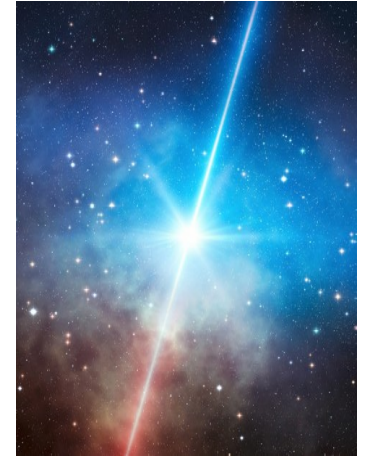
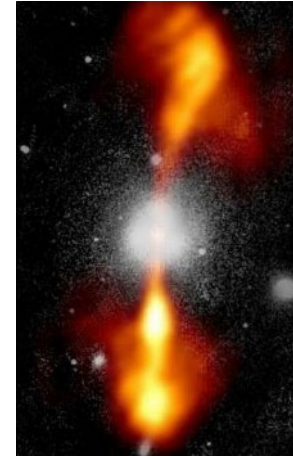
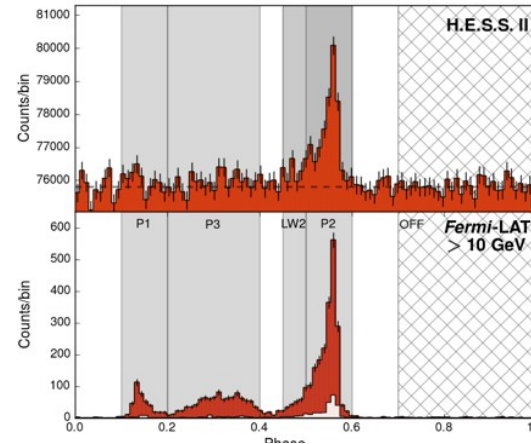


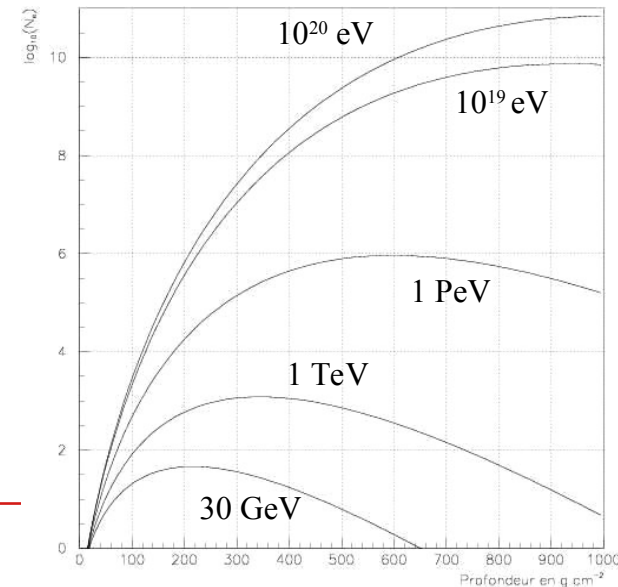
20 years of HESS in 20 min and ~20 slides (and beyond)

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

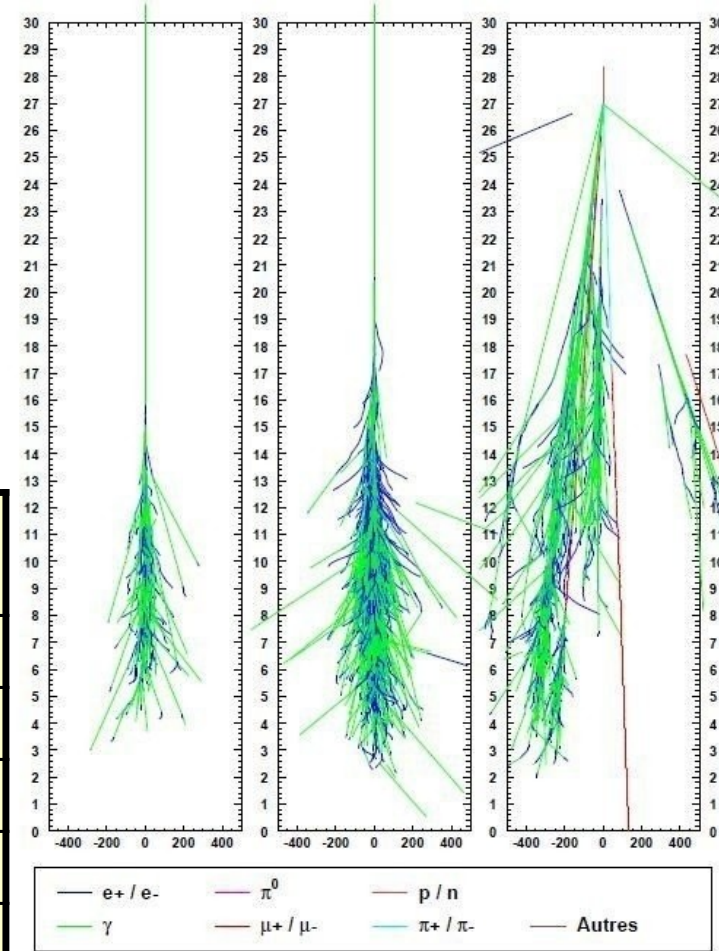


Ground-based Detection - Atmospheric Showers

- Atmosphere as inhomogeneous calorimeter
- Pair creation & Bremsstrahlung
⇒ extensive, atmospheric showers, ~ 10 km
- Additional processes in hadronic showers
- Altitude of max. devel. depends on energy



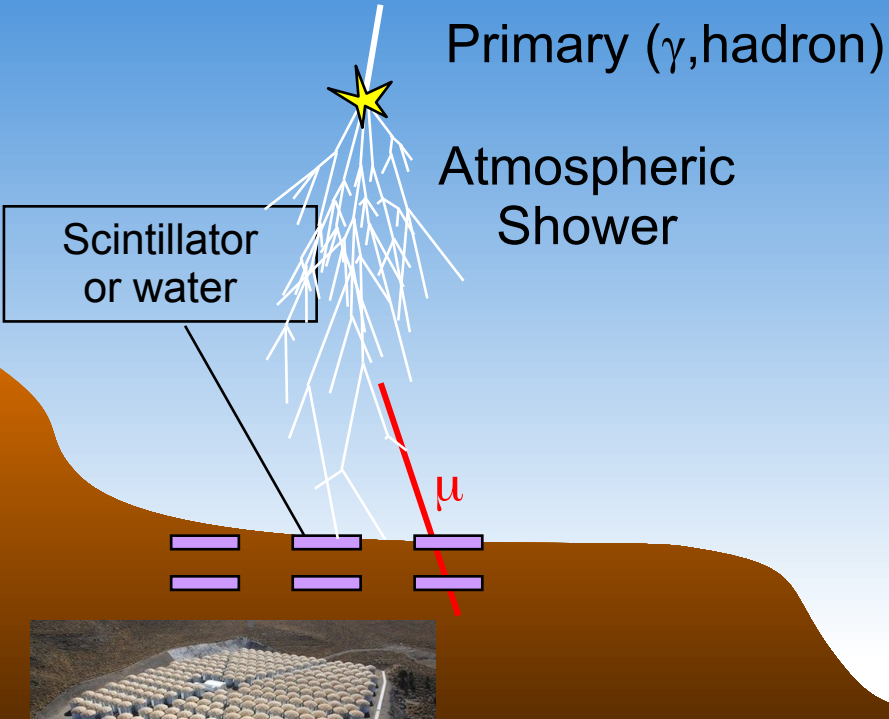
E_0	T_{\max} ($g\text{ cm}^{-2}$)	Altitude (m)	N_e (t_{\max})
30 GeV	216	12000	50
1 TeV	345	8000	1200
1000 TeV	600	4400	$0,9 \times 10^6$
10^{19} eV	936	1200	$7,4 \times 10^9$
10^{20} eV	1021	0	$7,0 \times 10^{10}$



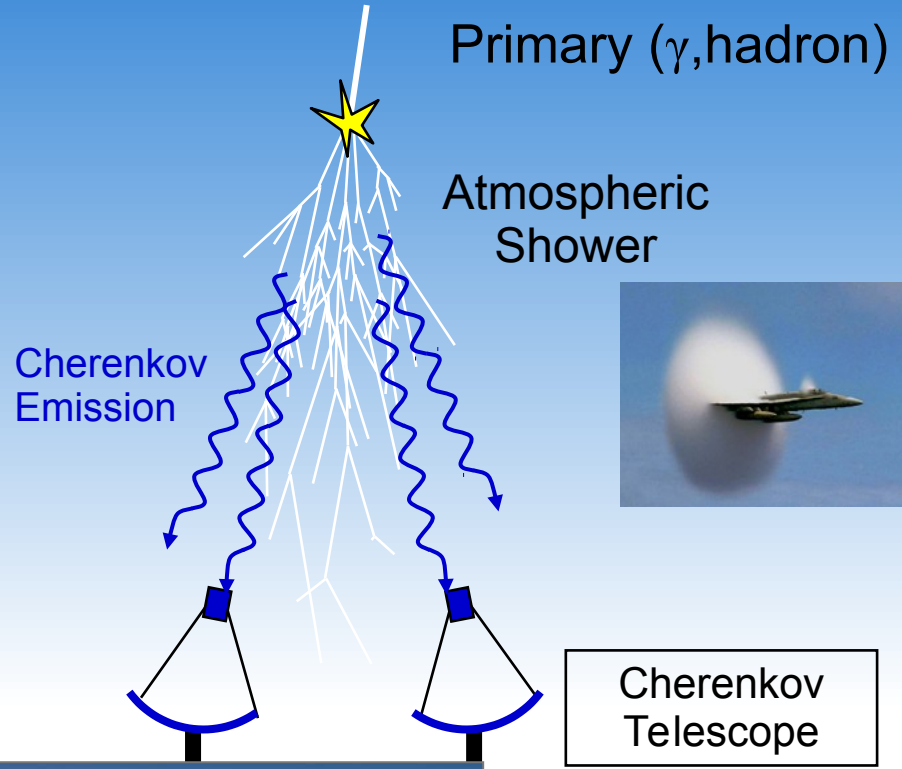
Ground-based Detection ($E > 10$ GeV)



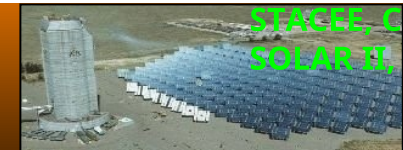
TIBET
LHAASO



HAWC



HESS, VERITAS, MAGIC, CTA



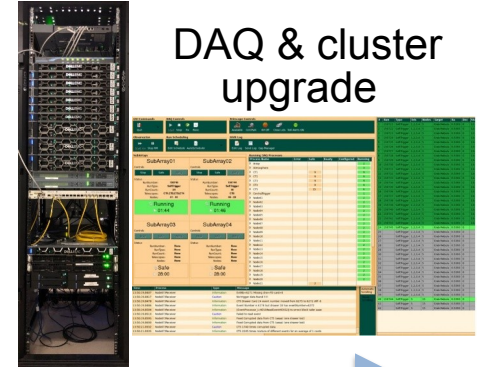
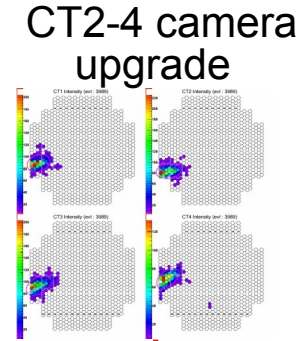
STACEE, CELESTE,
SOLAR FL, GRAAL

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: \varnothing 12 m, 107 m²
 - Stereoscopic reconstruction
 - 960 PMTs/camera, Field of view : 5°
 - Observations : ~1400 h/year
 - Source position : ~ 10''
 - H.E.S.S. phase 2 (09-2012):
 - 5th telescope, \varnothing 28 m, 600 m² (largest IACT in the world)
 - 2048 PMTs, Field of view : 3.5°
→ Energy threshold (zenith) ~ 30 GeV

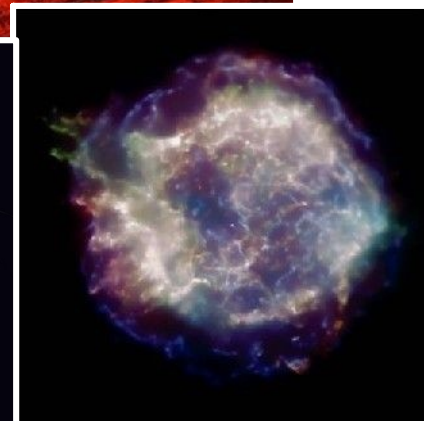
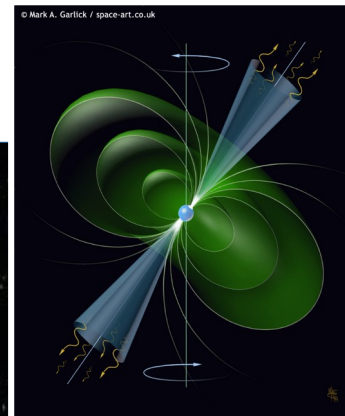
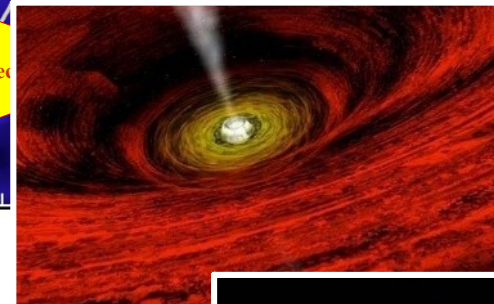
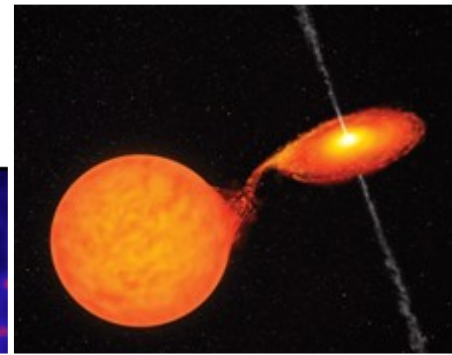
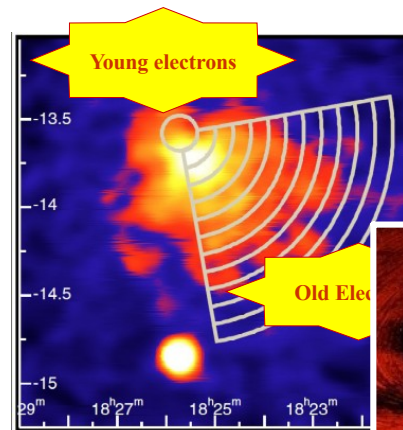
Evolution of H.E.S.S.



Operation until ≥ 2028 approved

Physics of H.E.S.S.

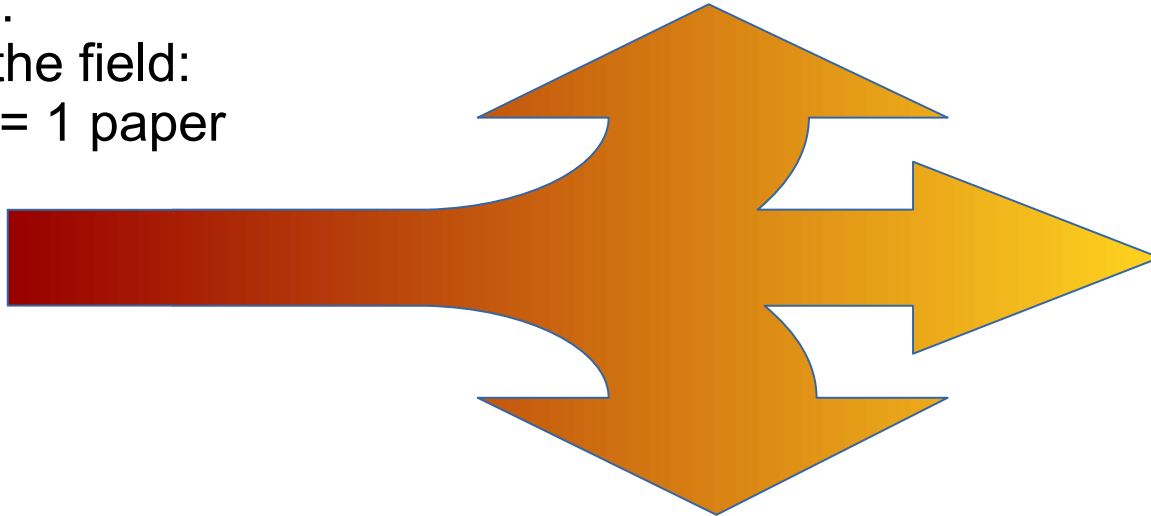
- Cosmic Ray Accelerators
Acceleration mechanisms,
max. energy, Gal/Egal transition
- Propagation of Cosmic Rays
(IGMF, EBL, ...)
- Search for dark matter (CDM, Axions, ...)
- Search for new physics (LIV, ...)
- The transient sky
- ...



Evolution of the Field

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

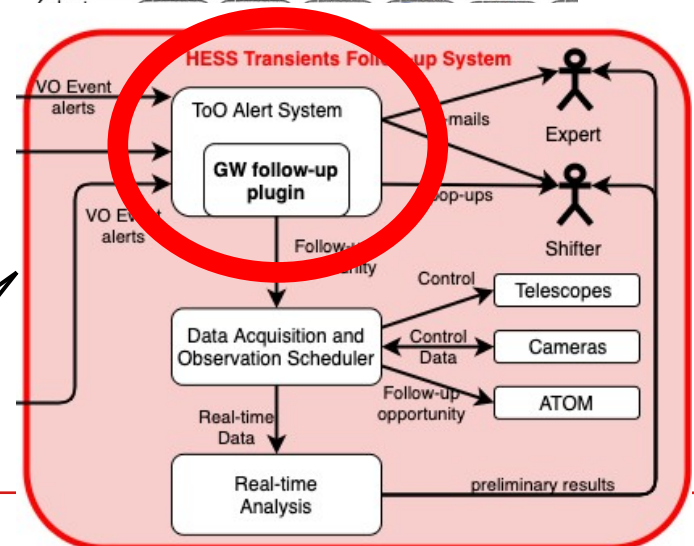
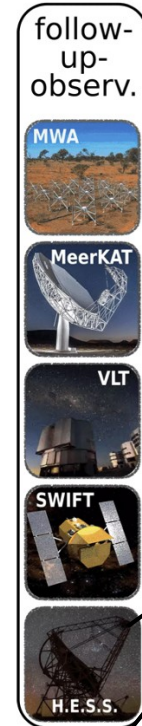
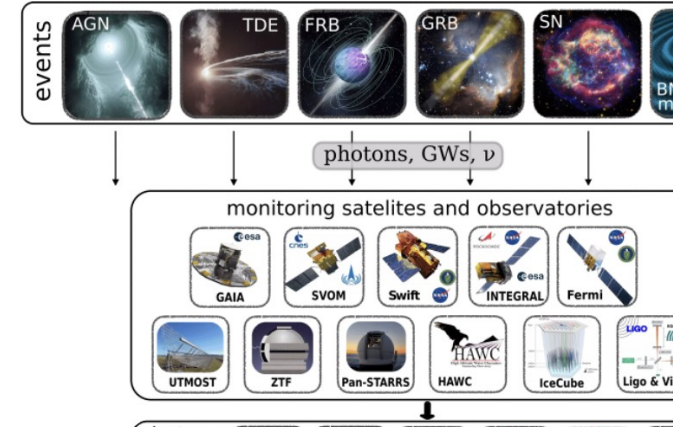
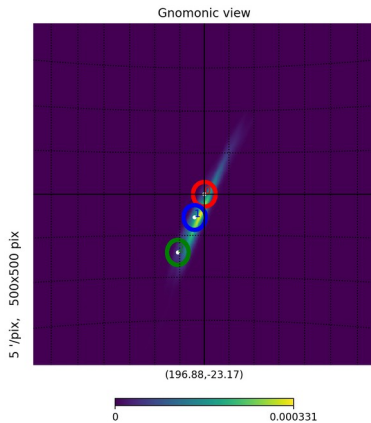
- Dark Matter
- Exotic Physics

H.E.S.S. Transients Follow-up systems

- Automatic response to selected transients (GRBs, GW, ...)
- Automatic decision on follow-up
- Optimization of pointing using **tilepy**
- Response time < 1 minute for most cases and < 2 minutes for all cases, including telescope slewing time



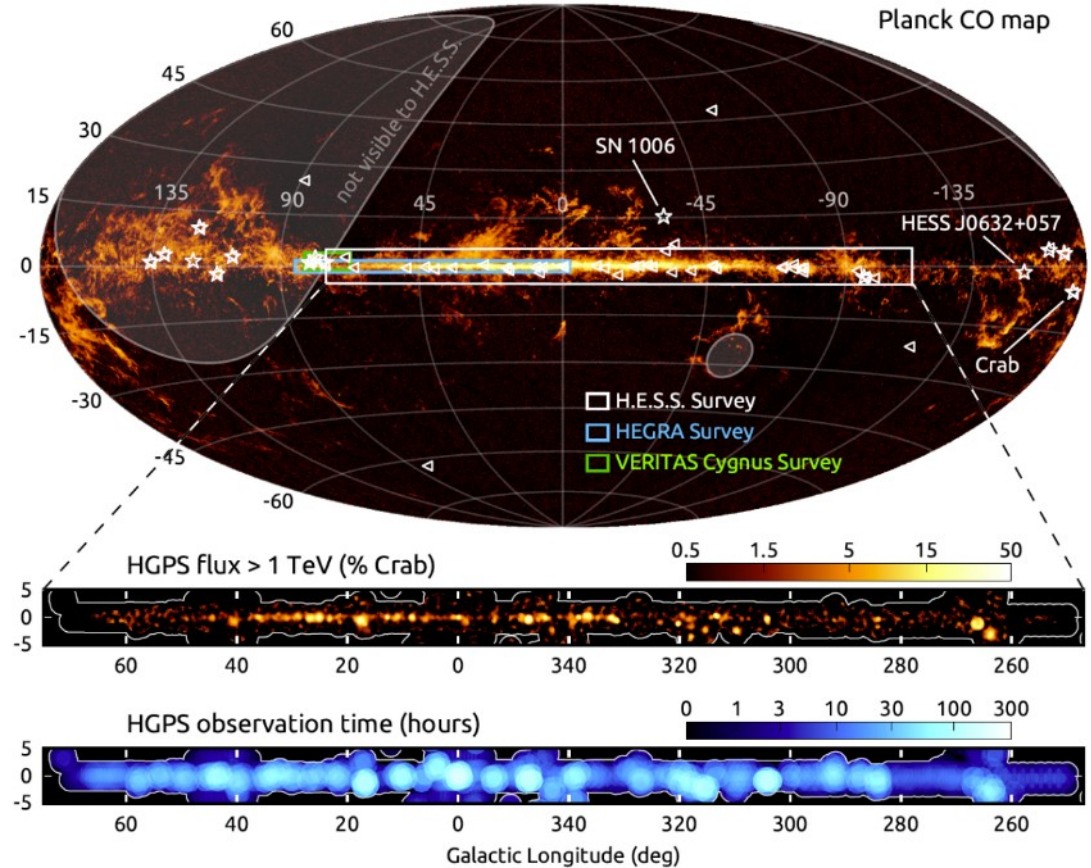
Journees d



Mathieu de Naurois

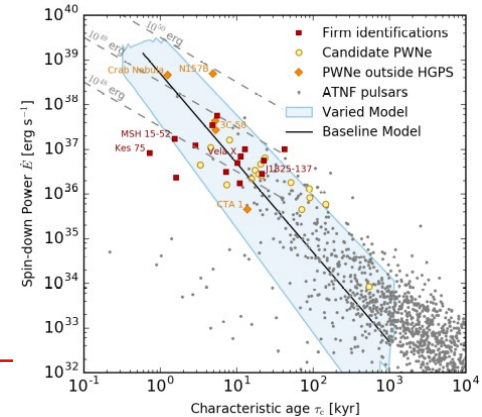
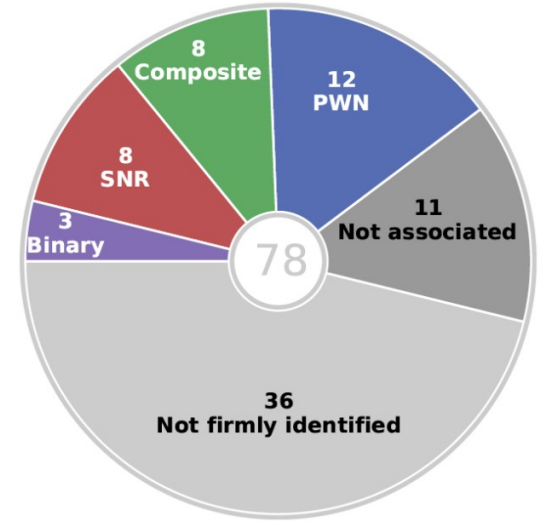
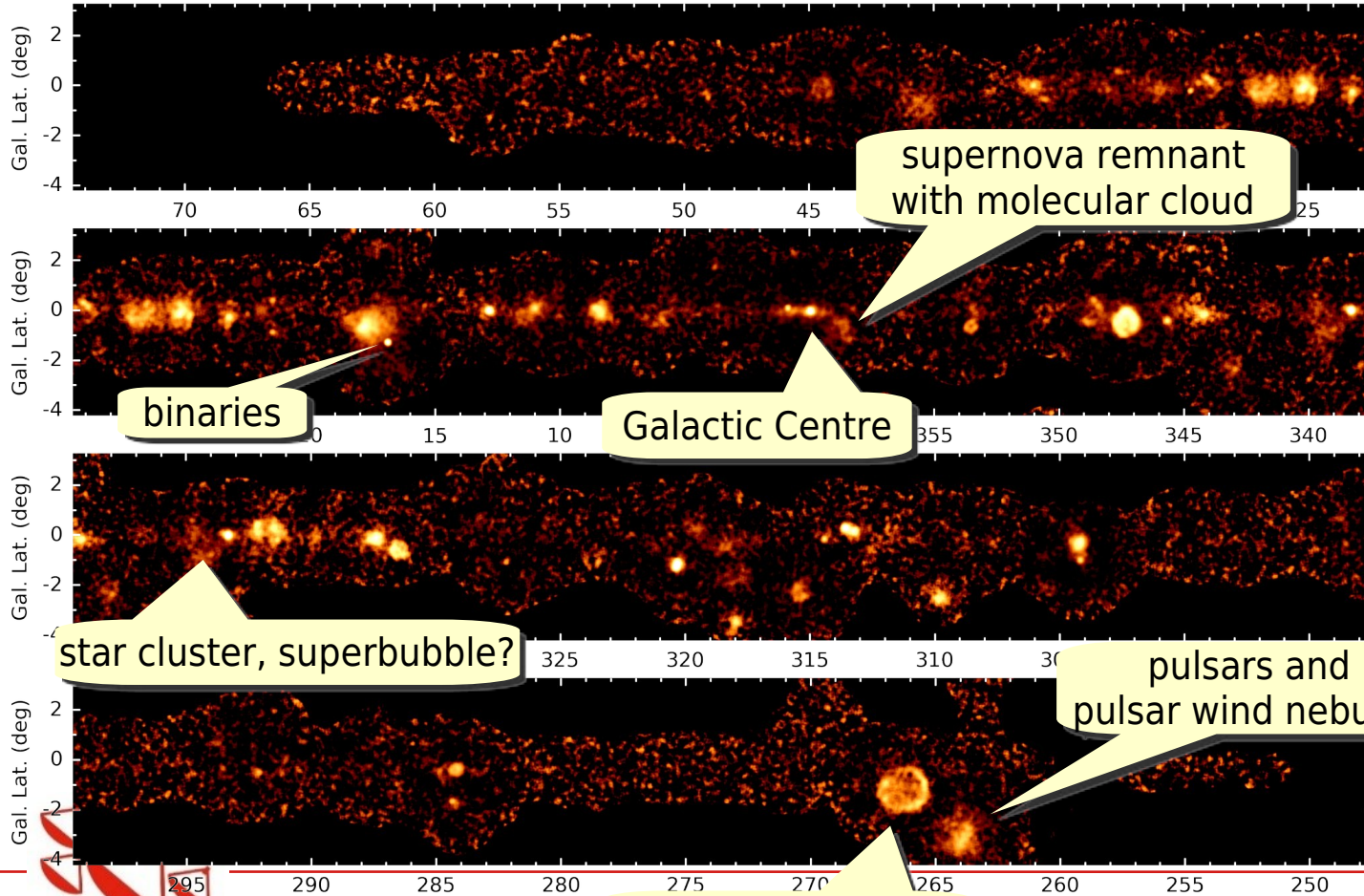
H.E.S.S. Legacy Survey

- Major H.E.S.S. project
- Data collected 2004 – 2013
 - 2673 h after quality selection
 - l in $[-110^\circ, 70^\circ]$
 - b in $[-5^\circ, 5^\circ]$
 - Inhomogeneous exposure (sources of particular interest)
- Largest VHE survey so far done by IACTs
- First population studies made possible



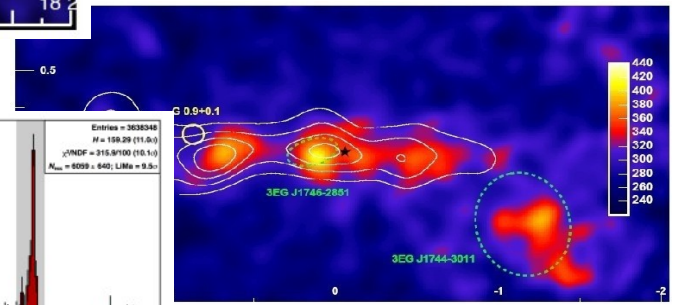
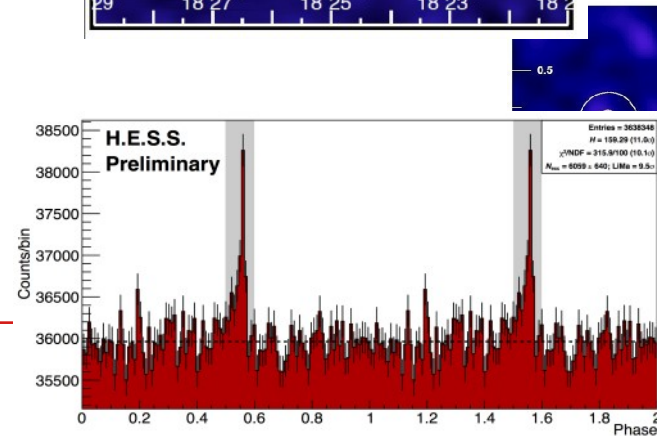
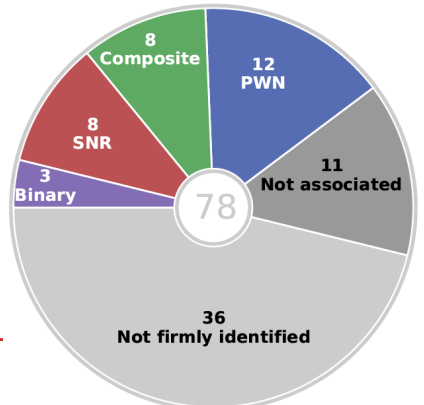
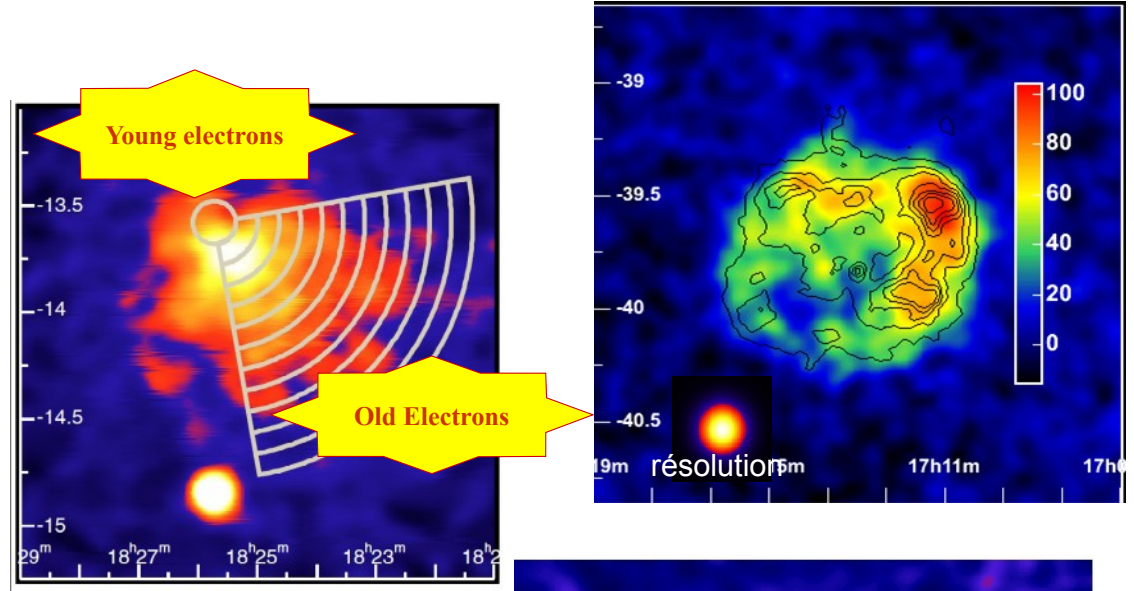
H.E.S.S. Collaboration - A&A 612 (2018)

H.E.S.S. Legacy Survey

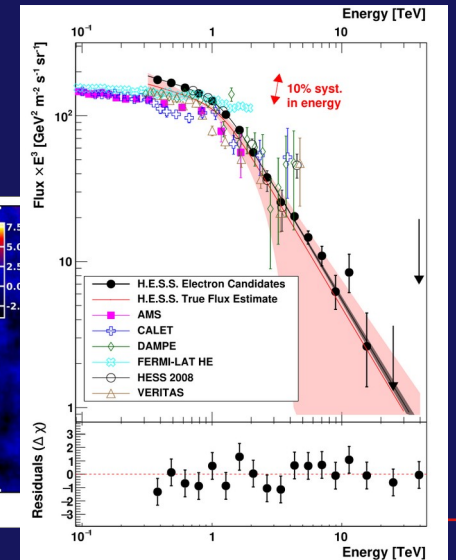
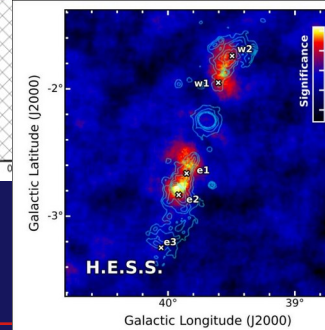
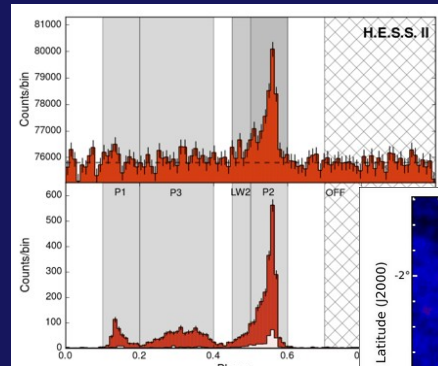


Galactic Bestiary in a nutshell

- A complete zoo :
 - Pulsar Wind Nebulae
 - Supernova Remnants
 - Galactic Centre
 - Interacting Binary Systems
 - Young, Energetic Pulsars
 - Diffuse Galactic Emission
 - ...



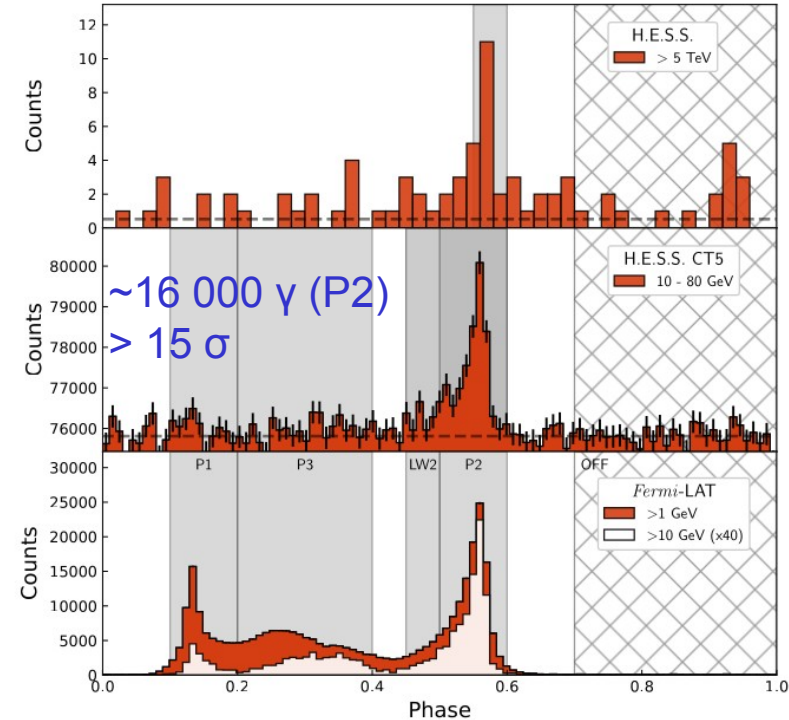
Selected recent highlight



Vela Pulsar – H.E.S.S. II

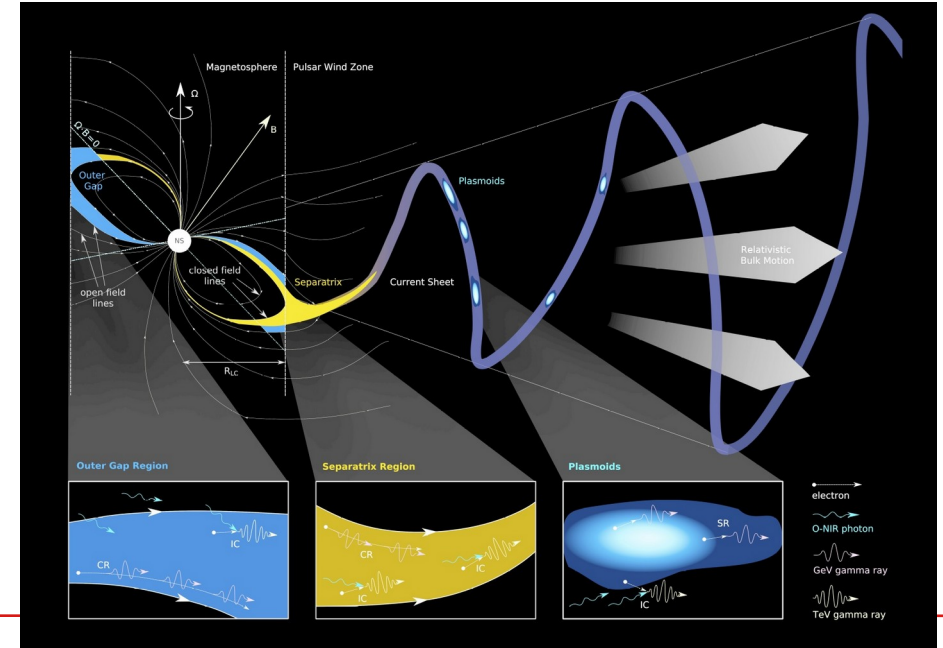
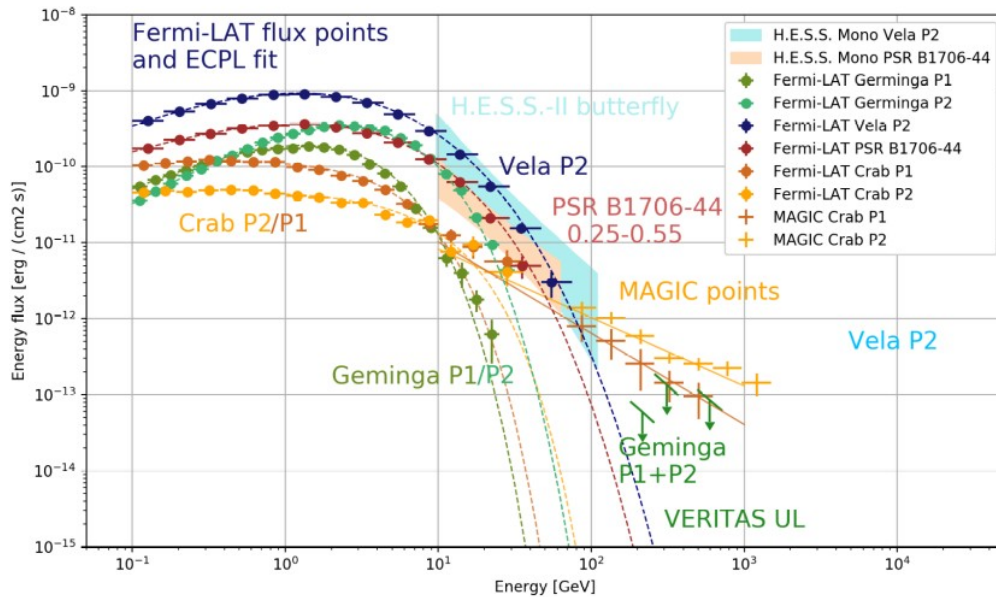
Nature Astronomy
October 5th 2023!

- 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 $> 3\sigma$ for both Fermi and HESS
 - Very hard VHE spectrum: distinct spectral component



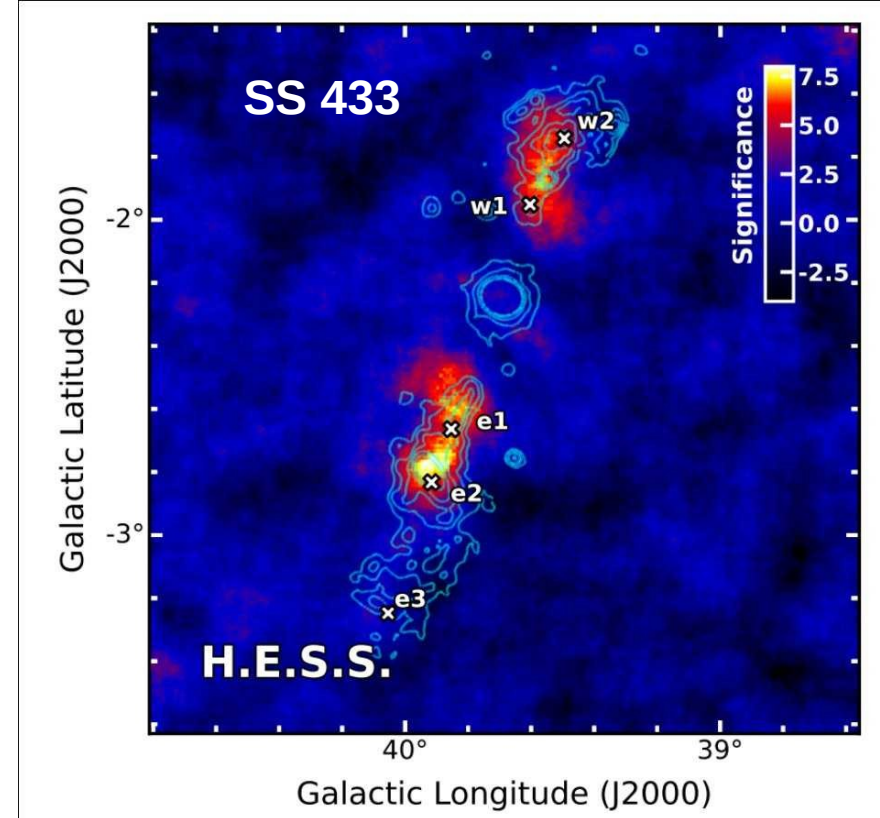
Pulsars from ground

- With PSR B1706-44, Geminga and PSR J1509-5850, 4 VHE pulsars
- Amongst brightest pulsars in Fermi 2PC catalogue
- Pulsar emerging as VHE accelerators
- Emission far from the light-cylinder (avoid sync. cooling)



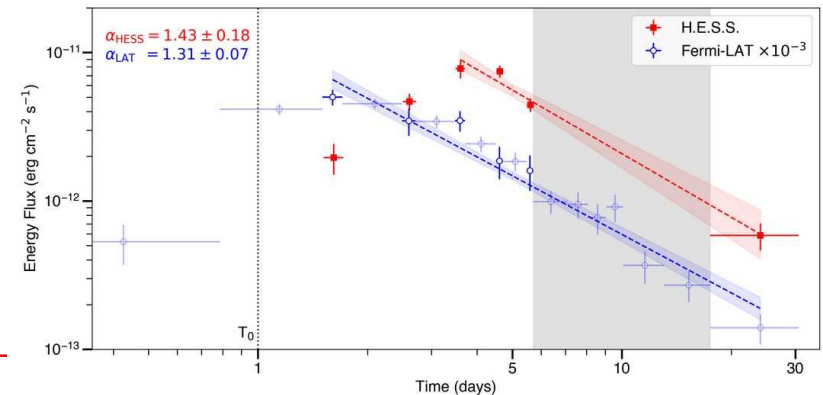
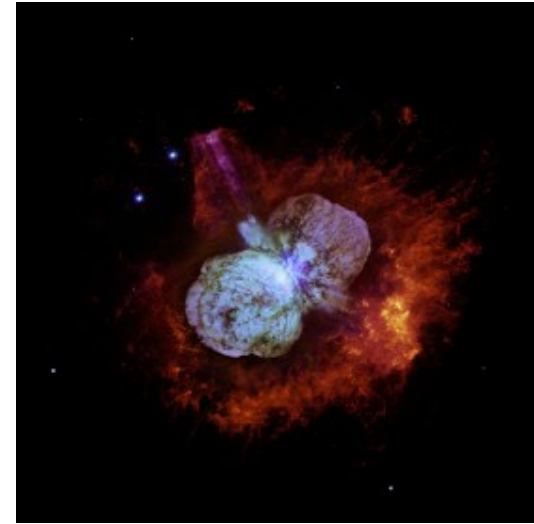
Microquasars

- HAWC detection of emission from both jets of SS 433 (2018)
- Deep H.E.S.S. observations (300 h)
 - Extended emission along jet direction (both sides), hadronic origin
 - Spectrum up to 40 TeV
 - Highest energies at e1/w1
 - Central BH not detected
 - Science 383, 402-406 (2024)
- V4641 Sgr recently detected (HAWC ≥ 200 TeV, H.E.S.S. paper in internal review)
- Microquasars emerging as possible Pevatrons (LHAASO)



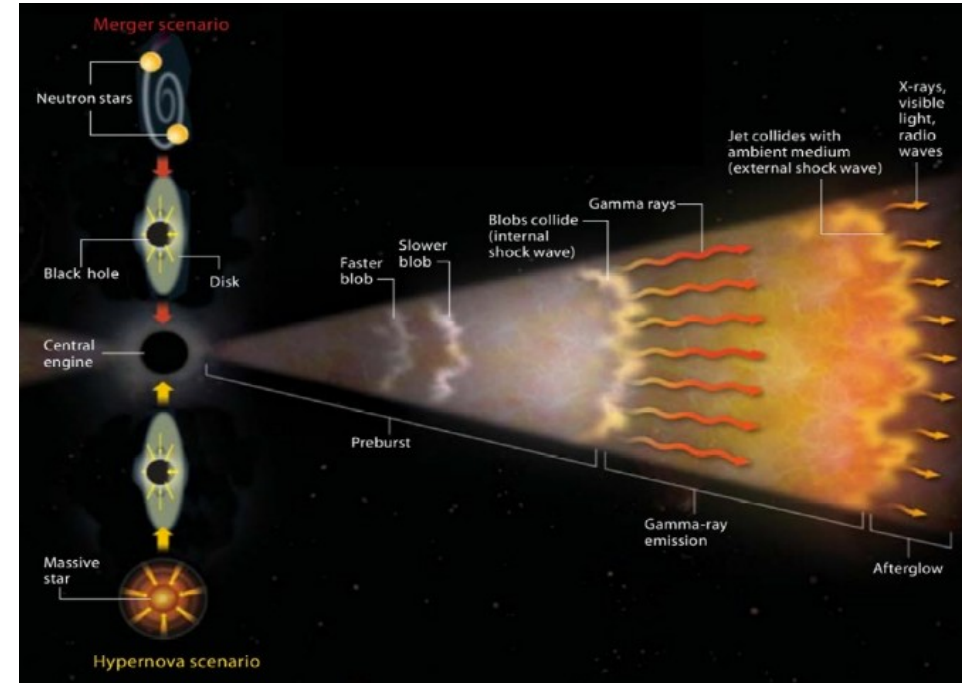
Other recent news from the Milky Way

- Recurrent Nova RS Ophiuchi
 - First Galactic transient observed in VHE (2021 flare)
 - VHE emission detected during 40 days
 - Hadronic emission scenario preferred
- Massive stellar clusters as new source class
 - Westerlund 1: Potential Pevatron (HESS, AA 666, 124, 2022)
 - New: R 136, 30 Dor C (LMC), HESS 2024



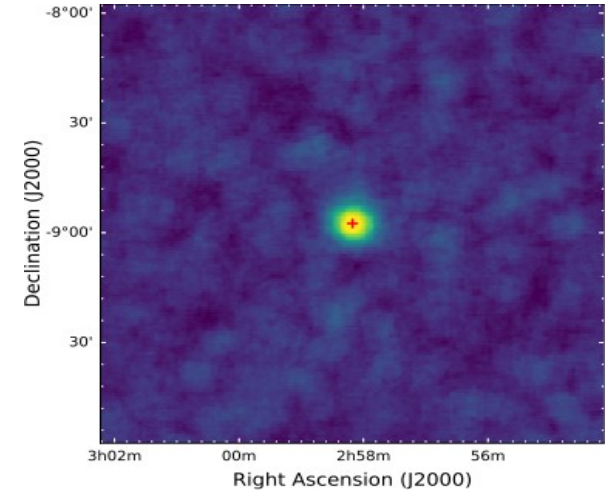
Gamma Ray Bursts

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

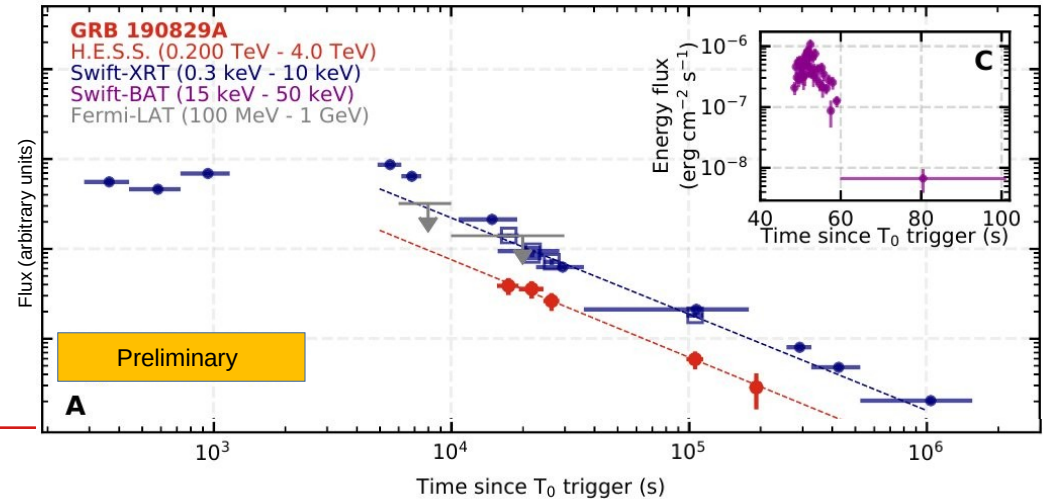
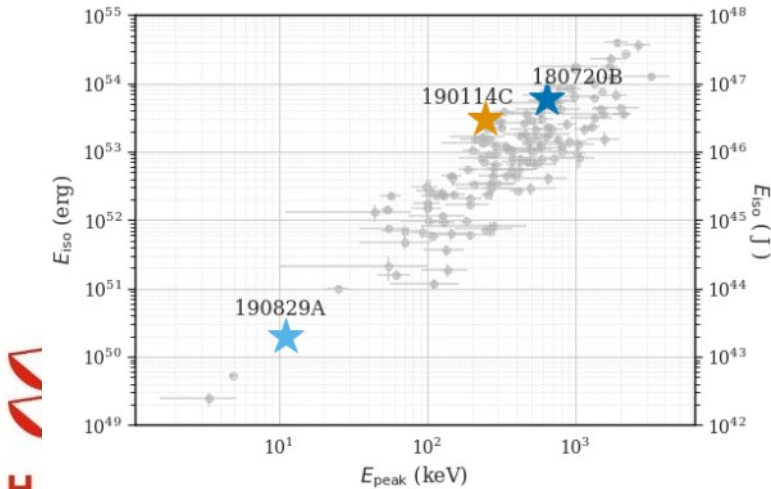


GRB 190829A

- Long GRB ($t_{\text{GBM90}} \sim 60$ s, $t_{\text{BAT90}} \sim 60$ s) @ $z = 0.078$
- Observation started at $t_0 + 4\text{h}20$ (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

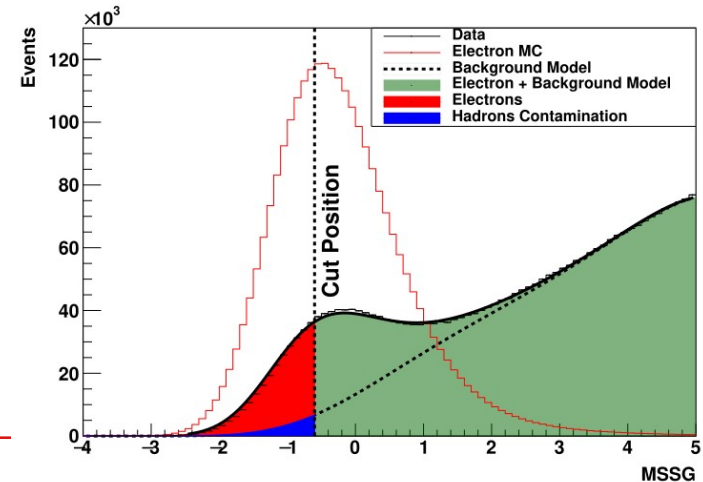
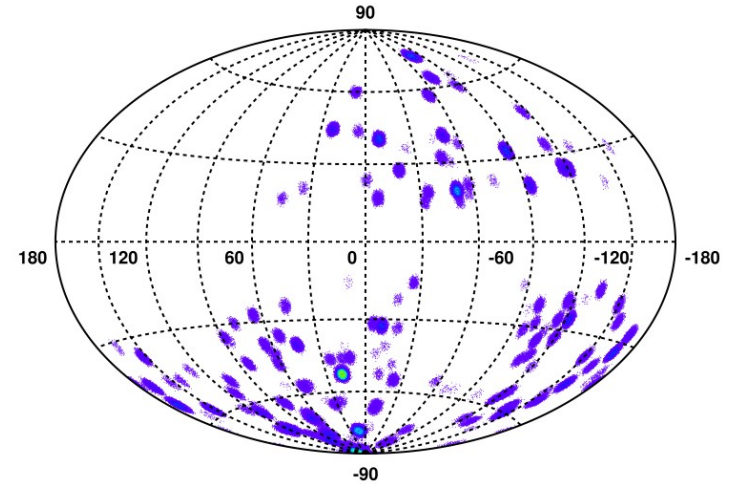


H.E.S.S. Collaboration - Science 372 (2021)



Beyond γ -rays: Cosmic Electron Spectrum

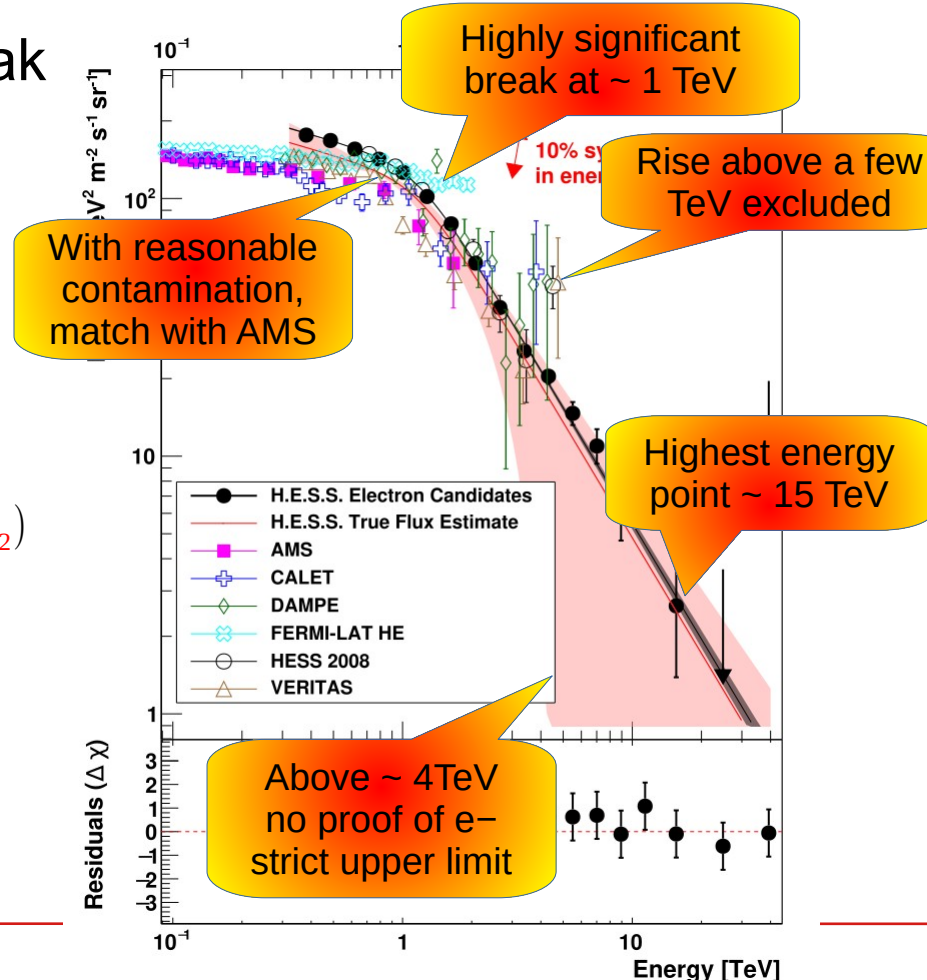
- Huge data set (> 3000 hr) excl. Gal. Plane ($|l| > 15^\circ$)
- Specific analysis with hard cuts (limit hadronic contamination)
- Novel analysis technique & IRFs production (“Runwise simulations”)



Beyond γ -rays: Cosmic Electron Spectrum

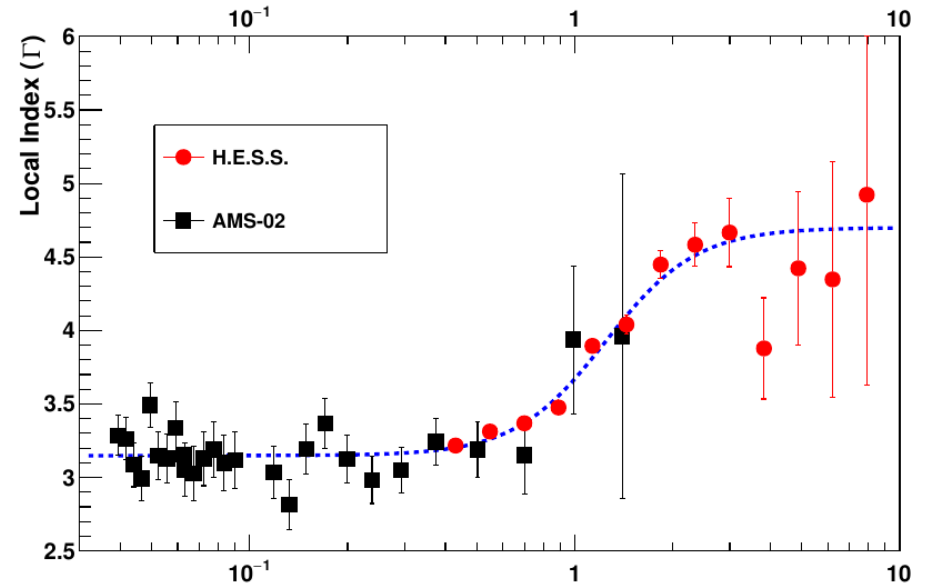
- Highly significant ($> 100 \sigma$) spectral break
- Best fit parameters:
 - $\Gamma_1 = 3.25 \pm 0.02_{\text{stat}} \pm 0.2_{\text{syst}}$
 - $\Gamma_2 = 4.49 \pm 0.04_{\text{stat}} \pm 0.2_{\text{syst}}$
 - $E_{\text{break}} = (1.17 \pm 0.04_{\text{stat}} \pm 0.1_{\text{syst}}) \text{ TeV}$
 - Sharpness $s = 0.21 \pm 0.02_{\text{stat}}$

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



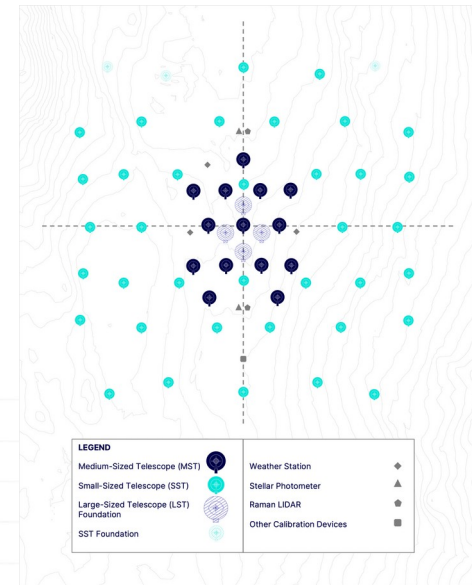
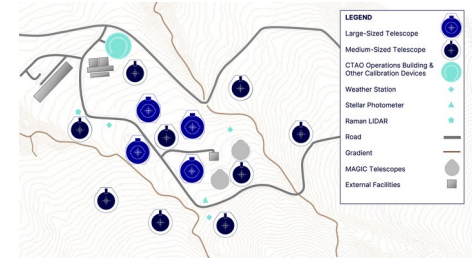
Beyond γ -rays: Cosmic Electron Spectrum

- Contribution of a handful (sharp break), nearby sources (cooling time)
- Steep spectrum very challenging for space instruments
- Published in PRL 2025

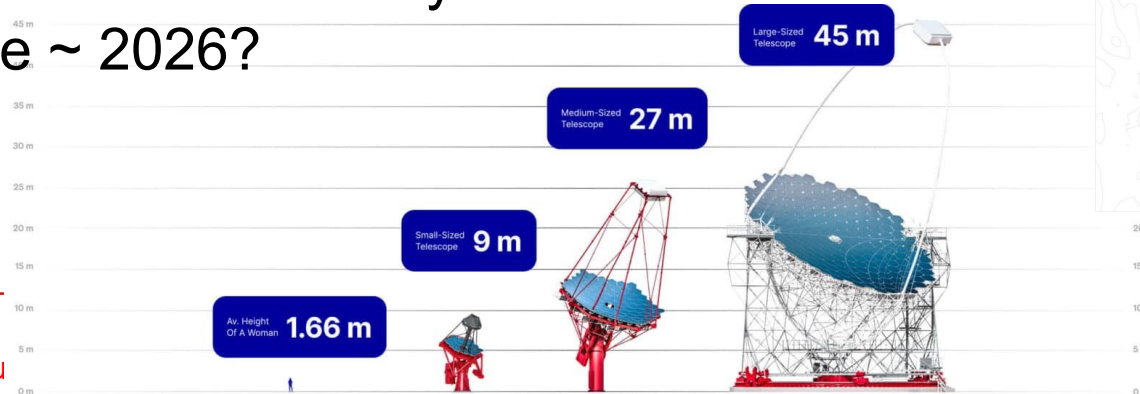


CTAO

- Next generation IACTs
- 2 sites, 3 sizes of telescopes (LST, MST, SST)
 - Canary Island: 0.5 km², 4 LST (in construction), 9 MST focus on extragalactic science
 - Chile, 3 km², 14 MST, 37 SST (+ 4 LST?) focus on pevatrons & galactic science
- ERIC signed January 7th, 2025
- Transfer agreement signed September 30th
- ERIC inauguration ceremony October 6th
- First science ~ 2026?



Jou



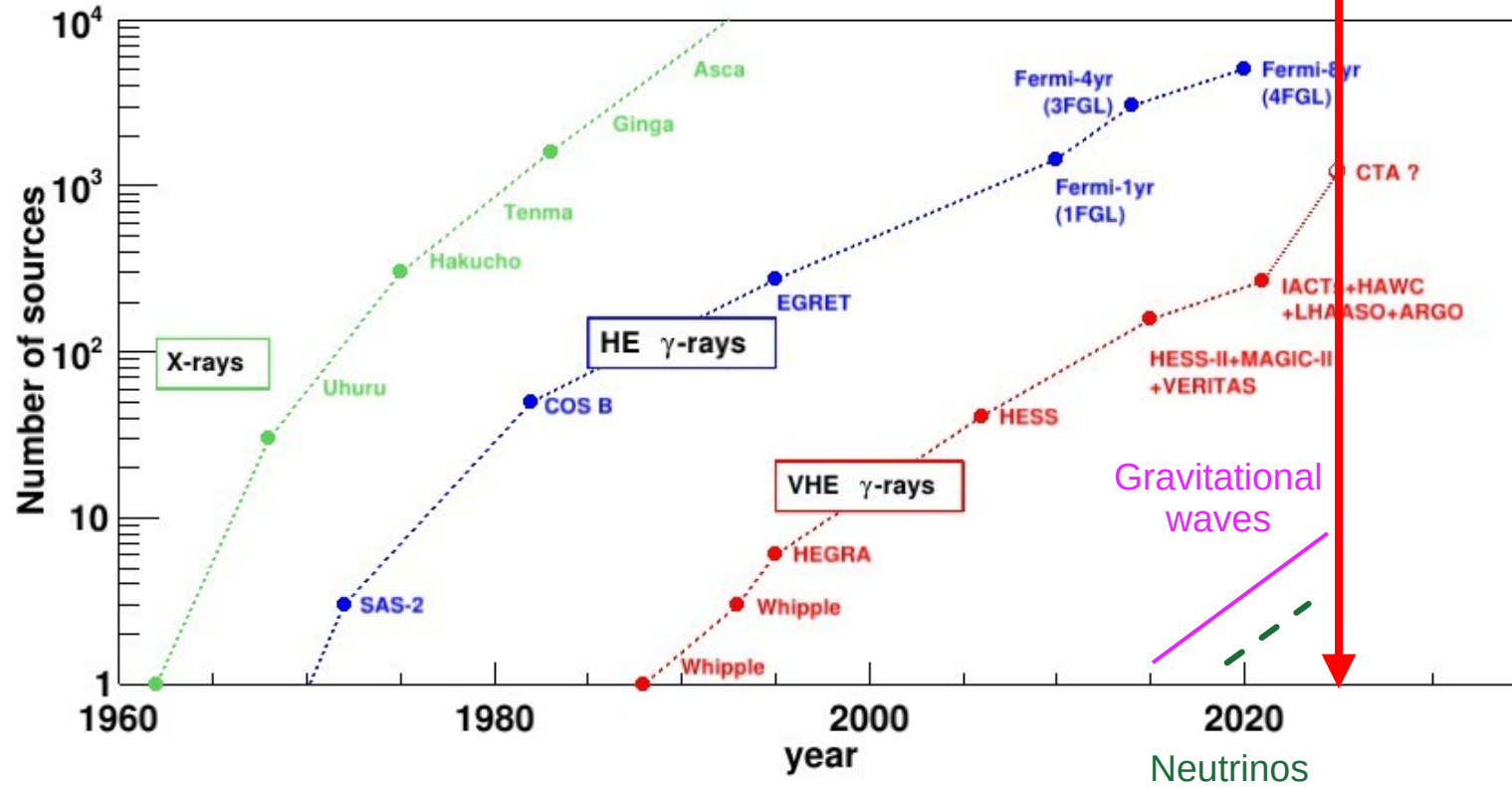
Mathieu de Naurois

22

Outlook

- After 2020 years, still many important results
- Recent studies use very extended data sets (600h+), obtained over many years with changing camera/telescope combinations
- A lot of technical work to go beyond classical analyses and to reduce systematics
 - Looking for (very) extended features, beyond the FoV of the instrument
 - More reliable RunWise simulations (simulate every run)
 - Open source tools, 3D Analysis, using gammapy as high-level tool
 - Paving the road for CTAO
- Many subjects not covered in this talk (Binaries, SNRs, LIV, Dark Matter, AGNs, ...)
- H.E.S.S. will operate until 2028, CTA ramping up

Conclusions



Number of sources vs time [T. Kifune]

Size of Crab PWN

- Energy dependent morphology of Crab, A&A 686, A308 (2024)
- Self-consistent analysis over 5 orders of magnitude.
- Size shrinks with E.
- Strength of B field decreases outwards.

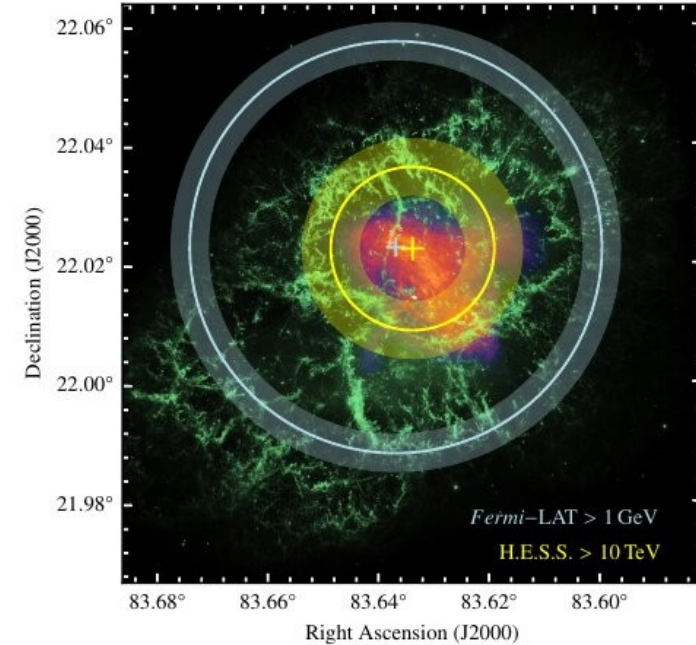
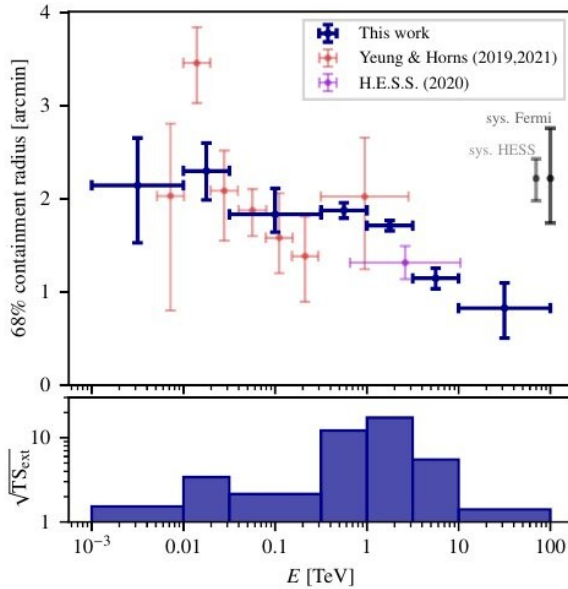
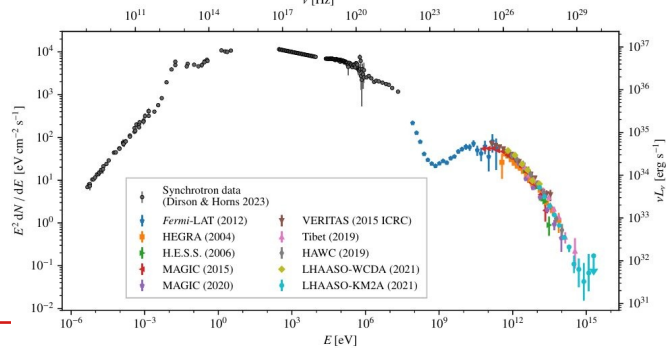


Fig. 7. Optical image of the Crab Nebula in green (credit: NAS).

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

