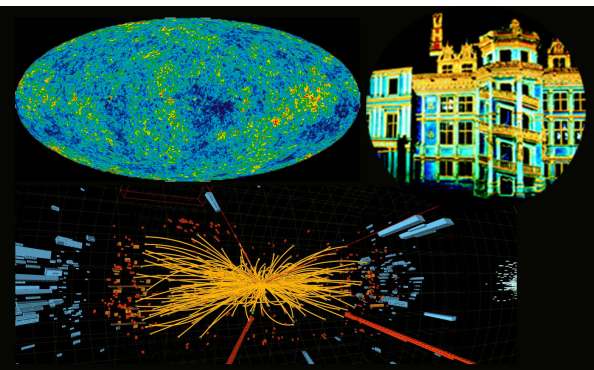




# *Multimessenger astroparticles/ HESS*

34<sup>th</sup> Rencontres de Blois : Particle Physics and Cosmology  
May 14-19, 2023, Blois, France

*Emmanuel Moulin for the H.E.S.S. collaboration  
CEA Saclay, Irfu, Université Paris-Saclay, France*



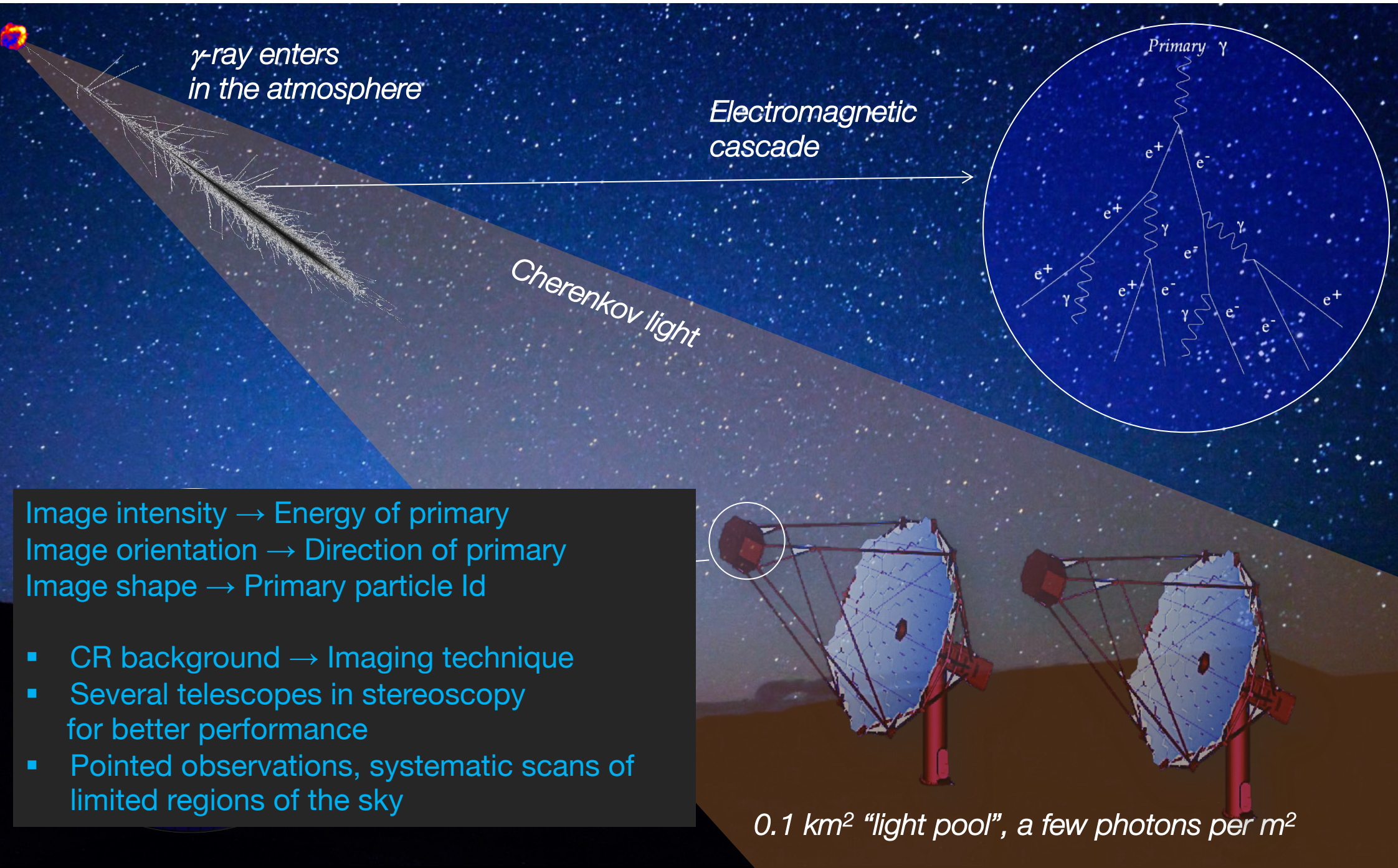
# The H.E.S.S. observatory

- Array of 5 Imaging Atmospheric Cherenkov telescopes
- Located in the Khomas Highlands of Namibia at 1800m
- In operation since 2002

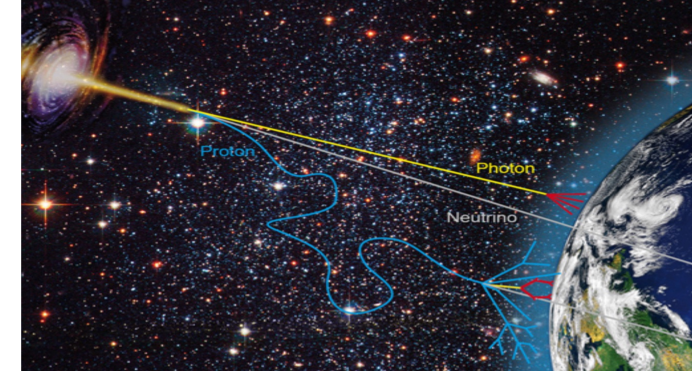




# Imaging Atmospheric Cherenkov technique



# Very-high-energy gamma rays: a few 10 GeV to a few 100 TeV



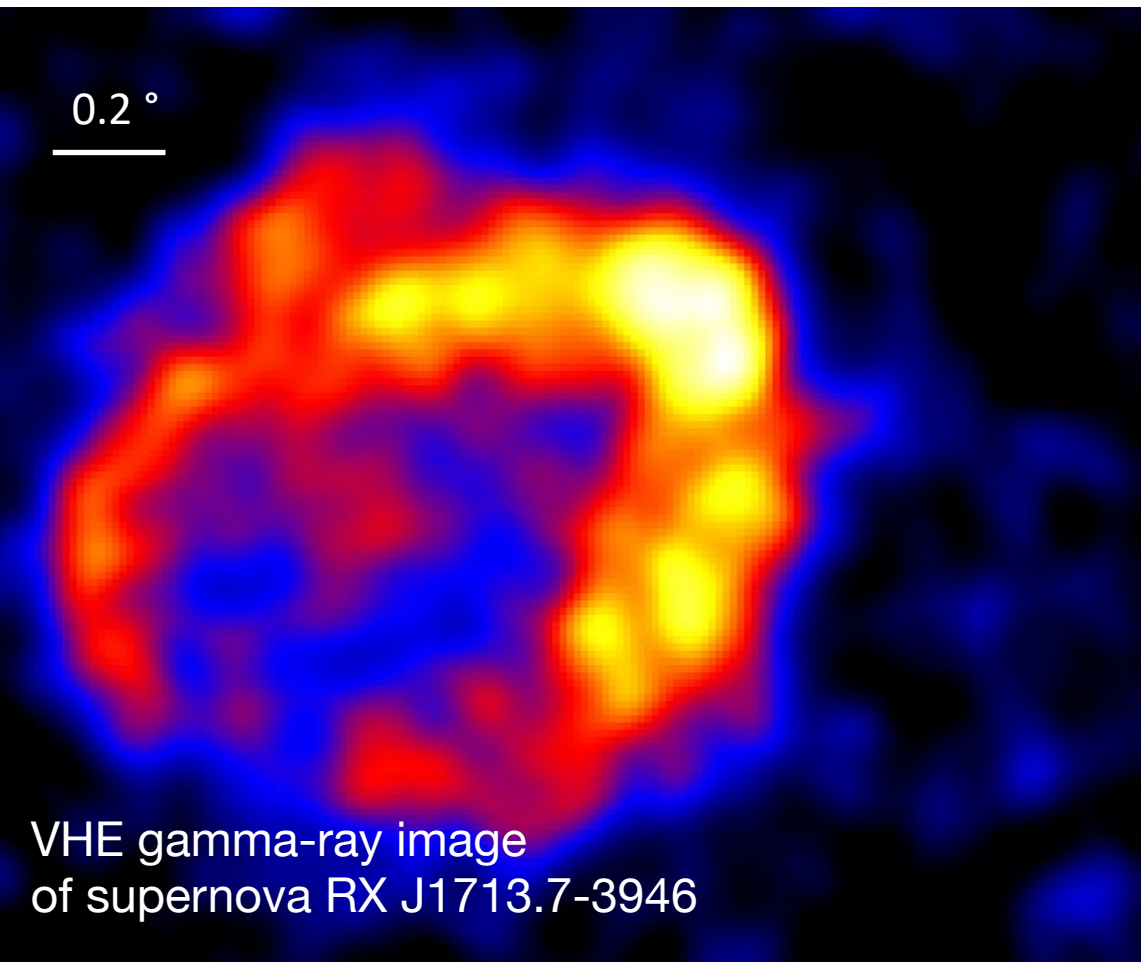
Radio waves

Infrared

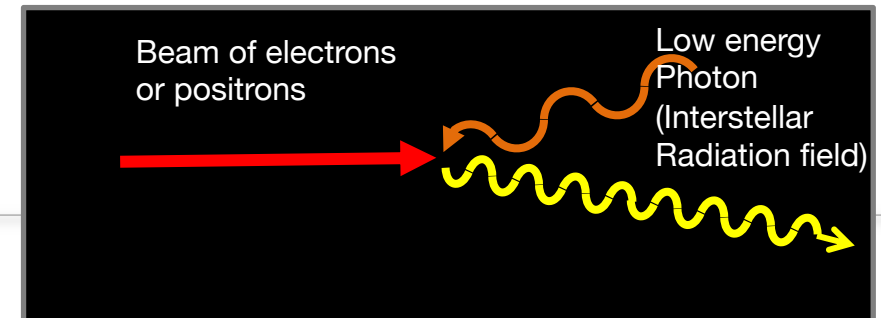
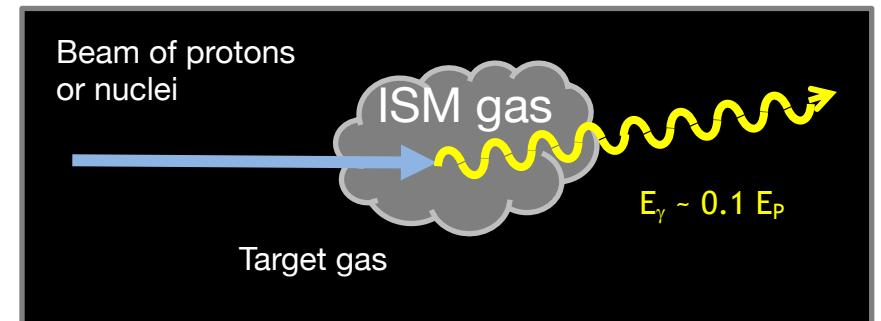
Vis UV

X-Rays

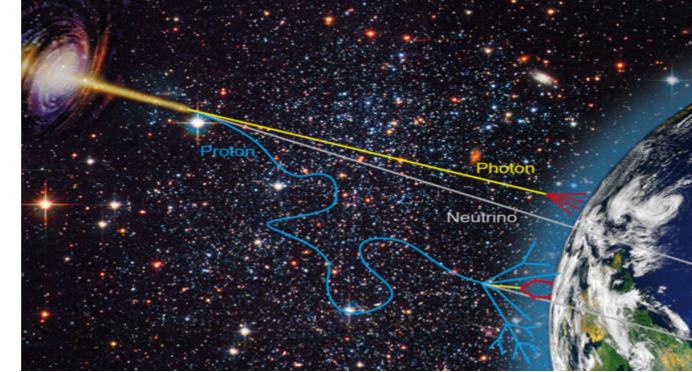
**Gamma Rays**



- are produced by non-thermal mechanisms
- trace high energy particles
- locate cosmic particle accelerators



# Very-high-energy gamma rays: a few 10 GeV to a few 100 TeV



Radio waves

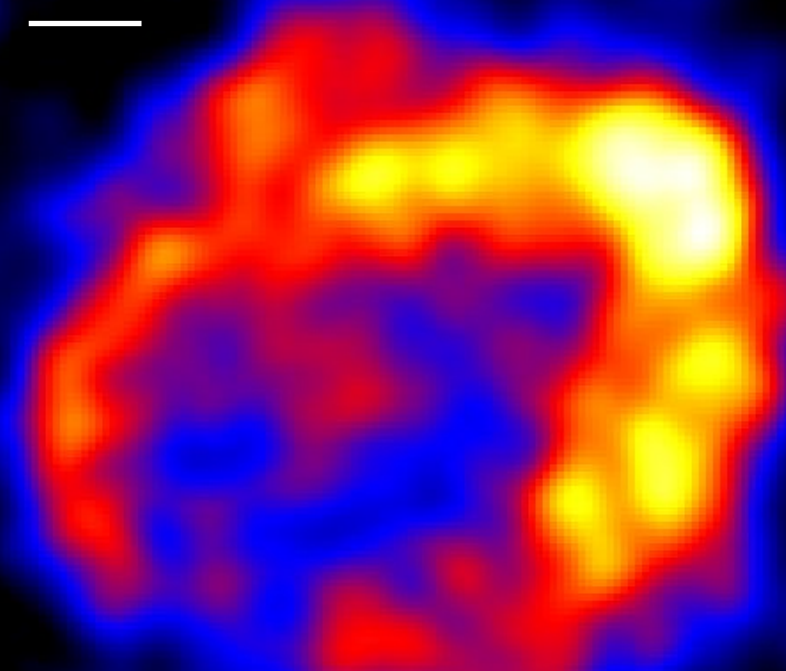
Infrared

Vis UV

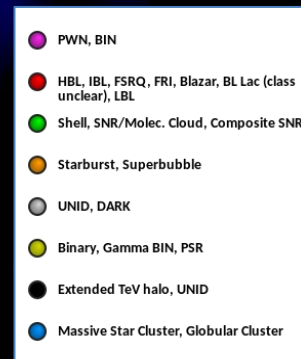
X-Rays

**Gamma Rays**

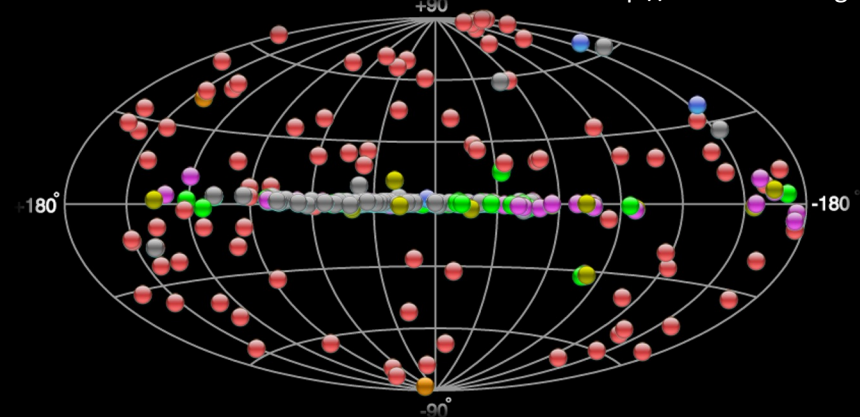
0.2°



VHE gamma-ray image  
of supernova RX J1713.7-3946



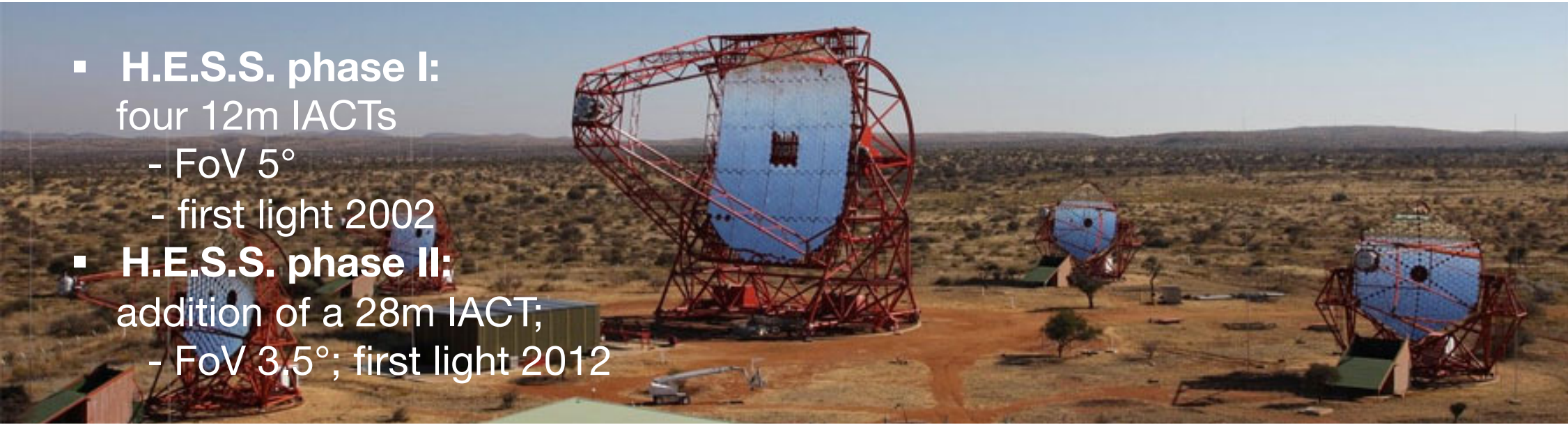
<http://tevcat2.uchicago.edu/>



- TeV particle acceleration everywhere in the cosmos
- > 200 detected sources
- Sky maps with 5' resolution
- 3 orders of magnitude in gamma ray flux
- Energy spectra over 3 decades in energy
- Light curves on all scales from minutes to years

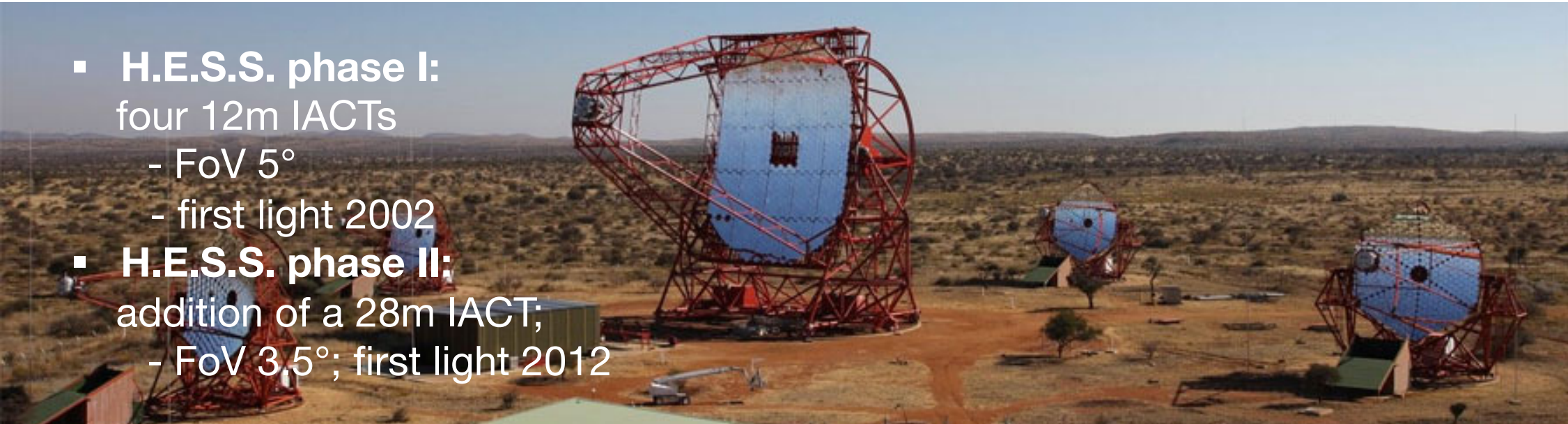
# The H.E.S.S. observatory

- **H.E.S.S. phase I:**  
four 12m IACTs
  - FoV  $5^\circ$
  - first light 2002
- **H.E.S.S. phase II:**  
addition of a 28m IACT;
  - FoV  $3,5^\circ$ ; first light 2012



# The H.E.S.S. observatory

- **H.E.S.S. phase I:**  
four 12m IACTs
  - FoV 5°
  - first light 2002
- **H.E.S.S. phase II:**  
addition of a 28m IACT;
  - FoV 3,5°; first light 2012



- **COVID restrictions starting Feb 2020:**
  - Observers not allowed to leave Namibia in March 2020.
    - Operations with local observers/telescope operators.
    - H.E.S.S. continued to take data throughout the entire pandemic
- **Full integration of moonlight/twilight observations**  
as of January 2021
  - ~1500h incl. conservative moonlight/twilight





# The H.E.S.S. observatory

- **H.E.S.S. phase I:**  
four 12m IACTs
  - FoV  $5^\circ$
  - first light 2002
- **H.E.S.S. phase II:**  
addition of a 28m IACT;
  - FoV  $3,5^\circ$ ; first light 2012

- **Camera upgrade** in 2015-2016 (H.E.S.S. I) and in 2020-2021 (H.E.S.S. II)
  - Nectar-chip based HESS1U cameras and FlashCam-prototype
  - Changes to operational procedures and monitoring
- All telescopes, cameras, subsystems show high operational efficiency.
- Average losses due to technical failures  $<2\%$ /telescope and  $<5\%$  full array
- Low weather losses  $\rightarrow >1200\text{h}$  darktime data

**H.E.S.S. collaboration:** ~250 members, at 38 institutes  
sin 13 countries



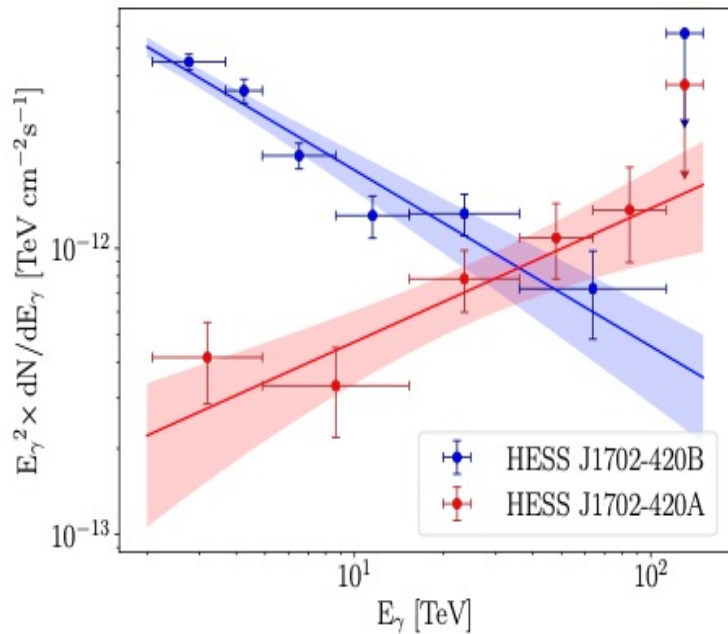
Emmanuel Moulin



# The H.E.S.S. instrument

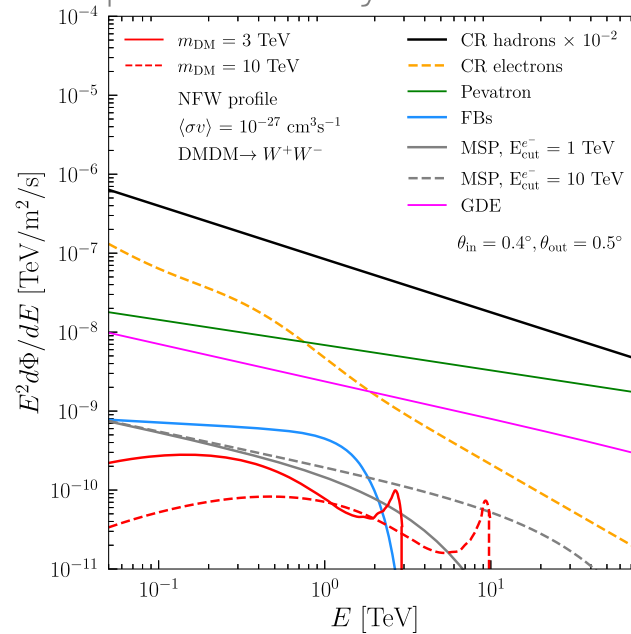
## Overall performances

Energy range  
up to 100 TeV



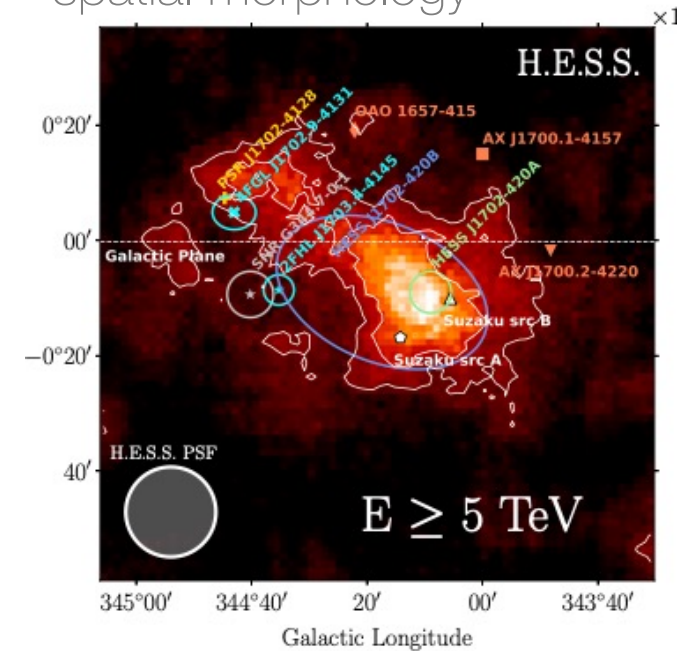
Energy resolution

~10% (68% cont.)  
spectral analysis



Angular resolution

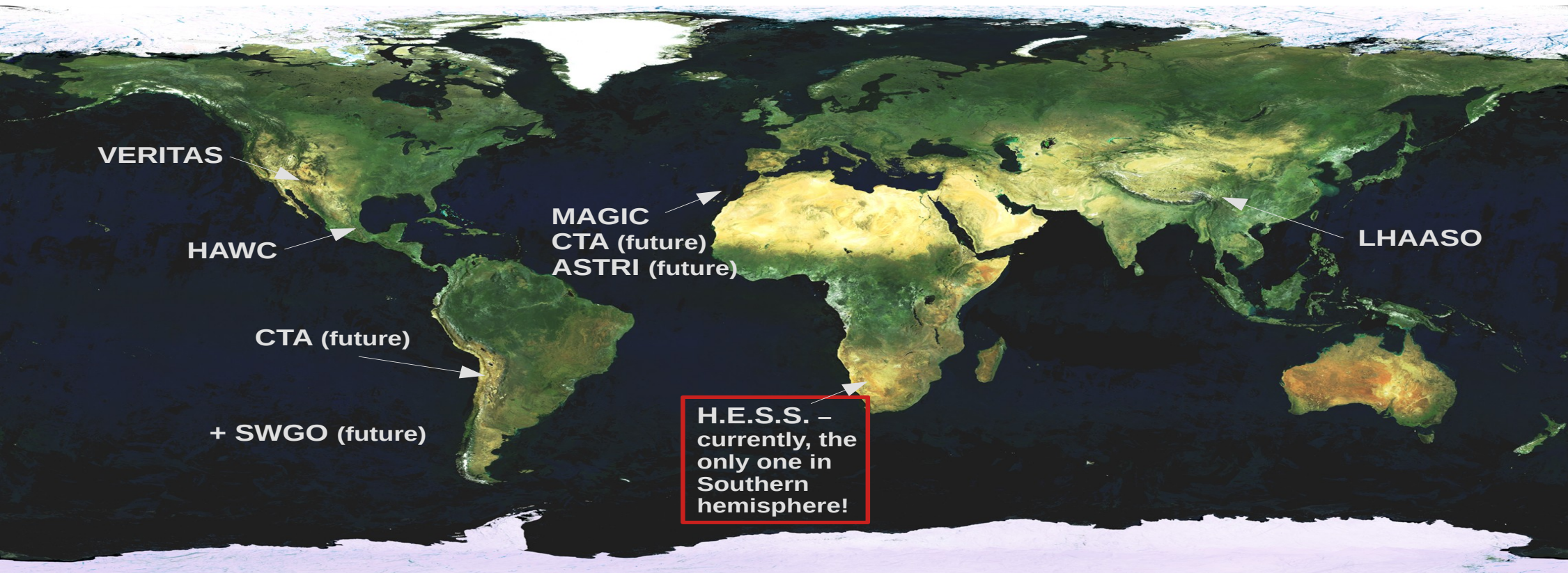
~0.06° (68% cont.)  
spatial morphology



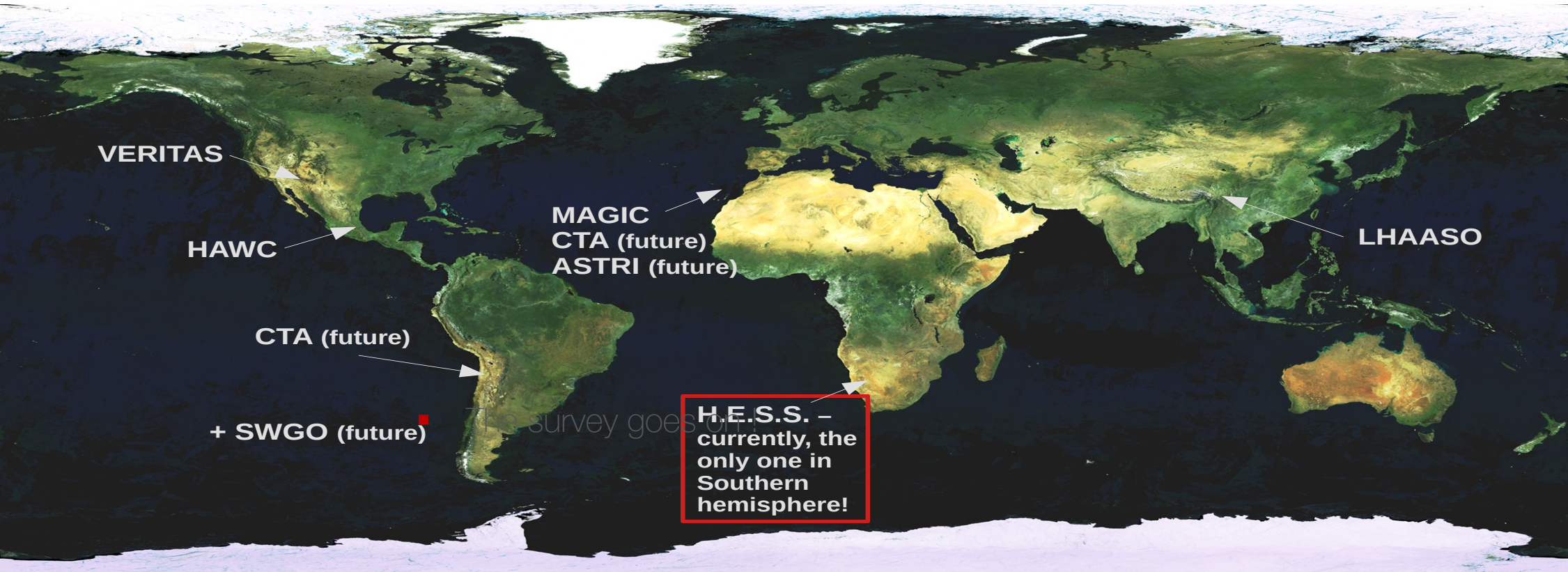
- 5° FoV with CT1-4: currently the widest in IACTs
- Angular resolution is crucial for morphological studies: less source confusion, easier source association



# VHE gamma-ray instruments



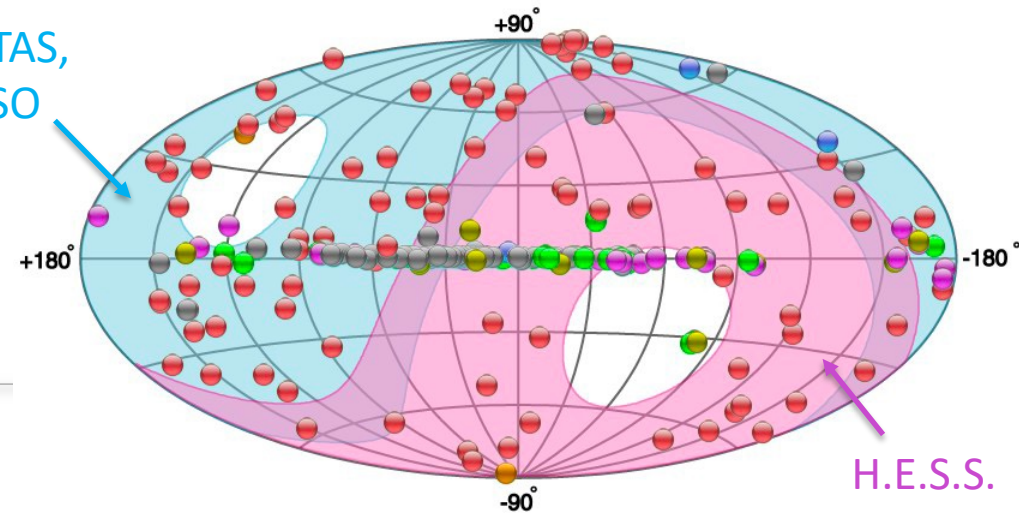
# VHE gamma-ray instruments



- **H.E.S.S. offers a unique visibility of the central part of the Galactic plane and the Galactic Center**

MAGIC, VERITAS,  
HAWC, LHAASO

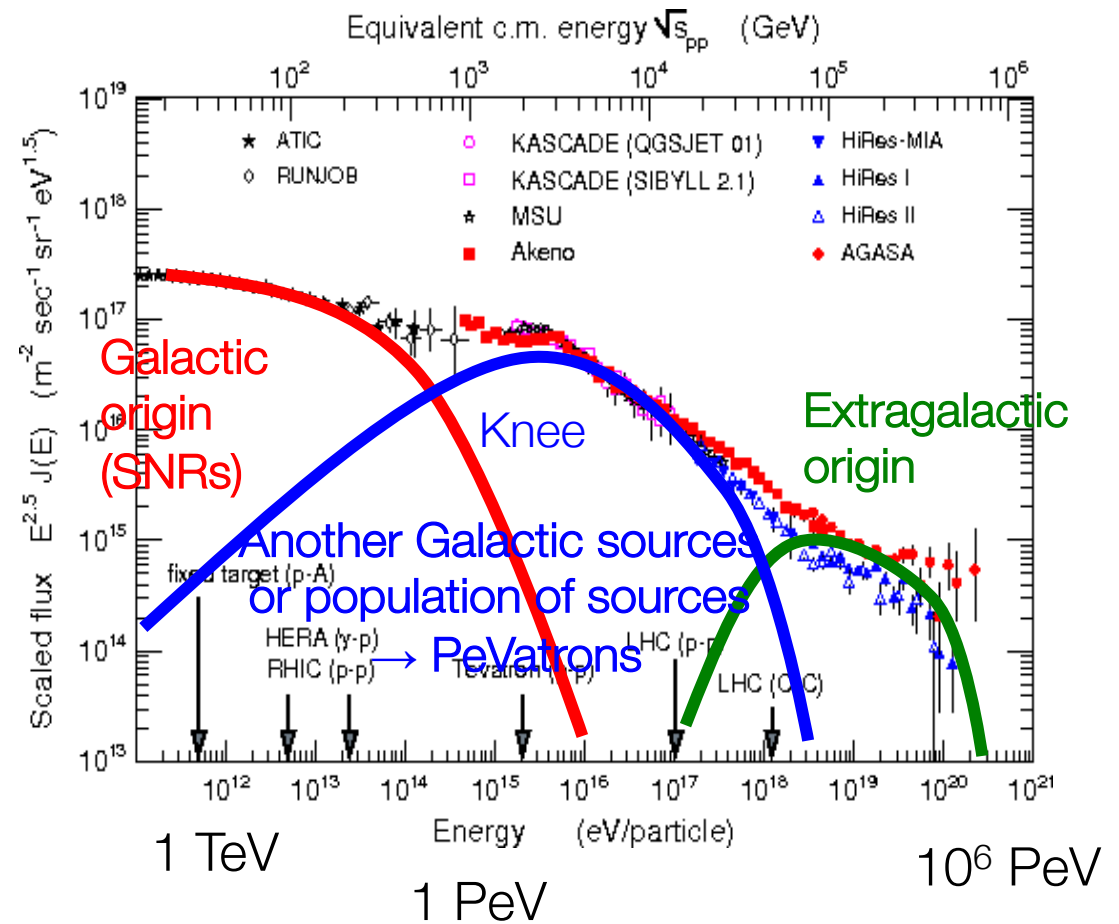
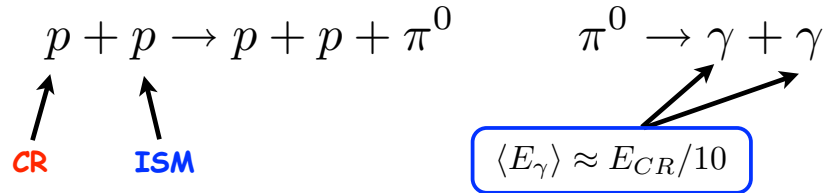
Visibility from North and South Hemisphere



H.E.S.S.

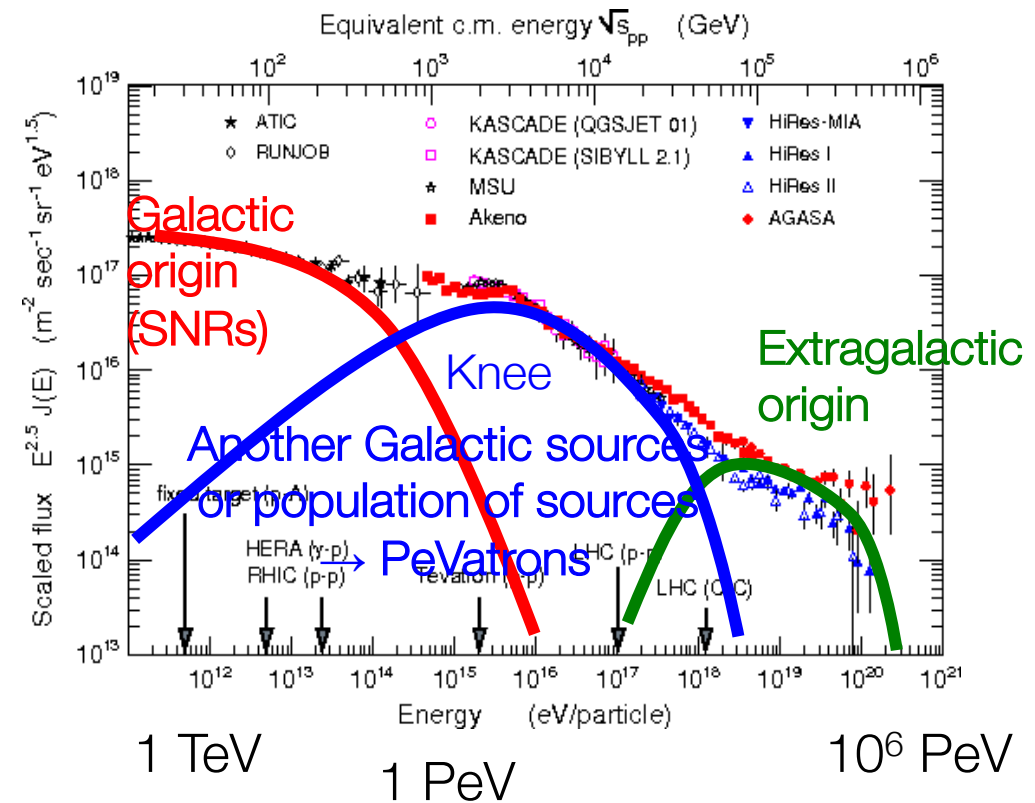
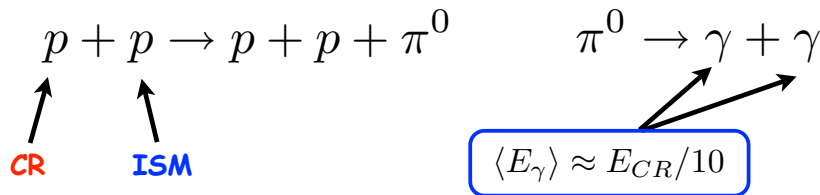
# Galactic Pevatrons and candidates

Inferred from hard gamma-ray spectra above  $\sim 50$  TeV  
 $E_\gamma \sim E_p/10$



# Galactic Pevatrons and candidates

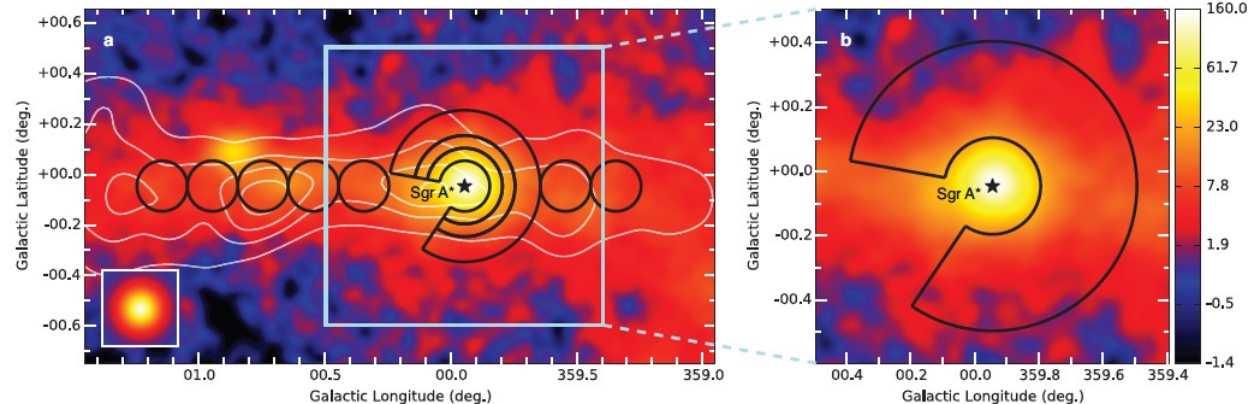
Inferred from hard gamma-ray spectra above ~50 TeV



## Galactic centre region

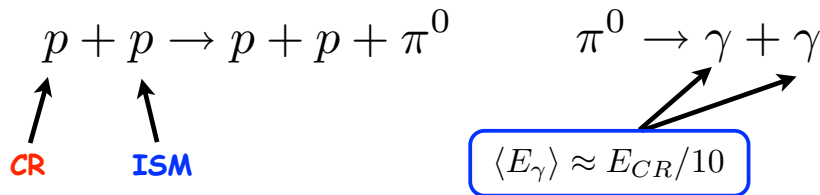
- Diffuse emission
- Proton mostly responsible for the emission
- First Galactic Pevatron detected
- Central BH Sagittarius A\* most likely the accelerator

*H.E.S.S. coll., Nature 531, 476 (2016)*



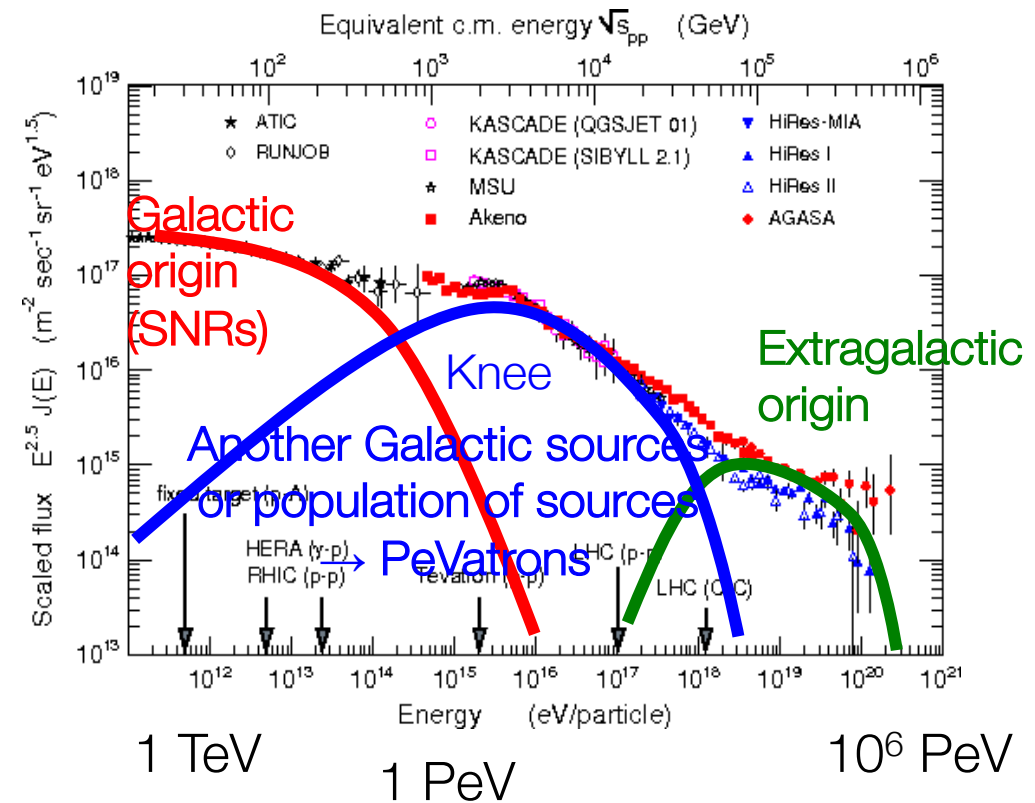
# Galactic Pevatrons and candidates

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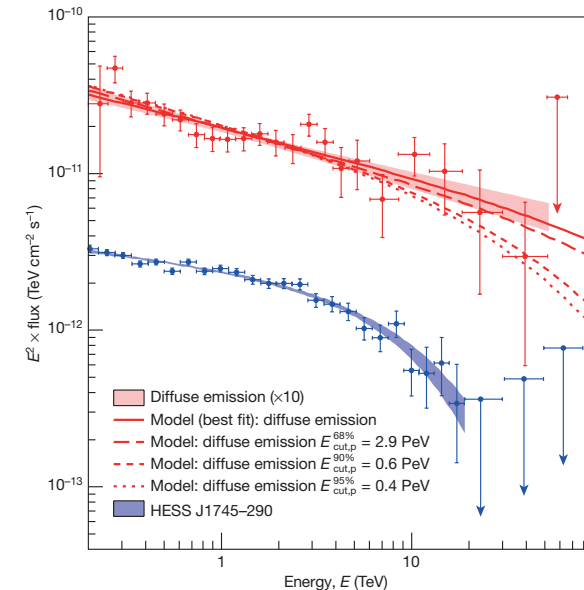
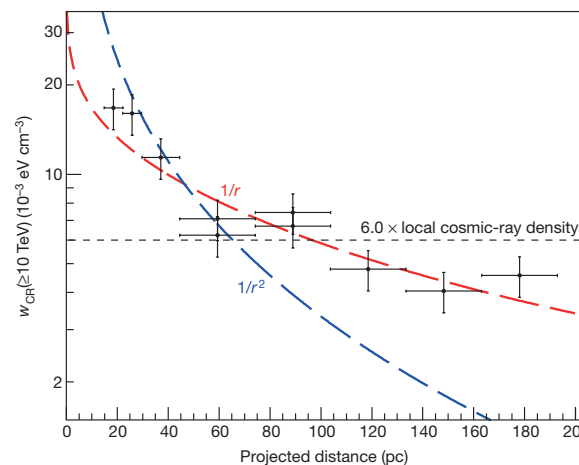


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*H.E.S.S. coll., Nature 531, 476 (2016)*

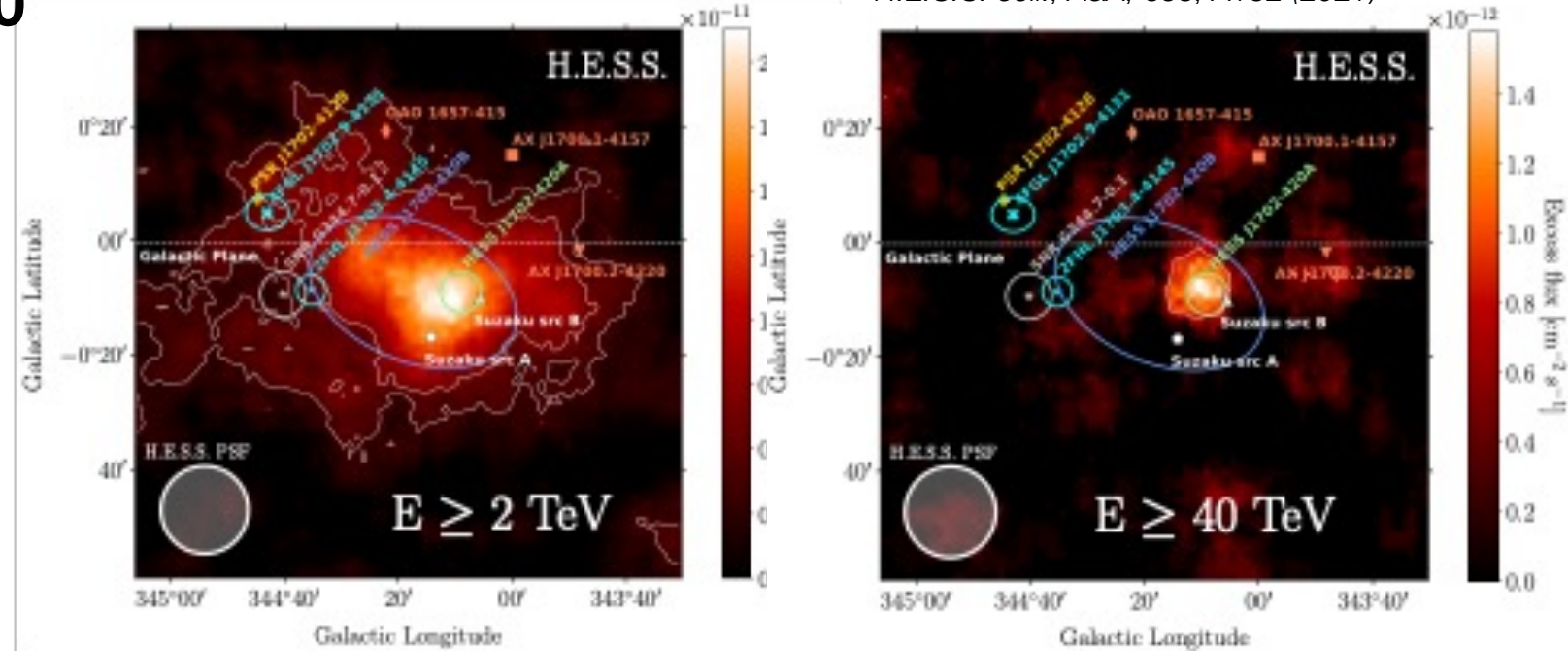


# Galactic science: Pevatrons and candidates

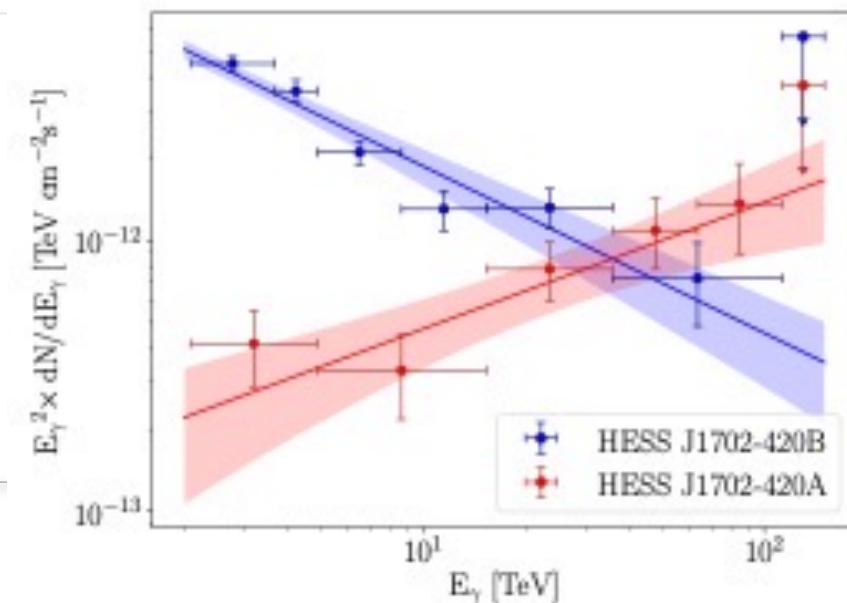
## ■ HESSJ1702-420

Gamma rays up to 100 TeV from the component HESS J1702-420A

*H.E.S.S. coll., A&A, 653, A152 (2021)*



- No obvious counterpart
- Hadronic scenario: cut-off energy of the protons is higher than 0.5 PeV (95% CL)
- A leptonic origin of the observed TeV emission cannot be ruled out either

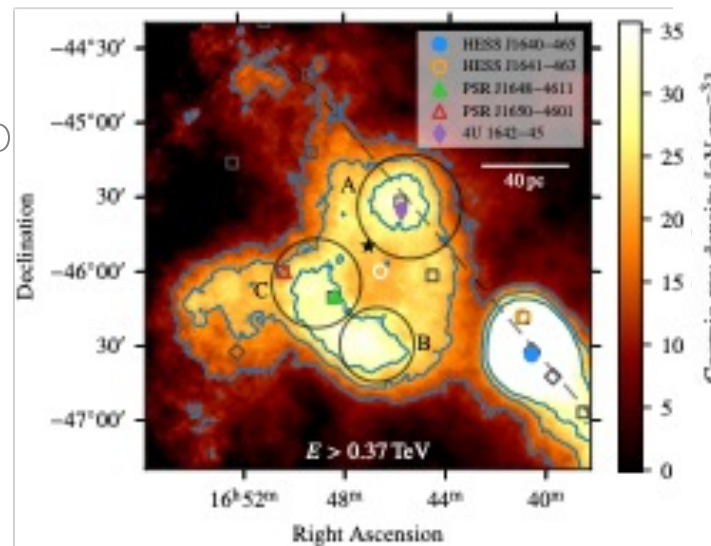




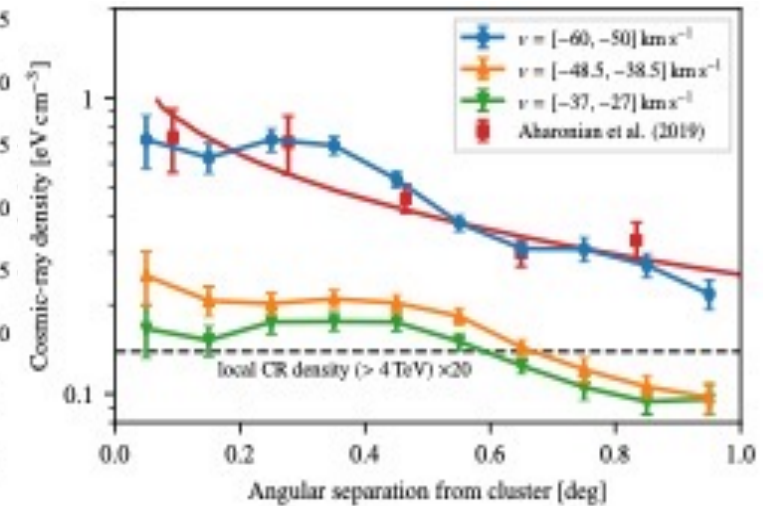
# Galactic science: Pevatrons and candidates

## ■ Westerlund1 stellar cluster

- TeV emission:  $2^\circ$
- TeV spectrum  $>50$  TeV
- Deeper observations reveal no spectral change with location.
- Shell-like structure centred on cluster. TeV+ISM comparison compatible with continuous CR injector.



H.E.S.S. coll., A&A, 666, A124 (2022)

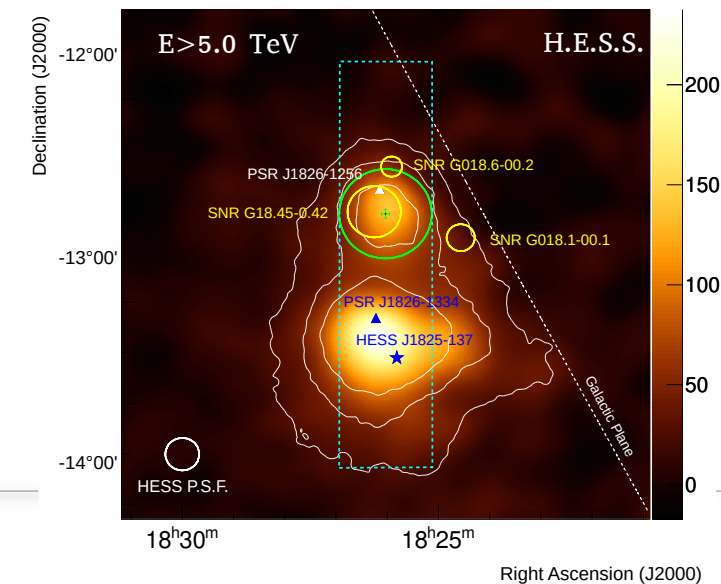
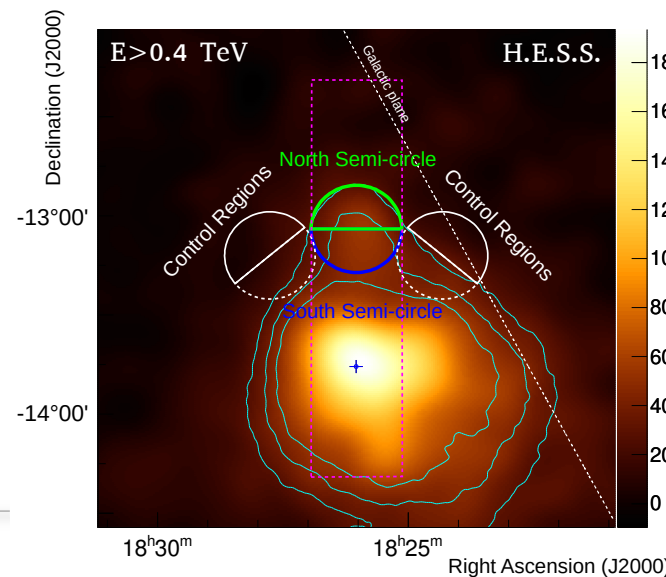


## ■ HESS J1826-130

- TeV flux to  $\sim 50$  TeV
- Overlaps dense ISM
- CRs escaping J1825 or PSR J1826-1256

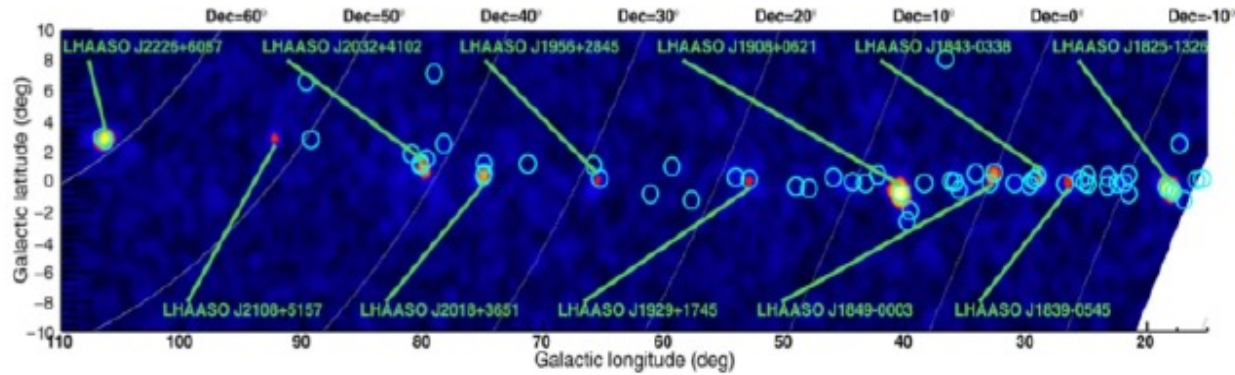
- Other examples:  
HESS J1809-193,  
HESS J1831-098

H.E.S.S. coll., A&A, 644, A1112 (2020)

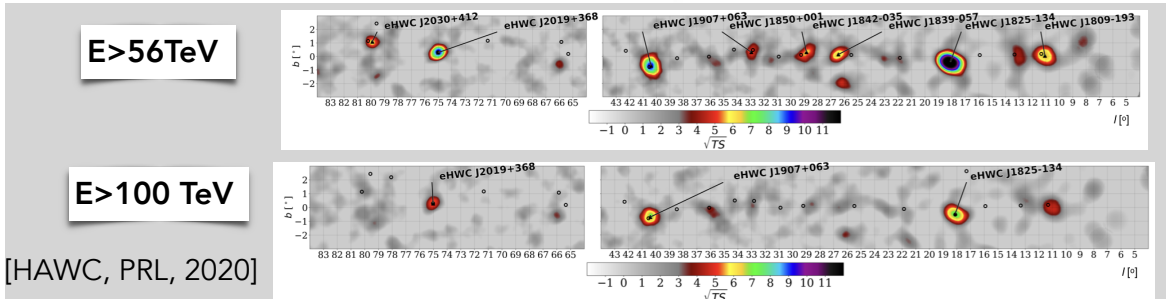
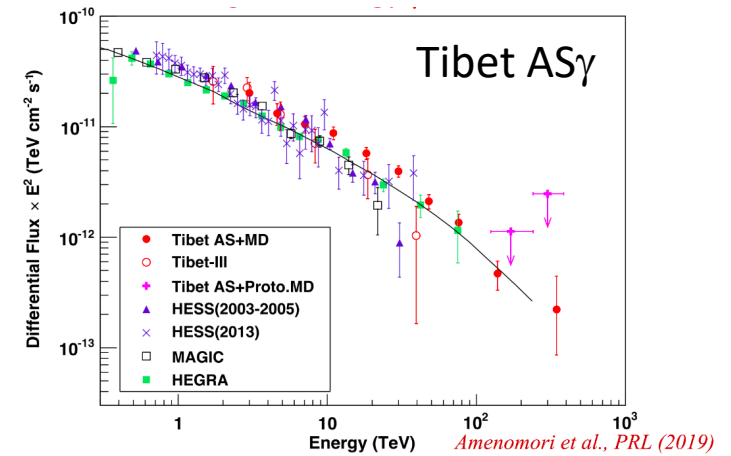


# Galactic Pevatrons and VHE gamma rays

PeVatron - UHE gamma-ray source ( $E_\gamma \gtrsim 100 \text{ TeV}$ )

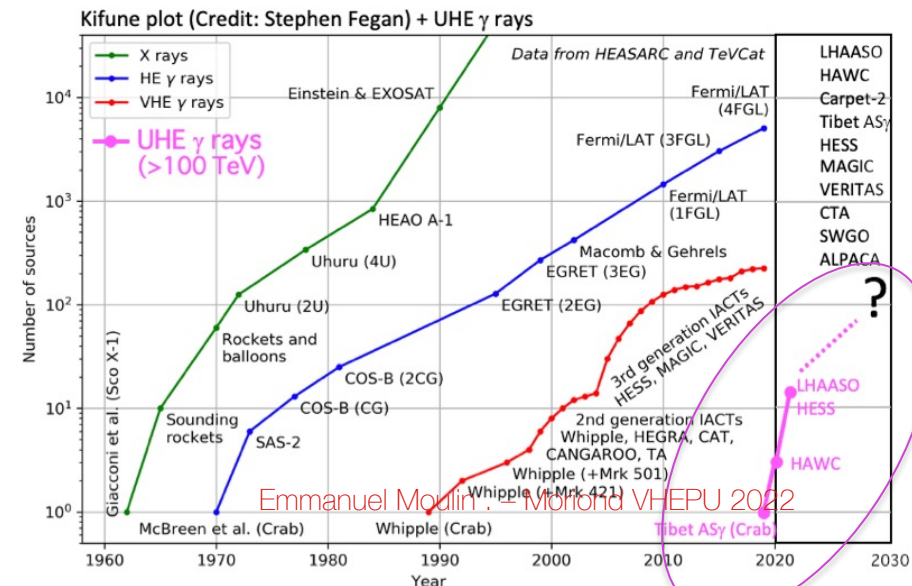


- 12 sources at  $> 0.1 \text{ PeV}$  detected by LHAASO so far



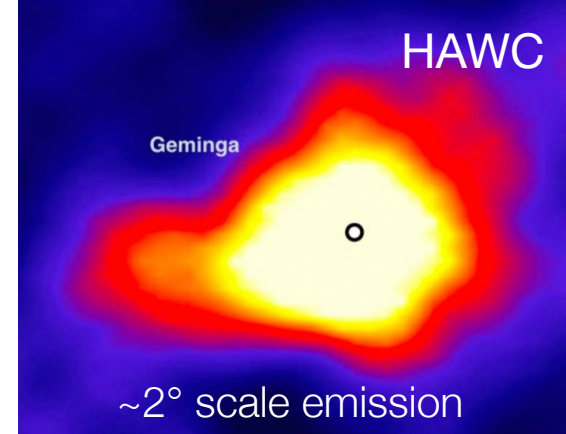
[HAWC, PRL, 2020]

- a PeVatron
  - Only hadronic accelerators?
  - “Leptonic PeVatrons”?
- When is it no longer a candidate?
  - Clear accelerator
  - Confirmed hadronic : coincident neutrinos

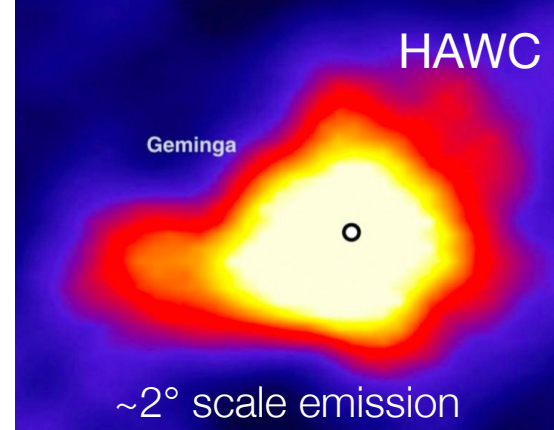


# Pulsar TeV halos - Geminga

- **New source class:** Geminga and Monogem pulsars are surrounded by a spatially extended region ( $\sim 20$  pc) emitting multi-TeV gamma-rays
  - Data implied the diffusion coefficient to be two orders of magnitude lower than the one in the Galaxy.



# Pulsar TeV halos - Geminga

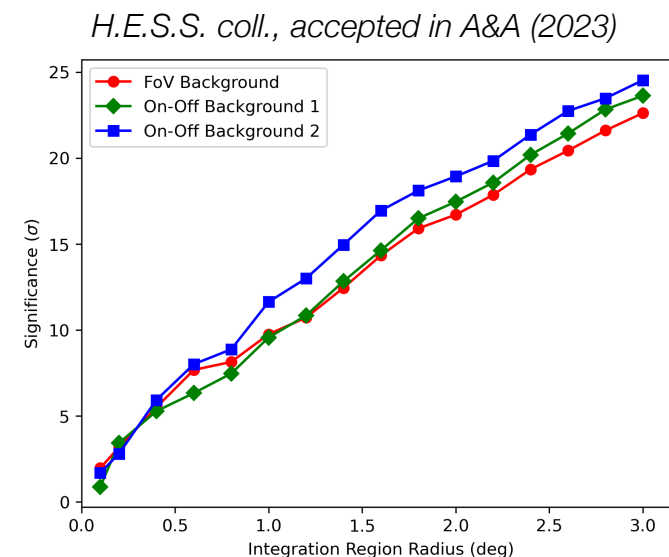
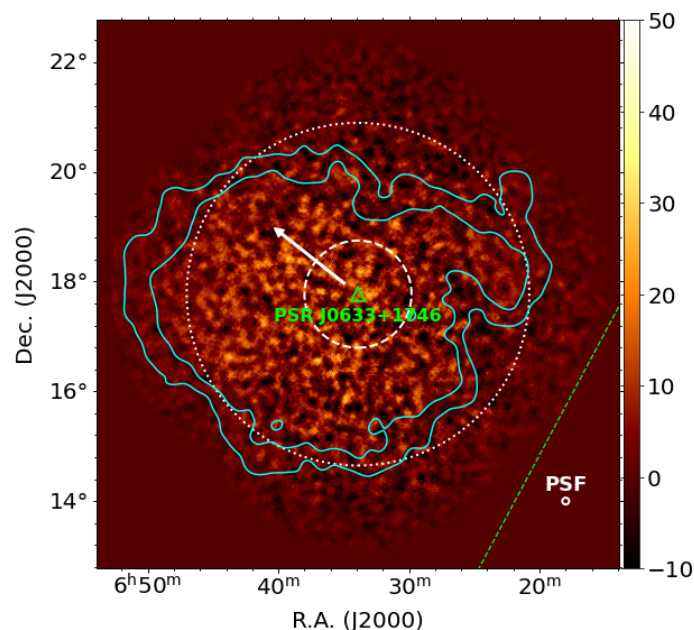


- New source class:** Geminga and Monogem pulsars are surrounded by a spatially extended region ( $\sim 20$  pc) emitting multi-TeV gamma-rays
  - Data implied the diffusion coefficient to be two orders of magnitude lower than the one in the Galaxy.

- H.E.S.S. has detected similar morphology**

- Detecting large, extended sources with IACTs is challenging, but possible
  - True emission extent likely larger than H.E.S.S. FoV
  - Largest H.E.S.S. source:  $\sim 5^\circ$  diam;  $\sim 20$ pc

HAWC detection of extended TeV emission

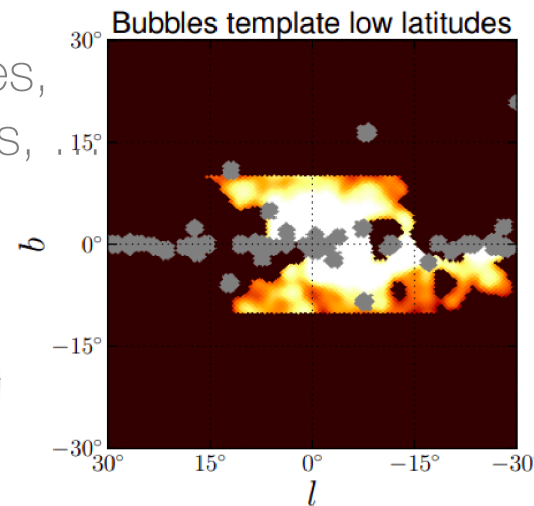
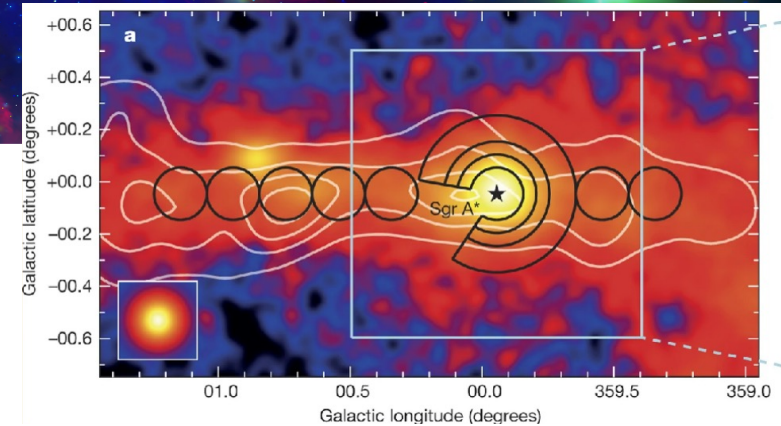


# The Galactic Center

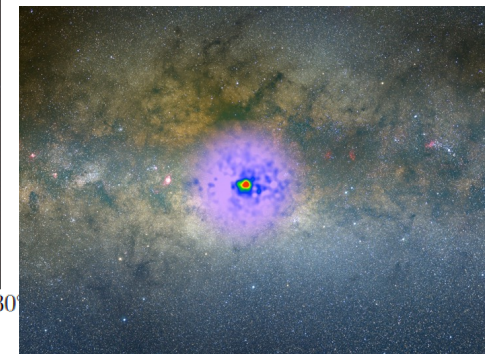
X-Ray: NASA/CXC/UMass/D. Wang et al.; Radio: NRF/SARAO/MeerKAT



- A very large data set for H.E.S.S (+800 hours), obtained over many years with changing camera/telescope configurations
- A crowded region at VHE: base of Fermi Bubbles, an hypothetical population of millisecond pulsars, with extended structures beyond single fov and/or source confusion

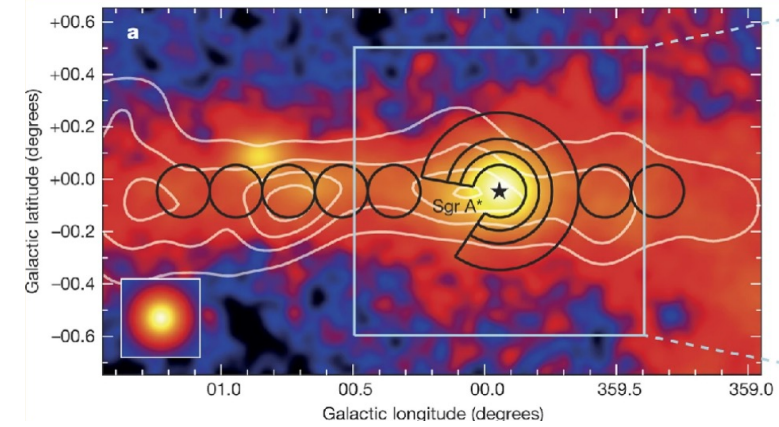


*The Galactic Centre Excess seen by Fermi-LAT*

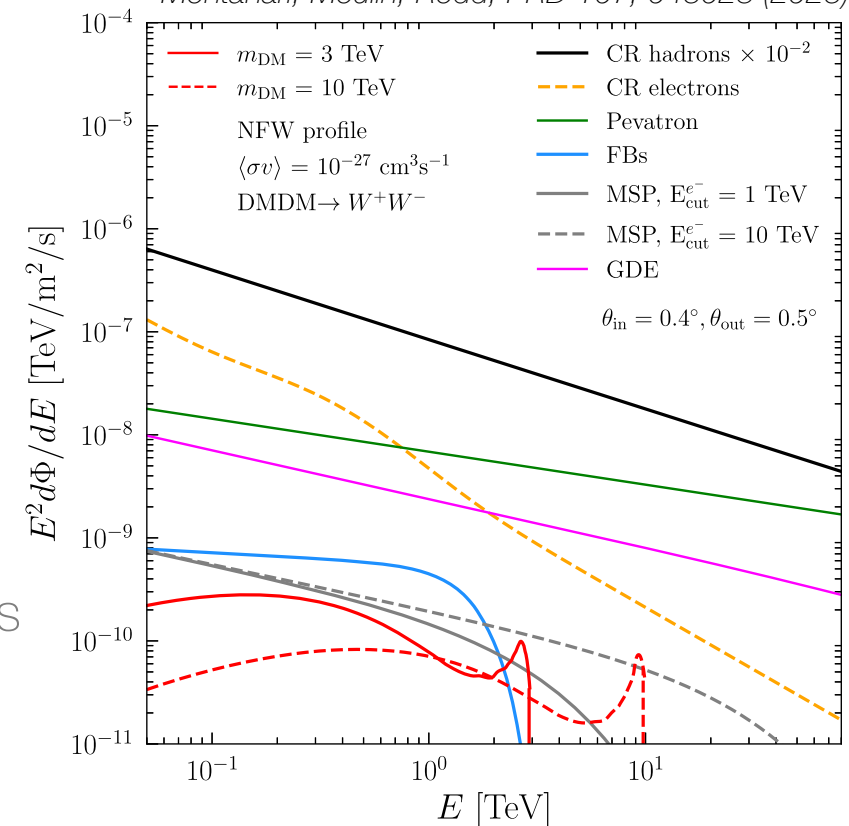


# The Galactic Center

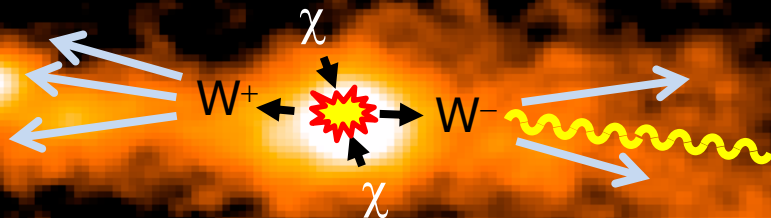
- **A very large data set for H.E.S.S (+800 hours), obtained over many years with changing camera/telescope configurations**
- ...a crowded region : Fermi Bubbles, an hypothetical population of millisecond pulsars, ... with extended structures beyond single fov and/or source confusion
- Challenges in treating systematics in large dataset, background estimation and rejection, separation of sources
- Also the region where the brightest gamma-ray signals of annihilating DM are expected



Montanari, Moulin, Rodd, PRD 107, 043028 (2023)



Weakly Interacting Dark Matter Particles

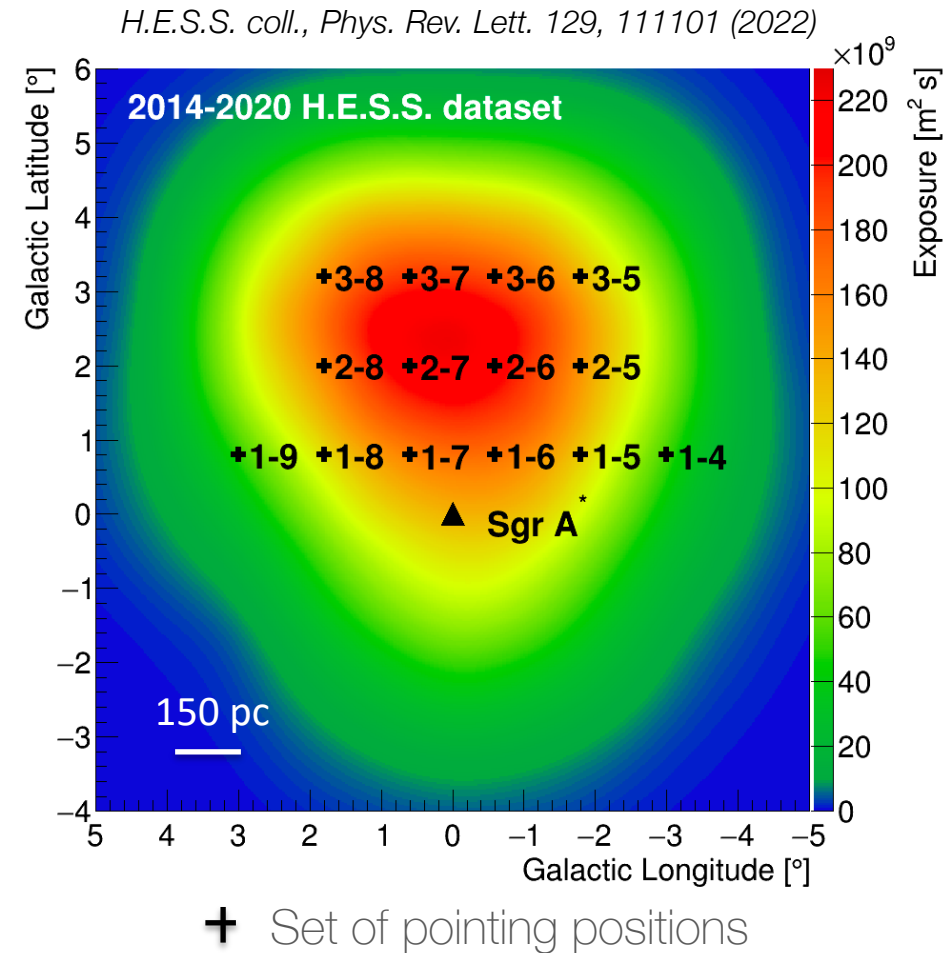


# The Galactic Center survey

- **H.E.S.S. is performing a survey of the inner few degrees of the Galactic Centre region since 2015**

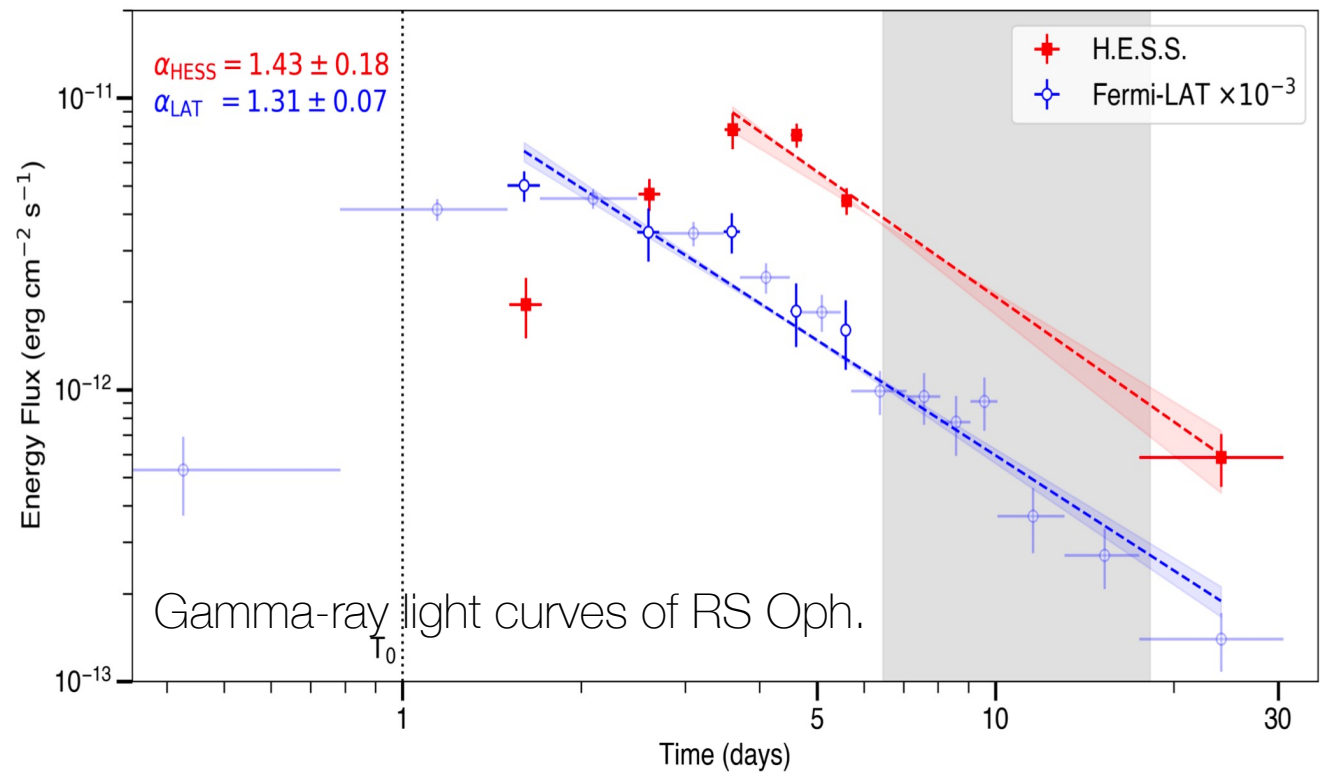
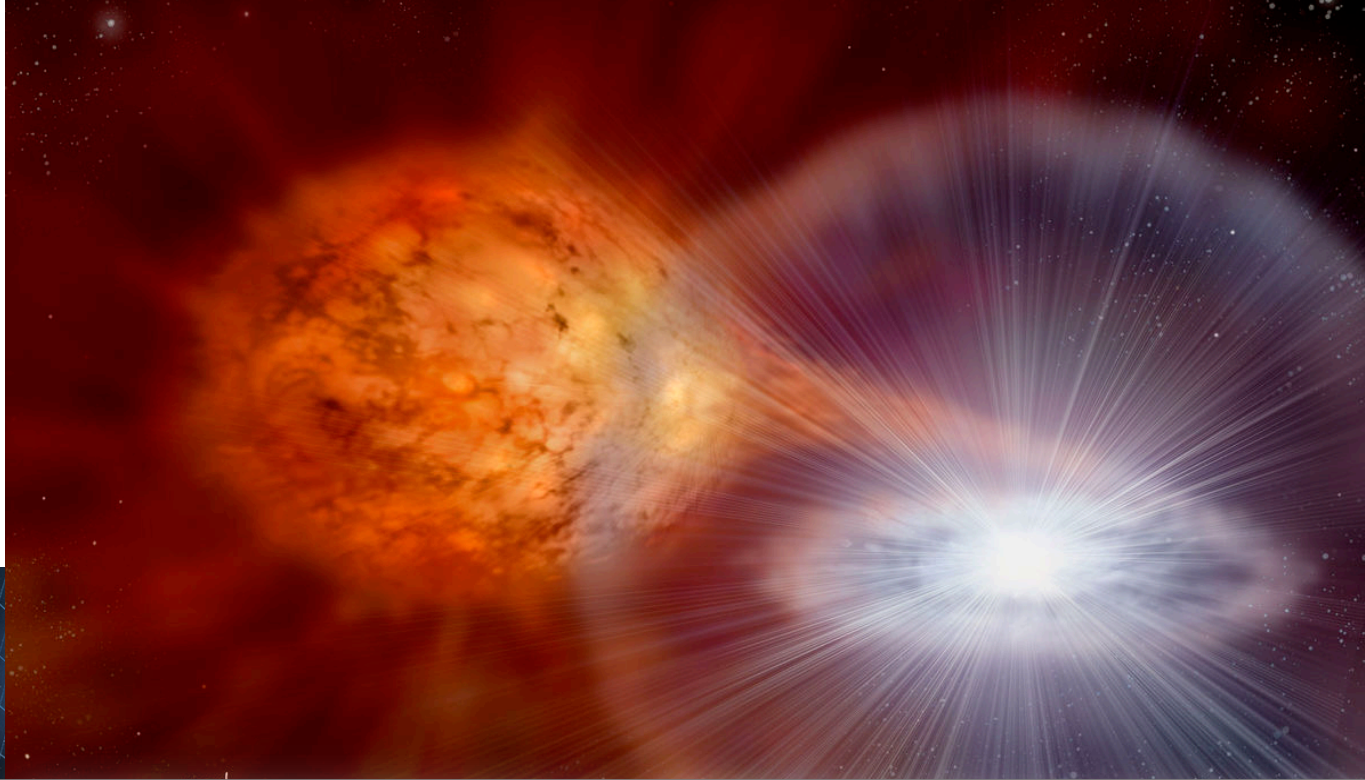
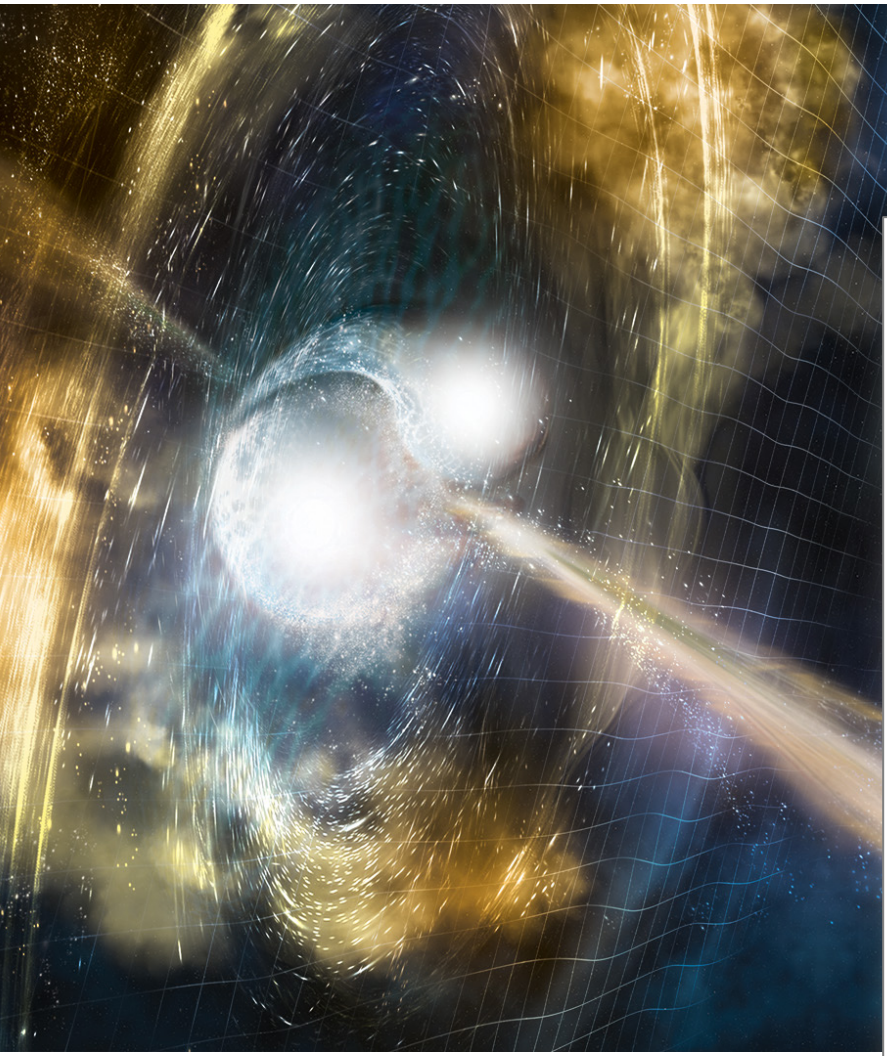
- provide unprecedented sensitivity to dark matter
- deeper study of the diffuse emission
- search for TeV outflows from the Galactic Centre

- The first ever conducted VHE gamma-ray survey of the Galactic Center (GC) region.



- Unique dataset to look TeV emission at the base of the Fermi bubbles
- The survey is going on !

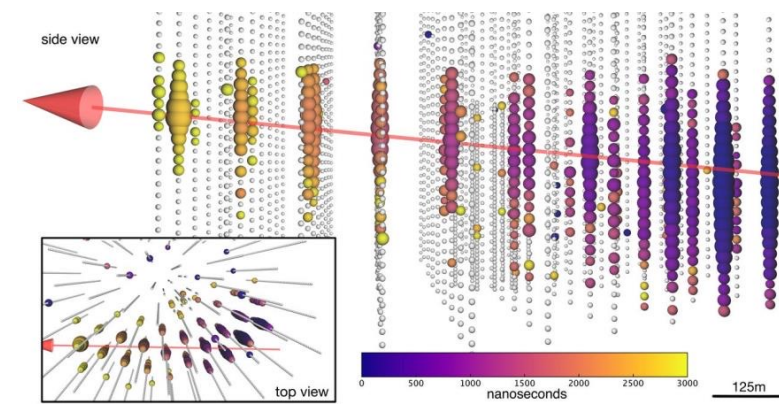
# Transient physics





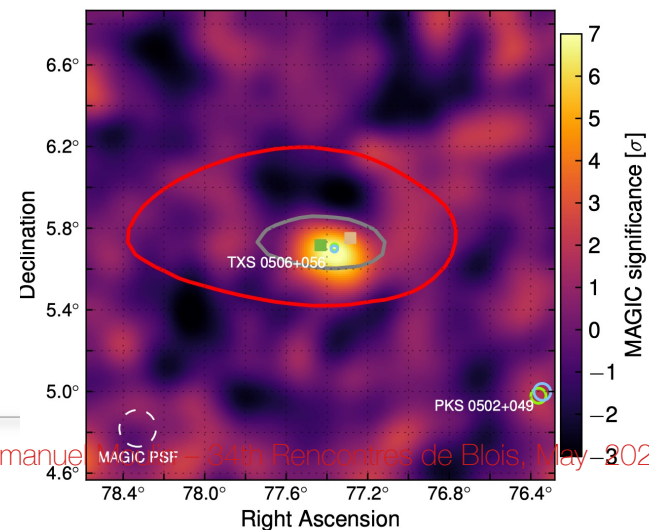
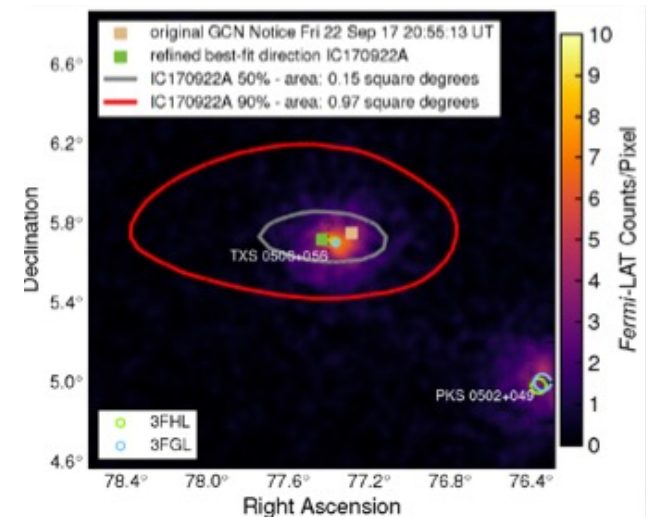
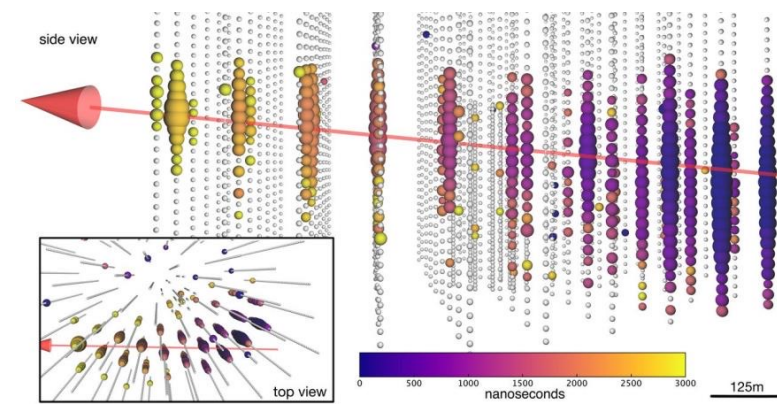
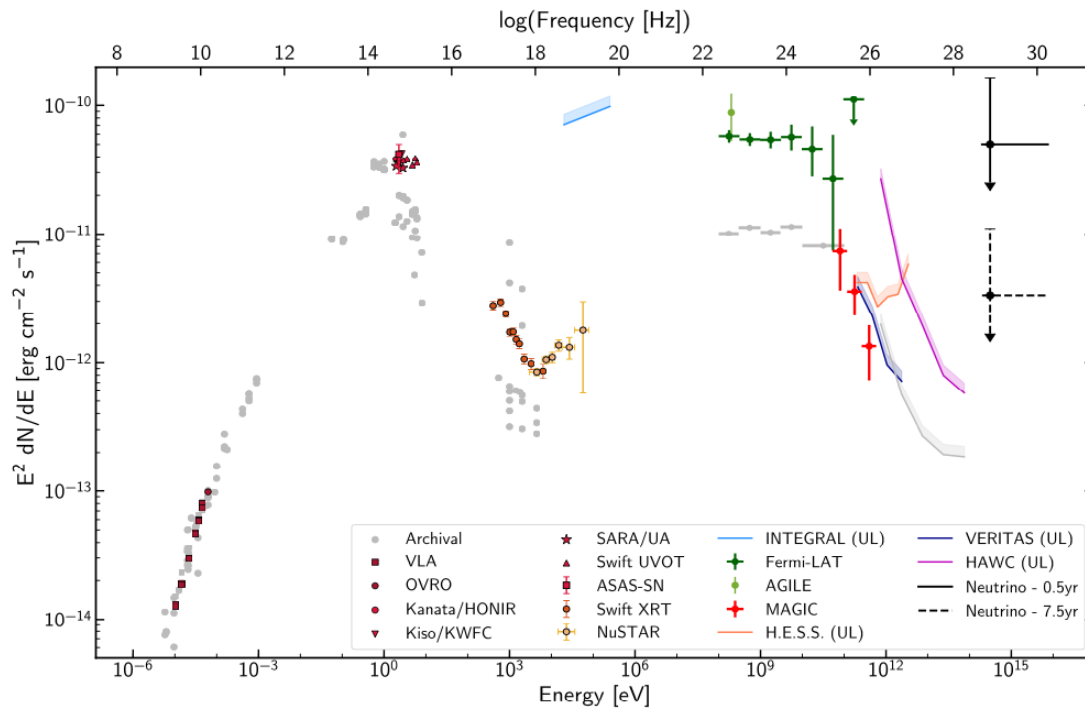
# Multi-messenger transients

- 2017: a neutrino with energy  $\sim 290$  TeV (IC170922) detected in coincidence with the blazar TXS 0506+056 during enhanced gamma-ray activity



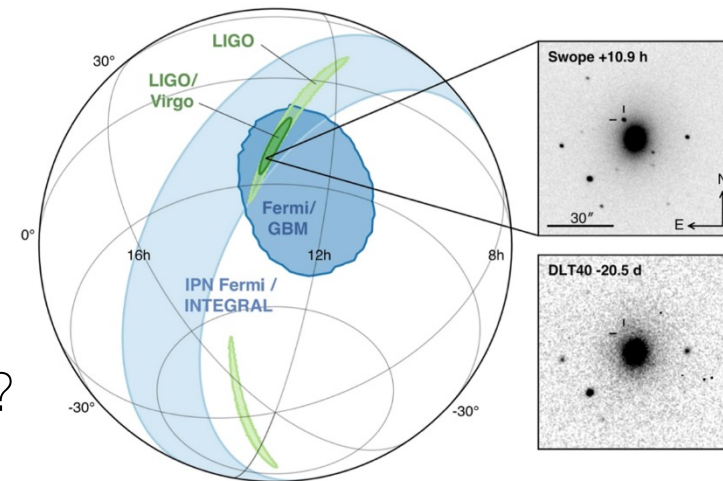
# Multi-messenger transients

- 2017: a neutrino with energy  $\sim 290$  TeV (IC170922) detected in coincidence with the blazar TXS 0506+056 during enhanced gamma-ray activity
- Follow-up observations by a myriad of instruments: Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, VLA, ...



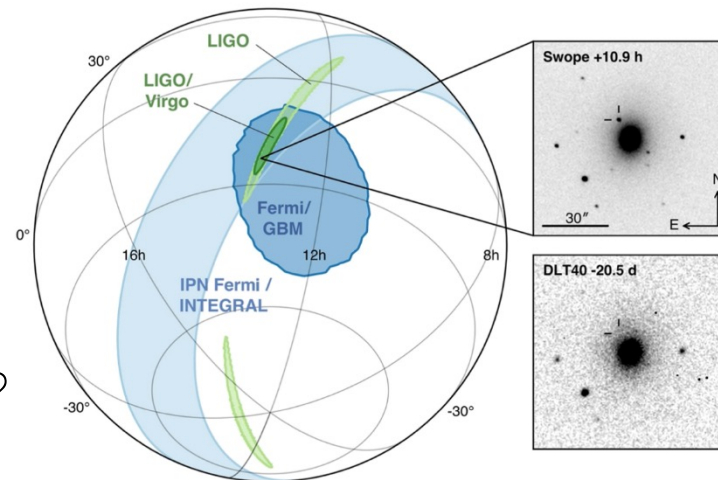
# Compact binary merger follow-up

- LIGO GW170817: smoking gun – relation between GW events (BNS mergers) and short GRBs
  - First joint detection EM and GW
  - Associated with GRB 170817A
  - Possible other EM counterpart : AT2017gfo ?

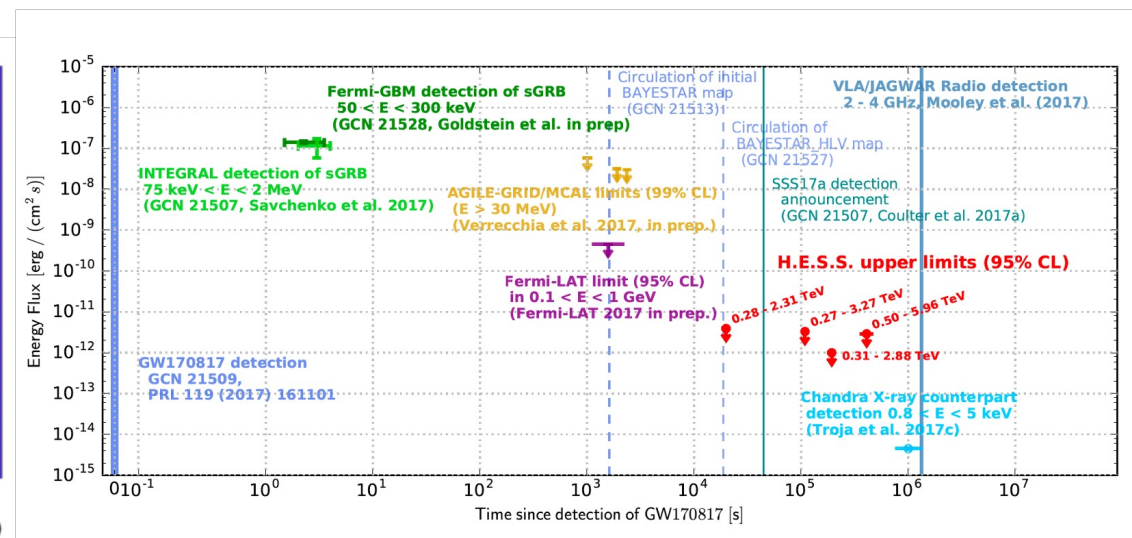
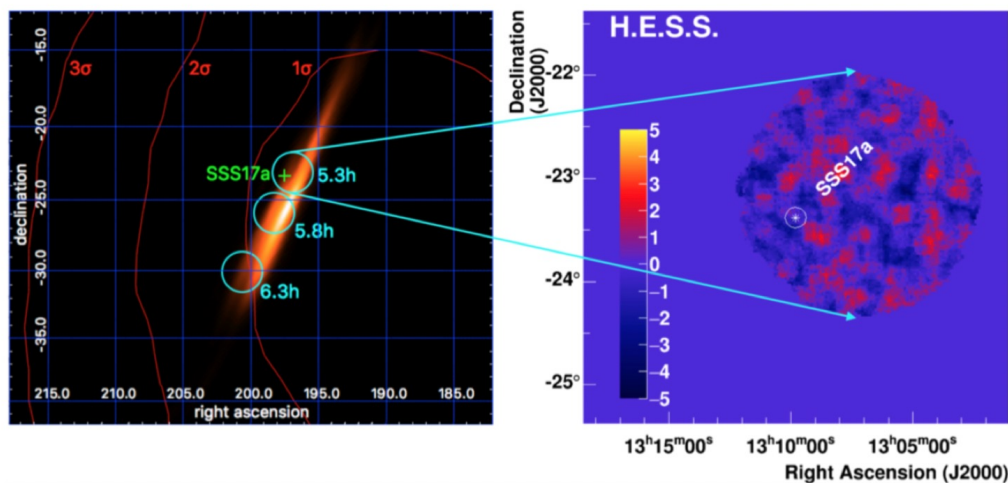


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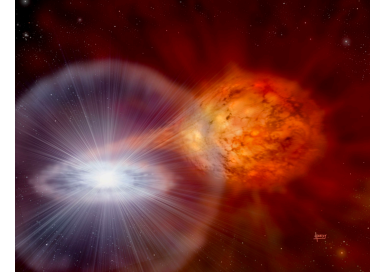
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  - First joint detection EM and GW
  - Associated with GRB 170817A
  - Possible other EM counterpart : AT2017gfo ?



- Short term follow-up: stringent upper limits on the VHE emission from a BNS merger

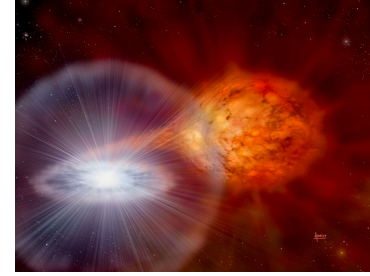


# The recurrent Nova RS Ophiuchi

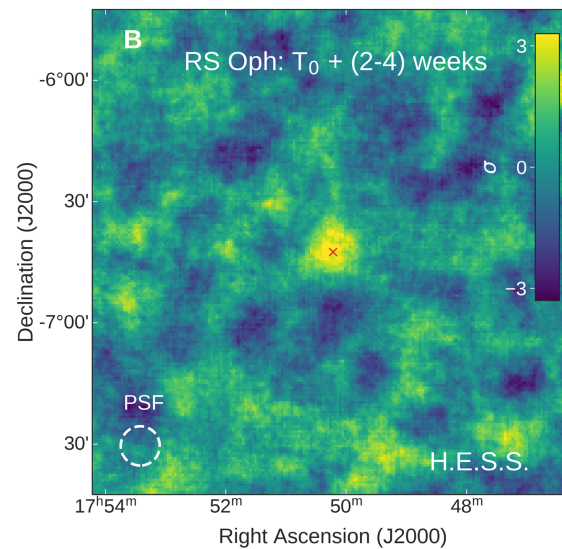
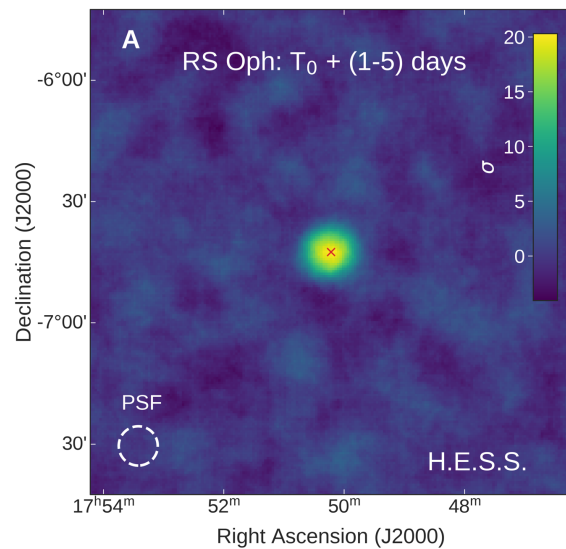


- Novae – outbursts from accreting binary systems of White Dwarf + massive donor
  - Detected in gamma rays, i.e., Fermi-LAT
- 1st Galactic transient source: RS Ophiuchi – 2021 flare
- Triggered by optical detection, VHE observations started with ~24h latency.

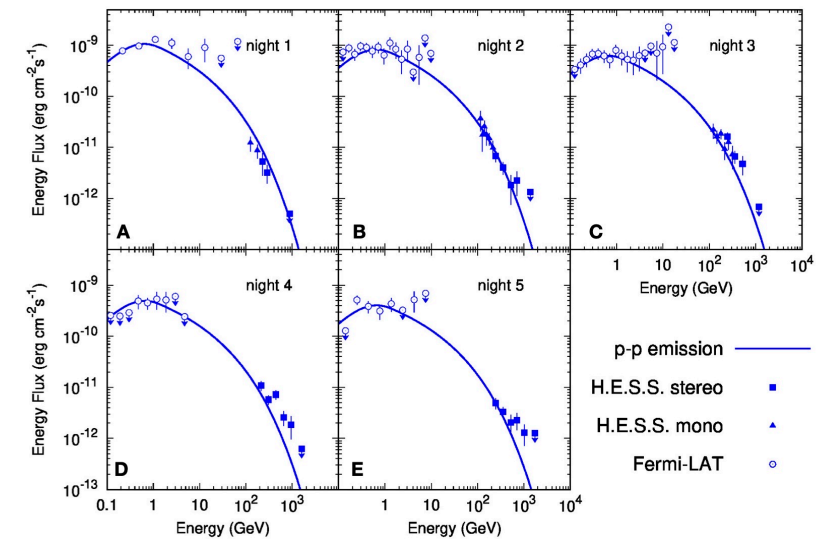
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*H.E.S.S. coll., Science 376 (2022) 6588*

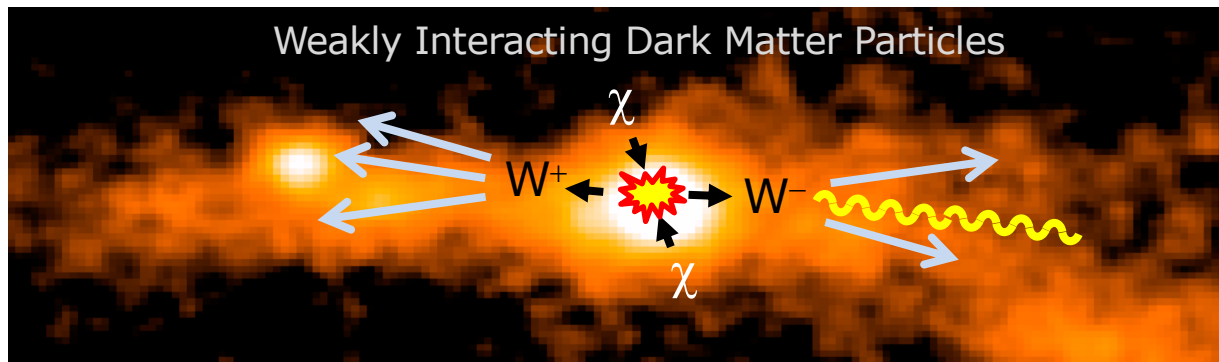


- Detection at  $> 6$  sigma on each night of first five nights
- Hadronic acceleration scenario preferred

# Dark matter / Fundamental Physics

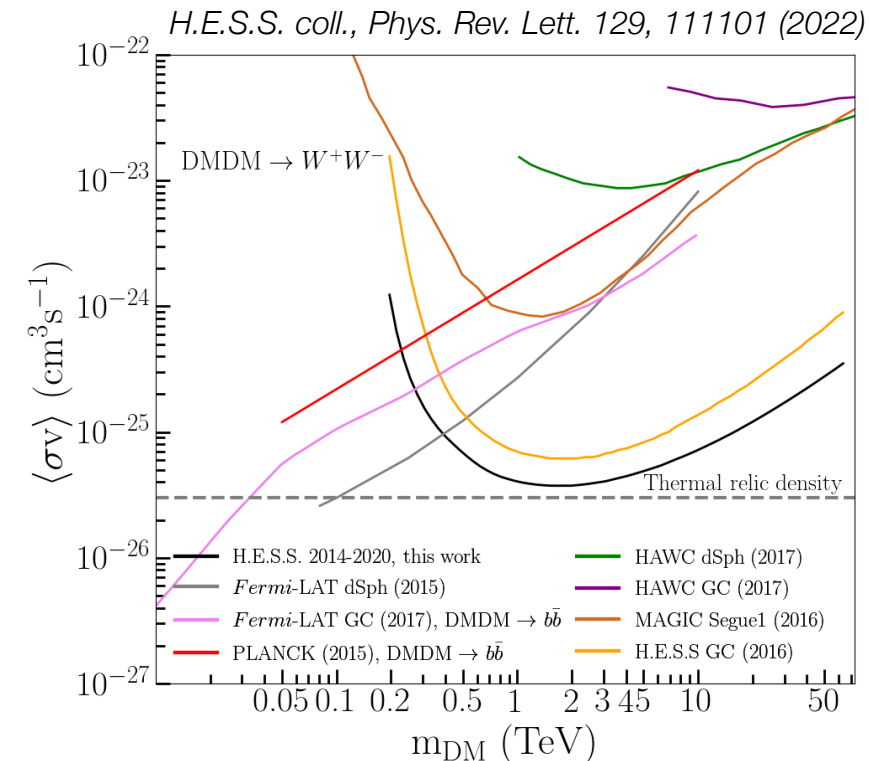


- A large DM programme has been carried over the last 15 years on a variety of targets including the Galactic Center, nearby dwarf spheroidal/irregular galaxies and galaxy clusters, Galactic globular clusters, ...



- H.E.S.S. reaches the sensitivity to probe thermal TeV WIMP models

See A. Montanari's talk  
in the DM session on Tue



# Dark matter / Fundamental Physics

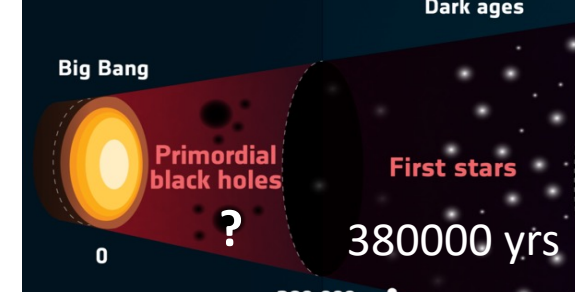


## ■ Primordial black holes

- An hypothetical type of black holes that formed in the early universe
- PBH may account for a significant fraction of the dark matter content
- Following Hawking radiation mechanisms , PBH would evaporate producing standard model particles including gamma rays in the final state
  - assuming an initial mass of  $\sim 10^{15}\text{g}$ , they should reach there final stage of evaporation today
    - search strategy: look for TeV photon burst over timescale of a few seconds to few minutes
- **All H.E.S.S.-I observations between 2004 and 2013 : 4816 hours of observations**
  - Background estimated from the data, by using the same photon list, but with randomized times of arrival



# Dark matter / Fundamental Physics

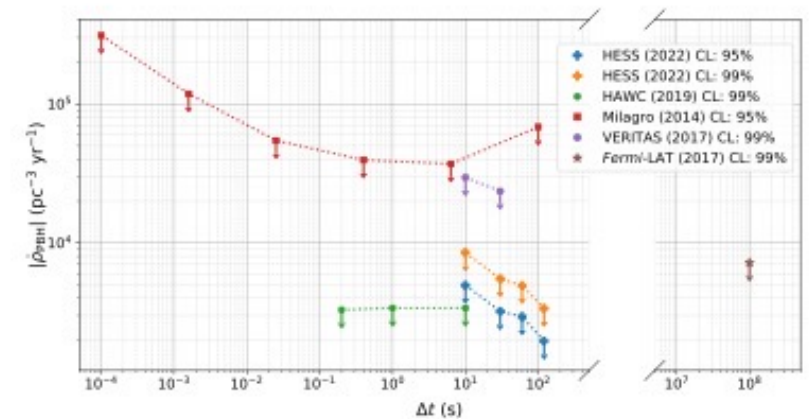


## ■ Primordial black holes

- An hypothetical type of black holes that formed in the early universe
- PBH may account for a significant fraction of the dark matter content

- No significant number of cluster of photons above background is found for 10s, 30s, 60s, 120s time scales

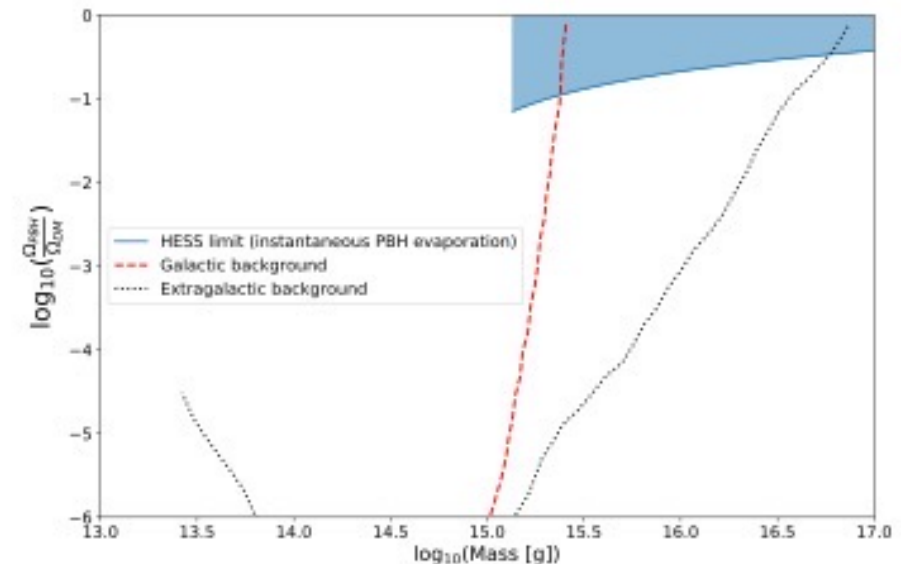
→ Limits on PBH evaporation rate



H.E.S.S. coll. JCAP 04 (2023) 040

- Assuming an initial mass distribution described by a power law, constraints on the fraction  $\Omega_{\text{PBH}}$  can be derived

F. Halzen et al. Nature 353, 807 1991



# New challenges

- Many studies combine very large data sets (+600 hours), obtained over many years (>10 yrs) with changing camera/telescope configurations, mapping extended structures beyond single fov and/or source confusion
- Challenges in treating systematics in large datasets, background estimation and – rejection as well as separation of sources
  - Extensive work improving calibration, background, and high-level analysis, e.g., choice of gammapy as high-level tool

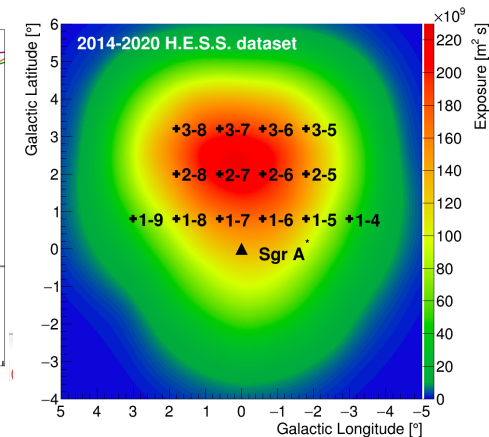
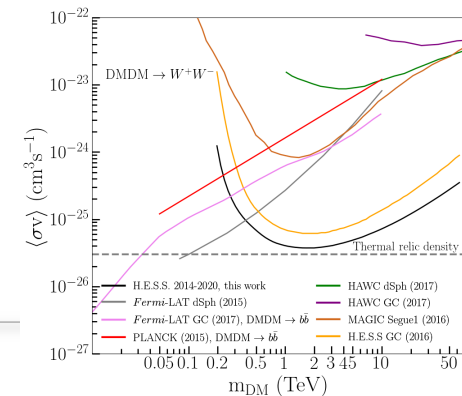
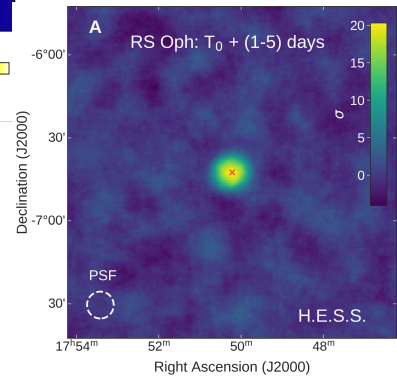
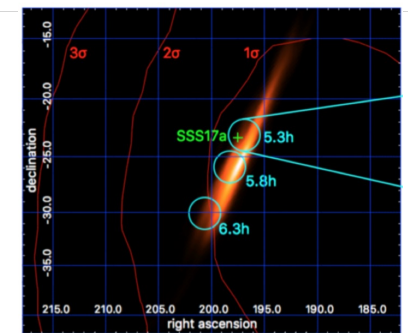
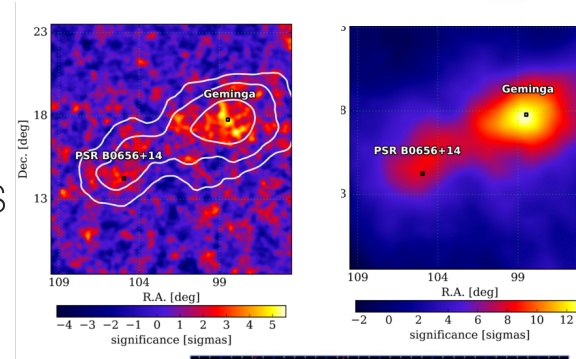
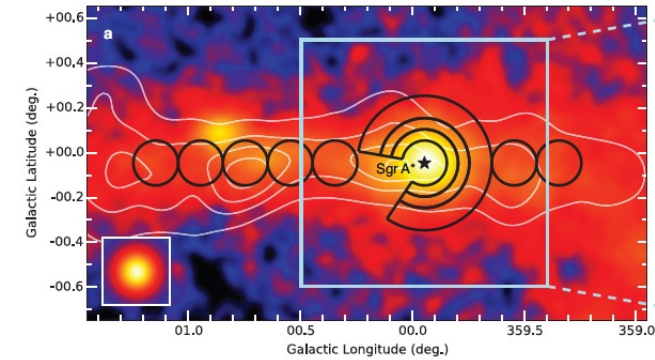
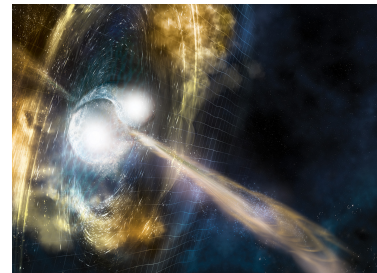


- **HESS 20th Anniversary Celebrations – Namibia, November 2022:**
  - 1<sup>st</sup> telescope inauguration and start of stereoscopic observations in 2002
- **The H.E.S.S. observatory still improves its operational performance and enables fascinating research**

# Summary

VHE gamma astrophysics is a lively field :  
HESS, MAGIC, VERITAS, HAWC, LHAASO, ...

- Many Galactic Pevatrons (candidates) being discovered
- TeV halos : probing CR diffusion nearby sources
- Galactic Novae: a new class of TeV emitters
- Birth of multimessenger astronomy : n/gamma coincident detection, gravitational wave follow-ups
- Surveys are going on: Galactic Center, LMC, ...
- Thermal TeV WIMP uncharted parameter space being probed



Thanks for your attention