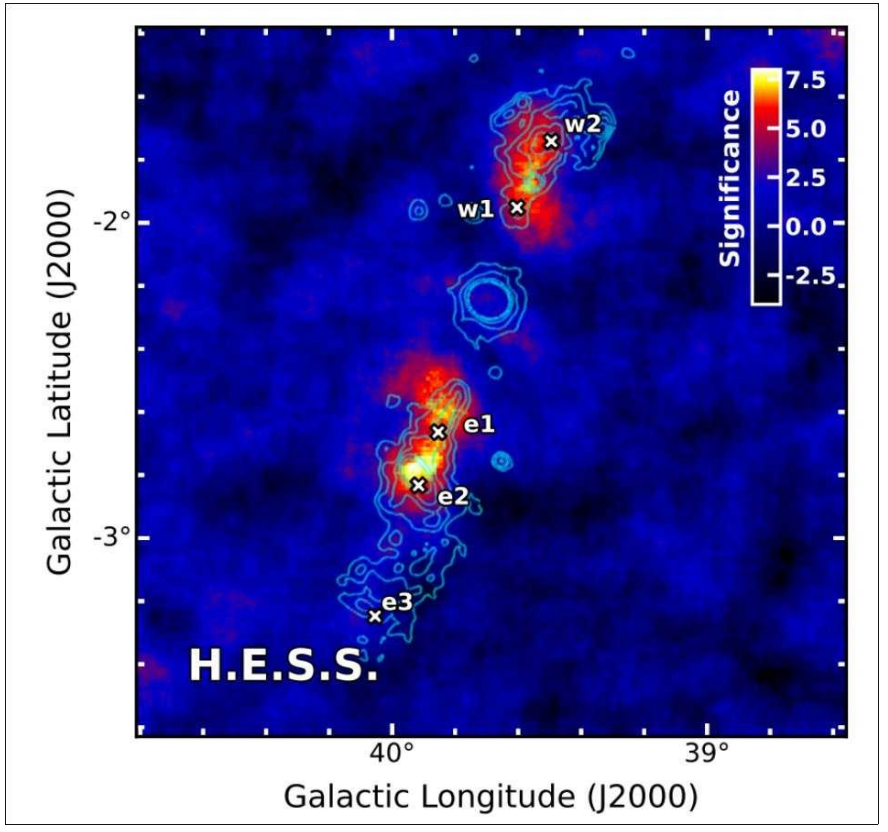
Pulsars from ground

- With PSR B1706-44, 3 VHE pulsars
- Amongst brightest pulsars in Fermi 2PC catalogue



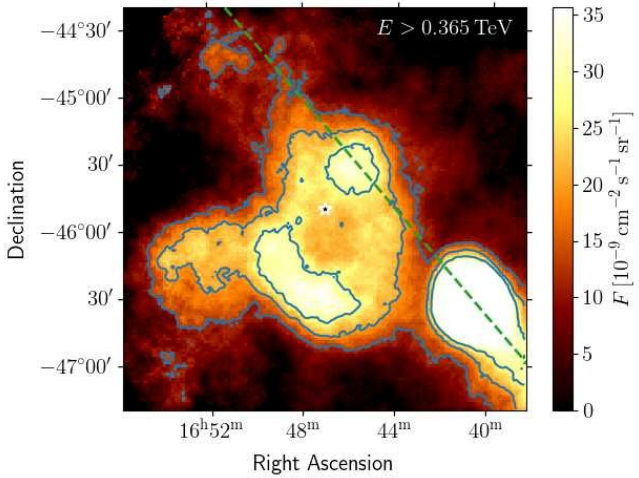
Microquasars – SS 433

- VHE upper limits with MAGIC (2018) based on ~18h of data
- HAWC detection of emission from both jets (2018)
- Deep H.E.S.S. observations (300 h)
  - Extended emission along jet direction (both sides)
  - Spectrum up to 40 TeV
  - Central BH not detected
  - Submitted to **Science**
- First VHE microquasar !

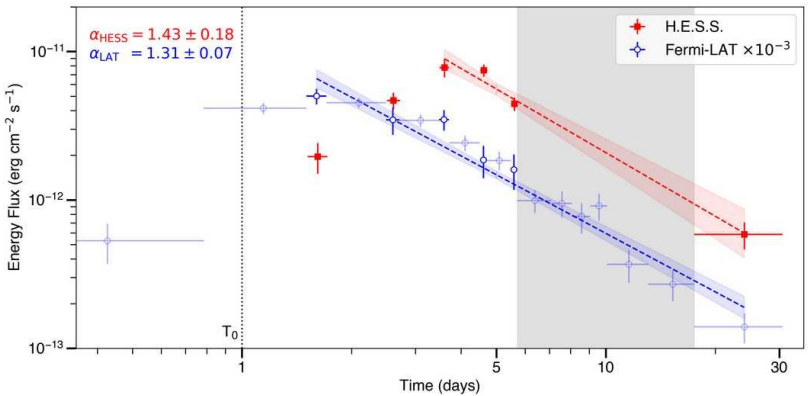


Other recent news from the Milky Way

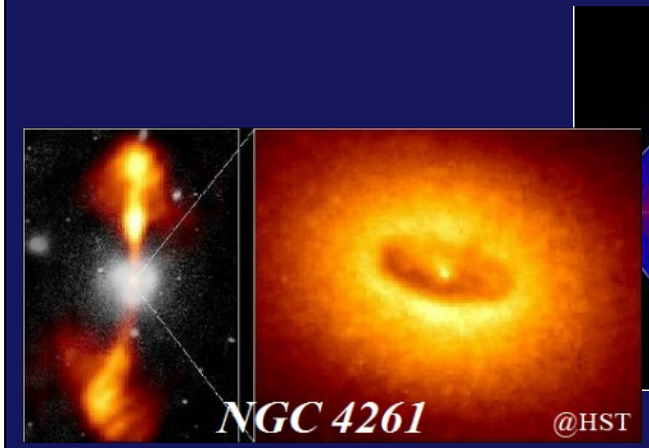
- Galactic stellar clusters: Westerlund 1
  - shell-like structure, centred on cluster
  - + 4 sources on top of/adjacent to the shell.
  - ⇒ CR acceleration at the cluster wind termination shock
- Inner Galaxy Survey – ongoing project



- Recurrent Nova RS Ophiuchi
  - First Galactic transient observed in VHE (2021 flare)
  - VHE emission detected during 40 days
  - Hadronic emission scenario preferred

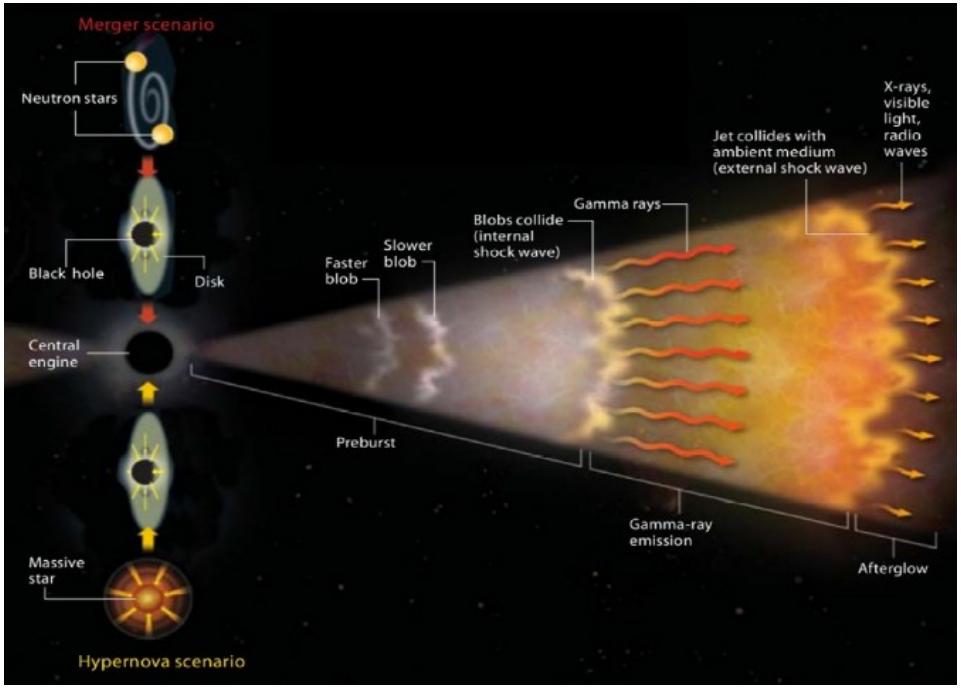


Extragalactic Science



Gamma Ray Bursts

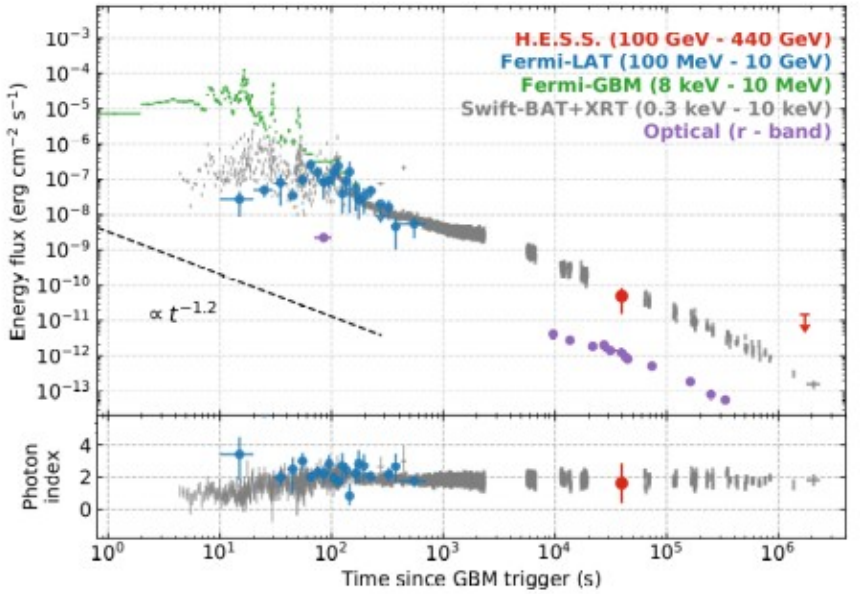
- Recent revolution in VHE astronomy
- Made possible by
  - Fast slewing
  - Aggressive observation strategies
  - Luck?
- Recent detections (Long GRBs):
  - GRB 180720B (HESS)
  - GRB 190114C (MAGIC)
  - GRB 190829A (HESS)
  - GRB 201216C (MAGIC)
  - GRB 221009A aka BOAT (LHAASO)
- Hint from short GRB
  - GRB 160821B (MAGIC, 3 σ)

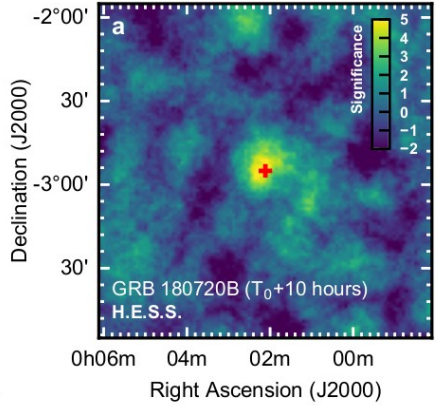


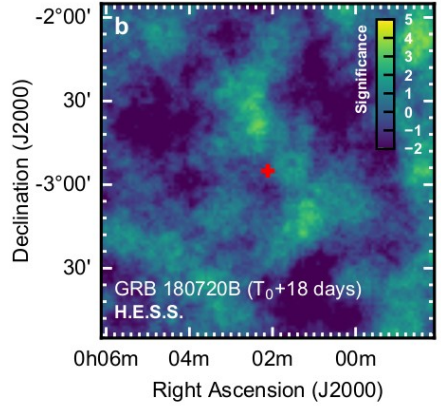
GRB 180720B

H.E.S.S. Collaboration - Nature 575 (2019)

- Extremely bright burst at z = 0.65:
  - 2nd brightest afterglow measured by Swift-XRT.
  - 7th brightest prompt emission detected by Fermi-GBM.
- HESS observation started at t_0+10h
- ~5.3 σ pre-trial, 5.0 σ post-trial
- Hard intrinsic spectrum (Γ = 1.6 ± 0.2)
- Energy flux similar to other energy ranges
- Afterglow falling at same rate in all wavelengths.

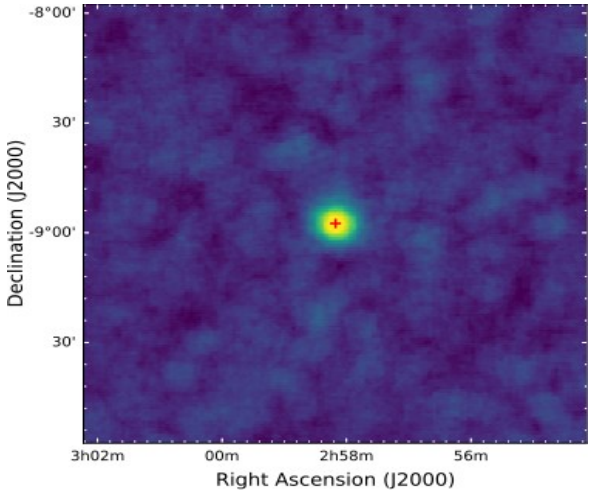




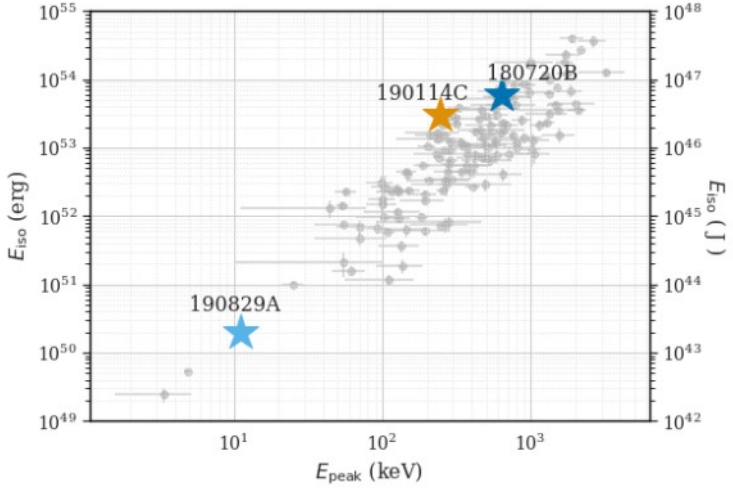


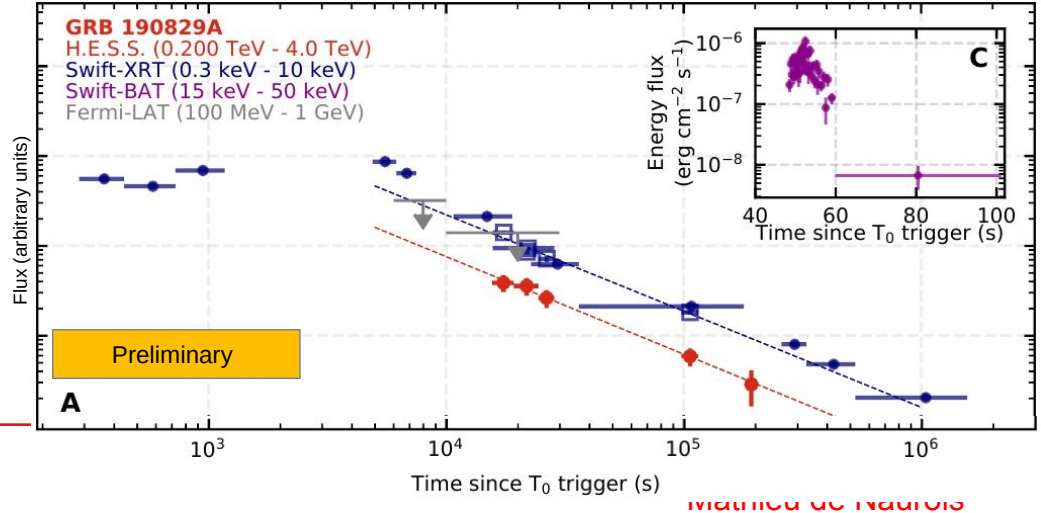
GRB 190829A

- Long GRB (t_{GBM90} ~ 60 s, t_{BAT90} ~ 60 s) @ z = 0.078
- Observation started at t_0 + 4h20 (ATel #13052)
- Followed during 3 nights (22, 6 and 3 σ)!
- Extending up to > 3 TeV
- Modest energy but one of the closest ever
- Similarly to GRB 180720B, afterglow falling at similar rate in all wavelength



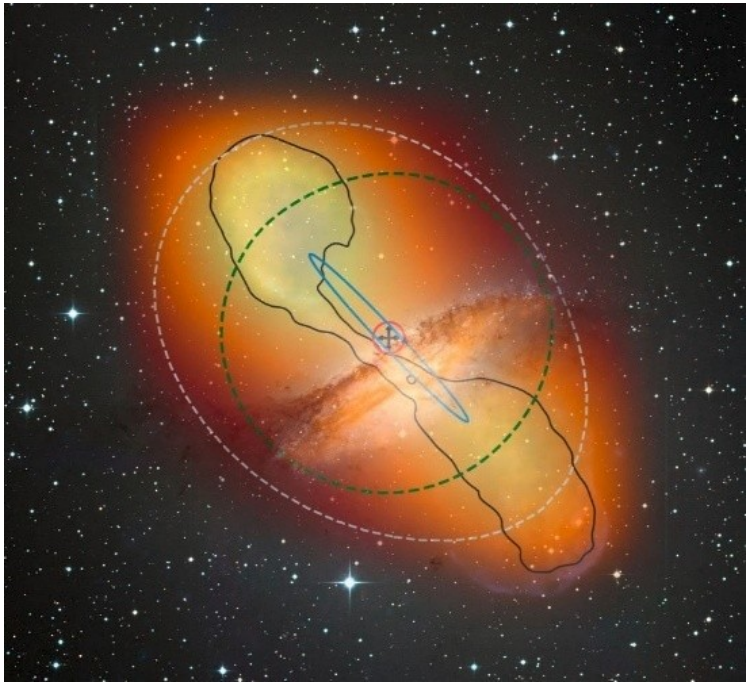
H.E.S.S. Collaboration - Science 372 (2021)





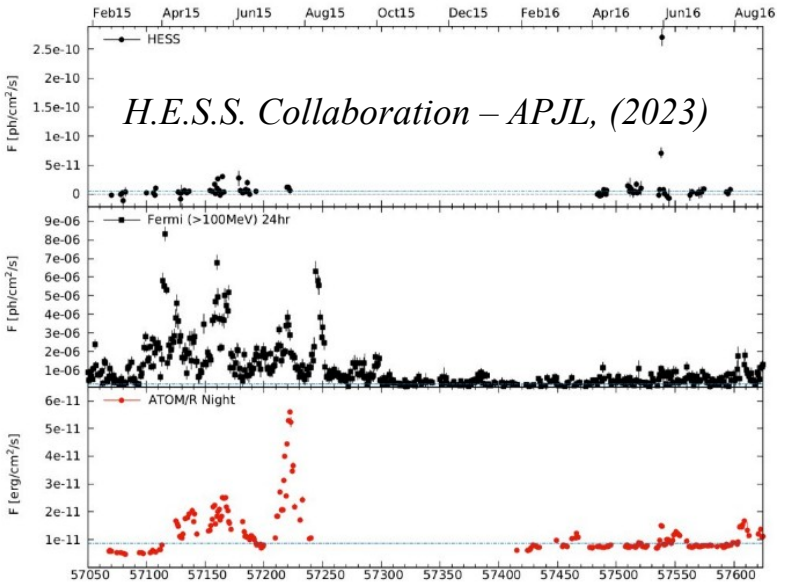
Centaurus A

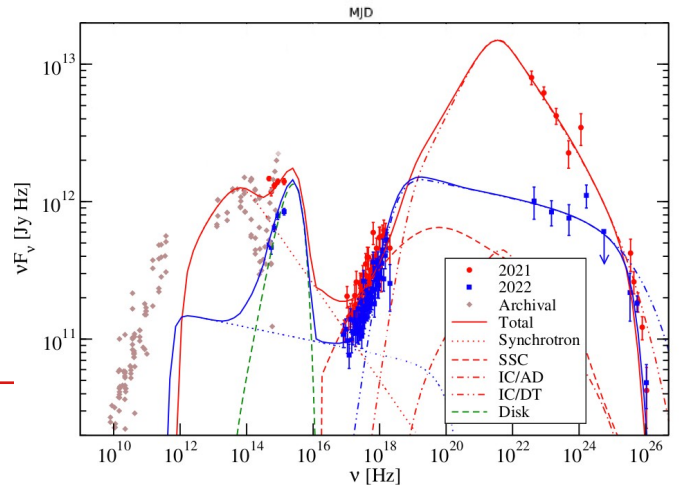
- Extended emission along the jets (~ 2.2 kpc)
- First extended extragalactic source
- Measurement made possible by new simulation paradigm (aka RunWise)
  - Better description of PSF
- Implies particle acceleration all along the jet ($\gamma \geq 10^7$)
- Radio-galaxies could contribute substantially to the diffuse gamma-ray background
- Could contribute to the redistribution of energy in the intergalactic medium



PKS 1510-089

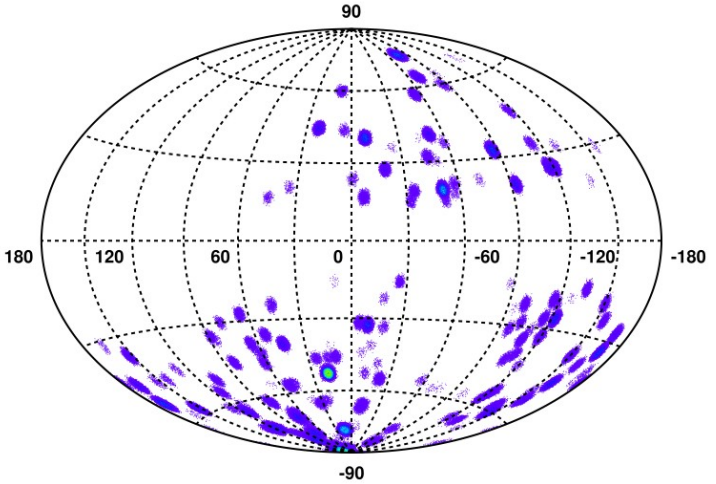
- First flat spectrum radio-quasar (FSRQ) detected by H.E.S.S in 2009 (z = 0.361)
  - Extreme TeV flare in may 2016, intranight variability
  - Emission outside of broad-line regions (to avoid strong absorption)
  - Complex behaviour (orphaned TeV flares, γ-γ absorption, ...)
  - Another bright flare in July 2019, surprising behaviour: GeV flux dropped, not TeV flux
    Requires fast change in e^- distribution
    ⇒ recent paper, SOM 08/2023

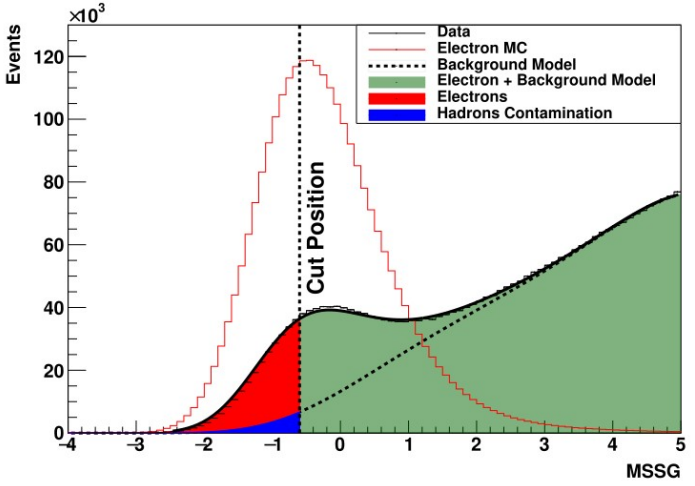




Beyond γ-rays: Cosmic Electron Spectrum

- Following & extending a pioneering work by Daniel Kerzberg
- Huge data set (> 3000 hr) excl. Gal. Plane (|l| > 15°)
- Specific analysis with hard cuts (hadronic contamination
- Diffuse, RunWise MC to derive precise response functions
- Many systematic checks
- Paper to be submitted soon

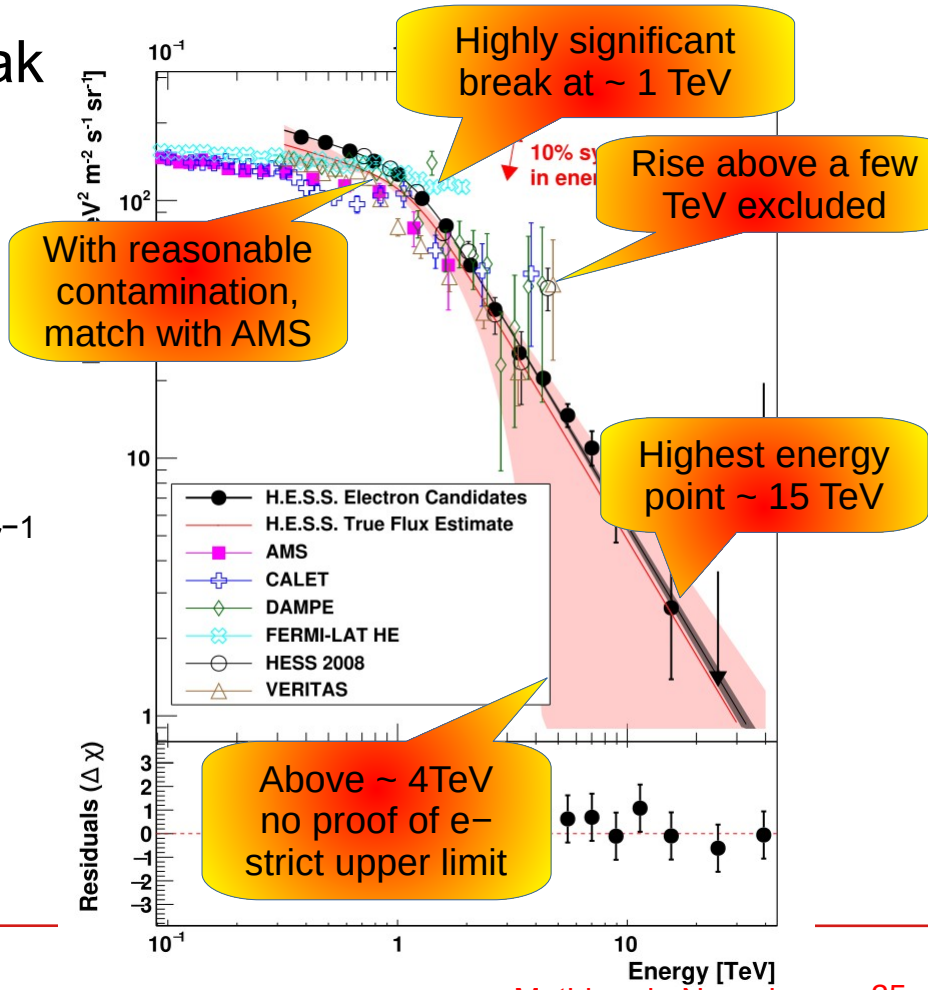




Beyond γ-rays: Cosmic Electron Spectrum

- Highly significant (> 100 σ) spectral break
- Best fit parameters:
  - $\Gamma_1 = 3.25 \pm 0.02_{stat} \pm 0.2_{syst}$
  - $\Gamma_2 = 4.49 \pm 0.04_{stat} \pm 0.2_{syst}$
  - $E_{break} = (1.17 \pm 0.04_{stat} \pm 0.1_{syst})$ TeV
  - Sharpness $s = 0.21 \pm 0.02_{stat}$
  - @ 1 TeV:
    $E^3 \times \Phi(E) = (126.1 \pm 0.5_{stat})$ GeV^2 m^{-2} s^{-1} sr^{-1}
    (not corrected for contamination)

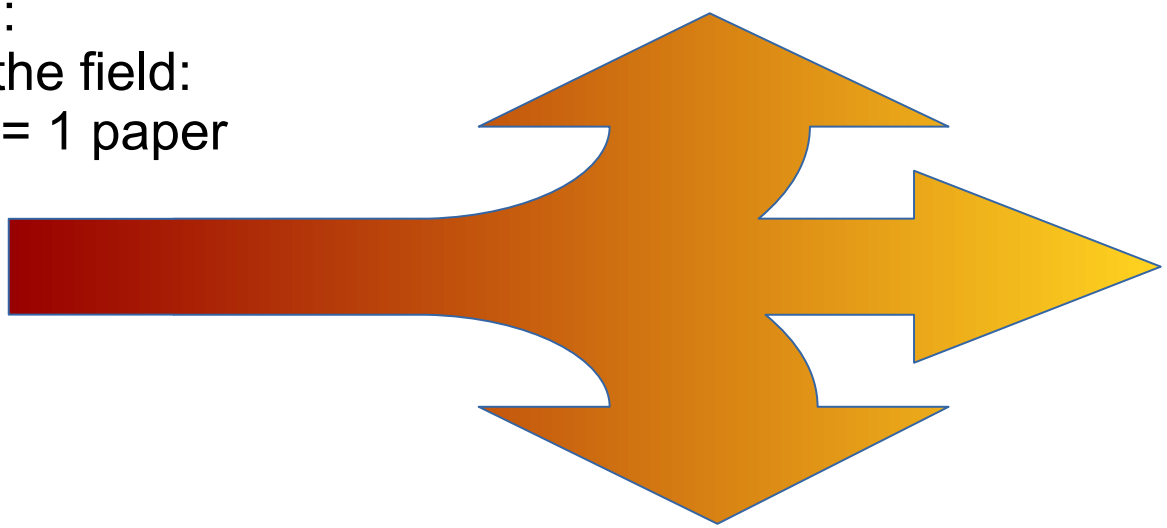
$$\frac{\mathrm{d}N}{\mathrm{d}E} = \Phi_0 \times \left(\frac{E}{E_0}\right)^{-\Gamma_1} \times \left(1 + \left(\frac{E}{E_{\mathrm{cut}}}\right)^{1/s}\right)^{s\times(\Gamma_1-\Gamma_2)}$$



Evolution of the Field & Conclusions

Surveys, populations studies

~2000-2010:
Opening of the field:
1 discovery = 1 paper



- Key Science projects,
- Deep investigation of specific objects
- Transients Sky

The Unknown, still searching for
- Dark Matter
- Exotic Physics

Challenges & Strategies

- Many studies use very extended data sets (600h+), obtained over many years with changing camera/telescope combinations
- Looking for (very) extended features, beyond the FoV of the instrument
- Challenges in treating systematics, background estimation and separation of sources (confusion).

  → A lot of technical work:
  - Improvement of calibration, background, and high-level analysis
  - More reliable RunWise simulations (simulate every run)
  - 3D Analysis, using gammapy as high-level tool

- Many subjects not covered in this talk (Binaries, SNRs, LIV, Dark Matter, ...)

Future of H.E.S.S.

- H.E.S.S. currently funded up to September 2024 (tomorrow…)
- Extension up to end of 2025 at the agenda of upcoming Steering Committee (not requiring re-negotiation of contacts)
- Starting discussion for another round of 3 years ⇒ 2028
  (Only array in the South, synergies with Fermi-LAT, Grav. Waves, etc.)

- Looking forward to fruitful collaboration with MAGIC.