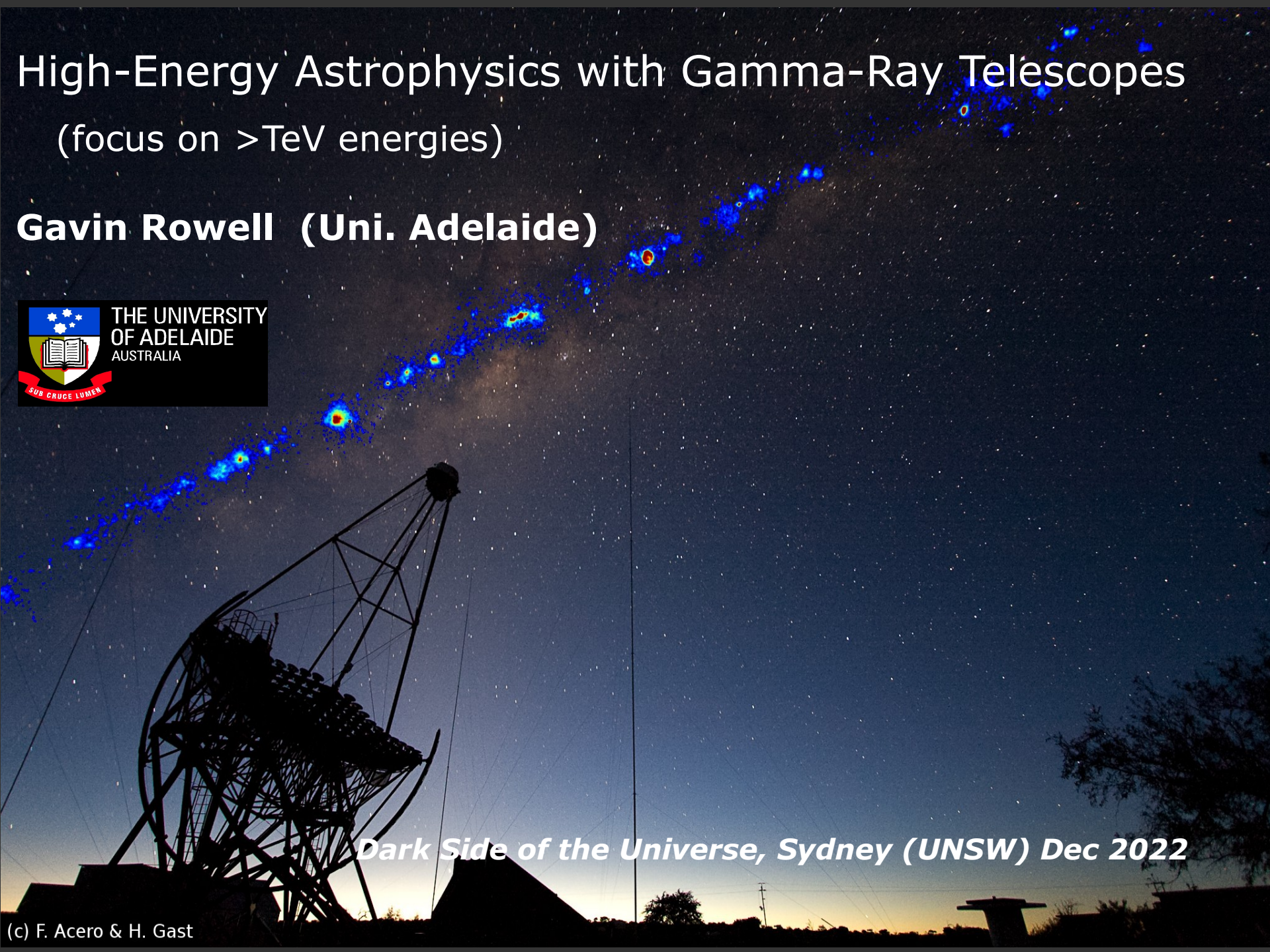


# High-Energy Astrophysics with Gamma-Ray Telescopes

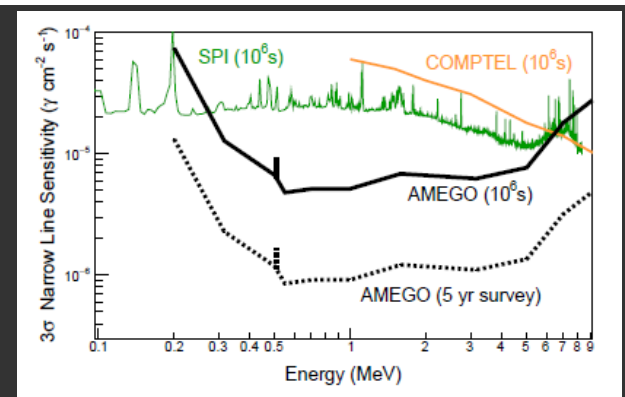
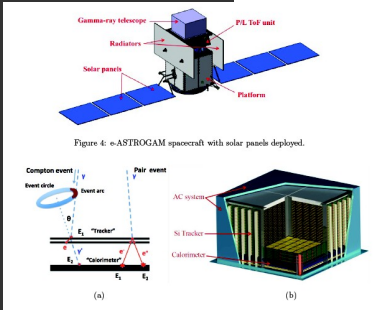
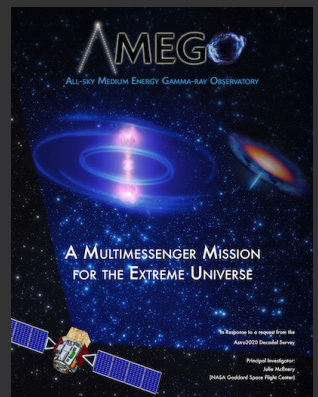
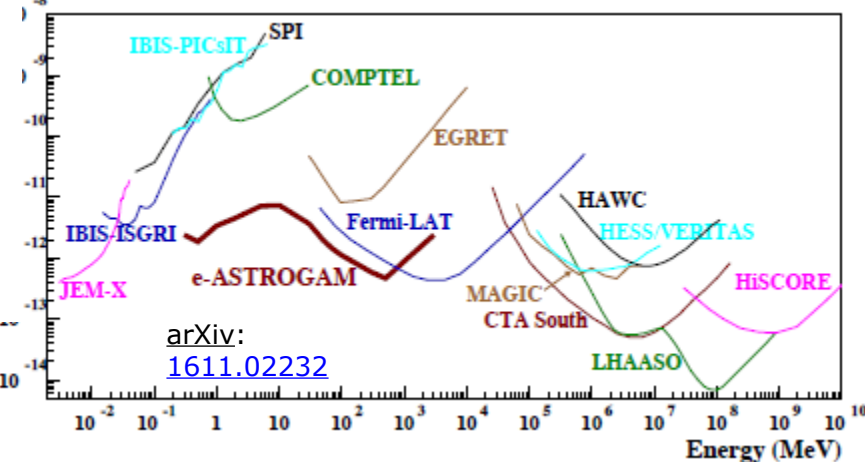
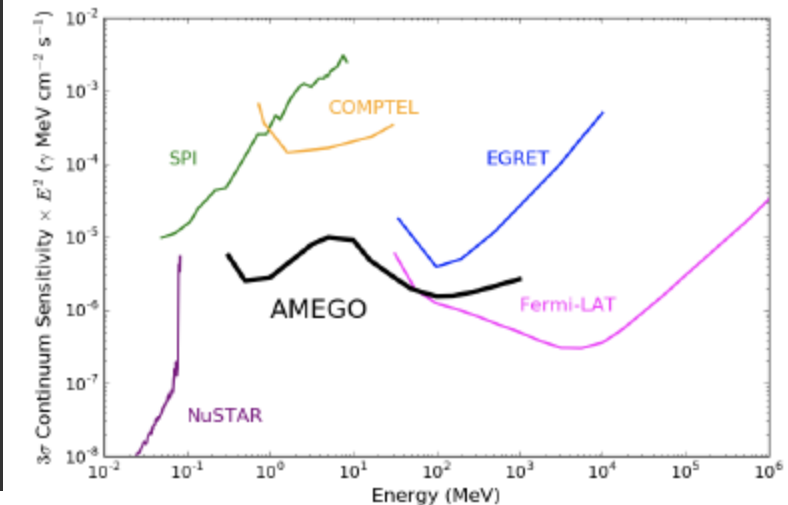
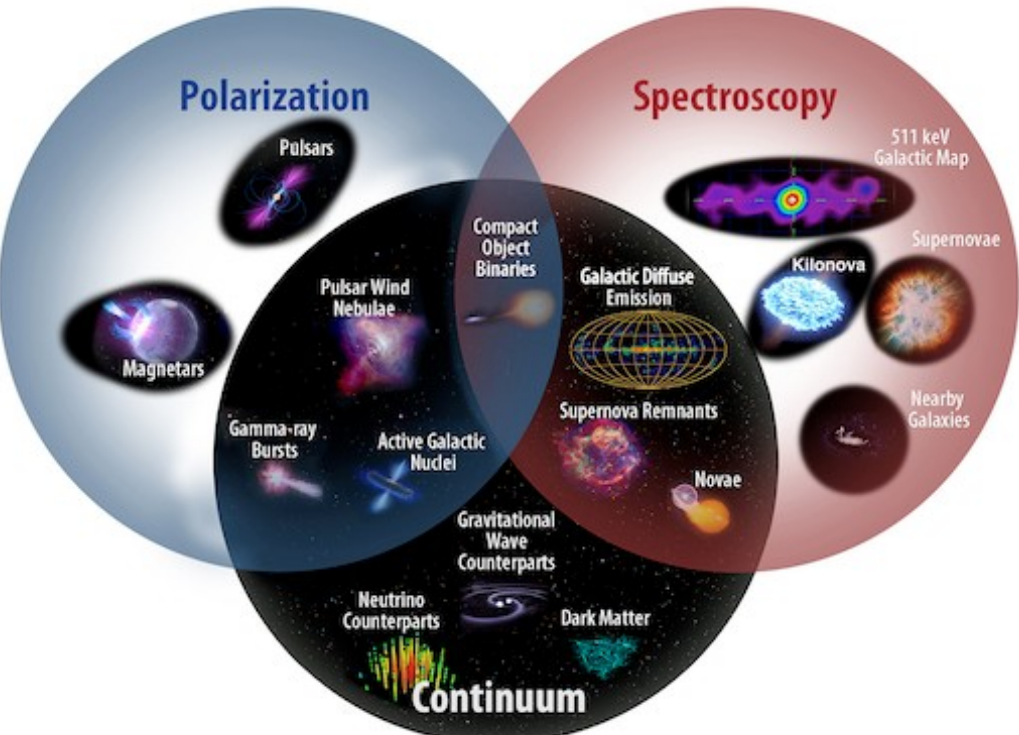
(focus on  $>TeV$  energies)

**Gavin Rowell (Uni. Adelaide)**



*Dark Side of the Universe, Sydney (UNSW) Dec 2022*

# MeV Gamma Rays



## AMEGO & e-ASTROGAM

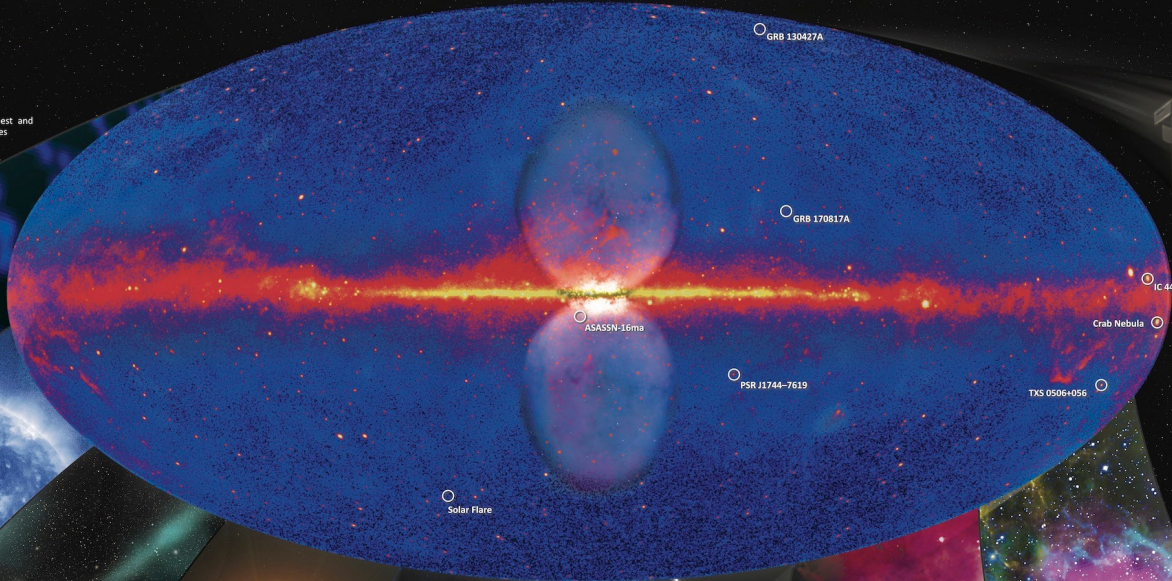
<https://asd.gsfc.nasa.gov/amego/index.html>



# Fermi's Decade of Gamma-ray Discoveries

### Fermi 10-year Sky Map

This all-sky view, centered on our Milky Way galaxy, is the deepest and best-resolved portrait of the gamma-ray sky to date. It incorporates observations by NASA's Fermi Gamma-ray Space Telescope from August 2008 to August 2018 at energies greater than 1 billion electron volts (GeV). For comparison, the energy of visible light falls between 2 and 3 electron volts. Lighter shades indicate stronger emission. NASA/DOE/Fermi LAT Collaboration



### GRB 130427A

On April 27, 2013, a blast of light from a dying star in a distant galaxy became the focus of astronomers around the world. The explosion, known as a gamma-ray burst and designated GRB 130427A, was detected by Fermi for about 20 hours. The burst included a 95 GeV gamma ray, the most energetic light yet detected from a GRB. NASA/DOE/Fermi LAT Collaboration

### Solar Flare

Although our Sun is not usually a bright gamma-ray source, solar flares can briefly outshine everything else in the gamma-ray sky. On March 7, 2012, Fermi detected flares erupting on the side of the Sun not visible to the spacecraft. The flares produced accelerated particles that fell onto the side of the Sun facing Earth, resulting in gamma rays Fermi could detect. NASA/DOE

### PSR J1744-7619

Discovered by Einstein@Home, a distributed computing project that analyzes Fermi data using home computers, PSR J1744-7619 is the first gamma-ray millisecond pulsar that has no detectable radio emission. NASA/DOE/Fermi LAT Collaboration/ASAS16, Zimmerman

### ASASSN-16ma

Fermi has discovered several novas, outbursts powered by thermonuclear eruptions on white dwarf stars. This was a surprise because novas weren't expected to be powerful enough to produce gamma rays. One event, dubbed ASASSN-16ma, shows that both gamma rays and visible light seem to be produced by the same physical process. NASA/DOE/Fermi LAT Collaboration

### GRB 170817A

This landmark event represents the first time light was seen from a source that produced gravitational waves. Fermi's detection of GRB 170817A coincided with a signal from merging neutron stars detected by the LIGO and Virgo gravitational-wave observatories. NASA/DOE/SLHA, Zimmerman

### TXS 0506+056

Among the nearly 2,000 active galaxies Fermi monitors, TXS 0506+056 stands out as the first one known to have produced a high-energy neutrino. Neutrinos are tiny, ghostlike particles that barely interact with matter and are thought to be produced in the same extreme physical environments as gamma rays. In July 2018, Fermi linked this galaxy to a detection by the Ice Cube Neutrino Observatory at the South Pole. NASA/Godard/Fermi LAT Collaboration

### Crab Nebula

The Crab Nebula, a young supernova remnant containing a pulsar, surprised Fermi astronomers with gamma-ray flares driven by the most energetic particles ever traced to a specific astronomical object. To account for the flares, scientists say electrons near the pulsar must be accelerated to energies a thousand trillion (10<sup>15</sup>) times greater than visible light. NASA/CHESTNUT/Hester et al.

### IC 443, the Jellyfish Nebula

The shock waves of supernova remnants like the jellyfish nebula can accelerate protons to near the speed of light. When they slam into nearby gas clouds, gamma rays are produced. Fermi detects this emission, confirming that supernova remnants accelerate high-energy cosmic rays. NASA/DOE/Fermi LAT Collaboration/NOAO/AURA/NSF, P. Green, UCL

### Galactic Center

The central region of the Milky Way is brighter in gamma rays than expected. Whether this excess is a collection of undiscovered millisecond pulsars or possibly evidence of annihilation of dark matter particles remains a mystery and will be part of Fermi's ongoing studies. NASA/Godard/Fermi LAT Collaboration/CALTECH, J. Simon, Univ. of Chicago

### Fermi Bubbles

Fermi data revealed vast gamma-ray bubbles extending tens of thousands of light-years from the Milky Way's plane. The Fermi Bubbles may be related to past activity of the supermassive black hole at our galaxy's heart. NASA/Godard

11 June 2018

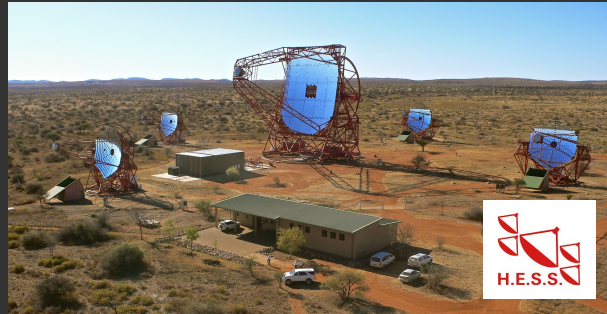
<https://www.nasa.gov/feature/goddard/2018/nasa-s-fermi-satellite-celebrates-10-years-of-discoveries>



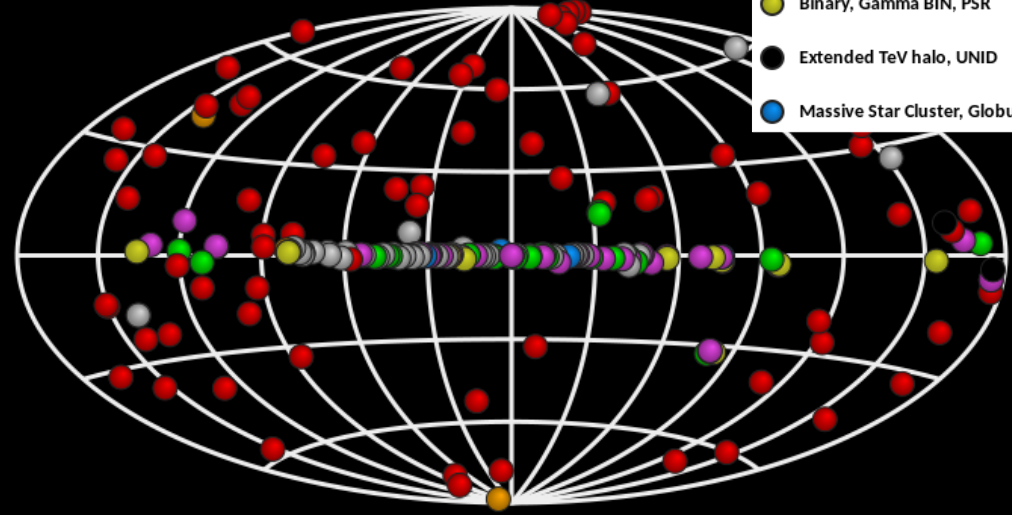
# Gamma-rays (~30 GeV to ~500TeV)

Ground-based detection of Cherenkov emission

V.High impact > 20 Nature, Science, PRL papers since 2004

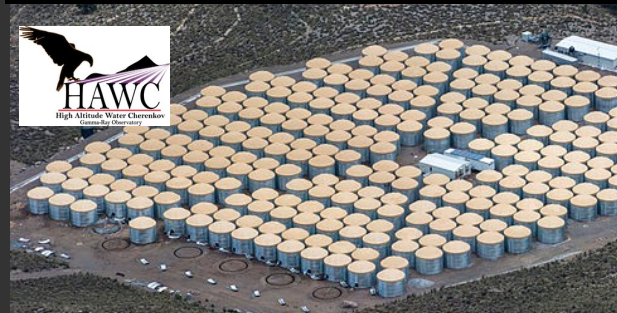


<http://tevcat.uchicago.edu/>



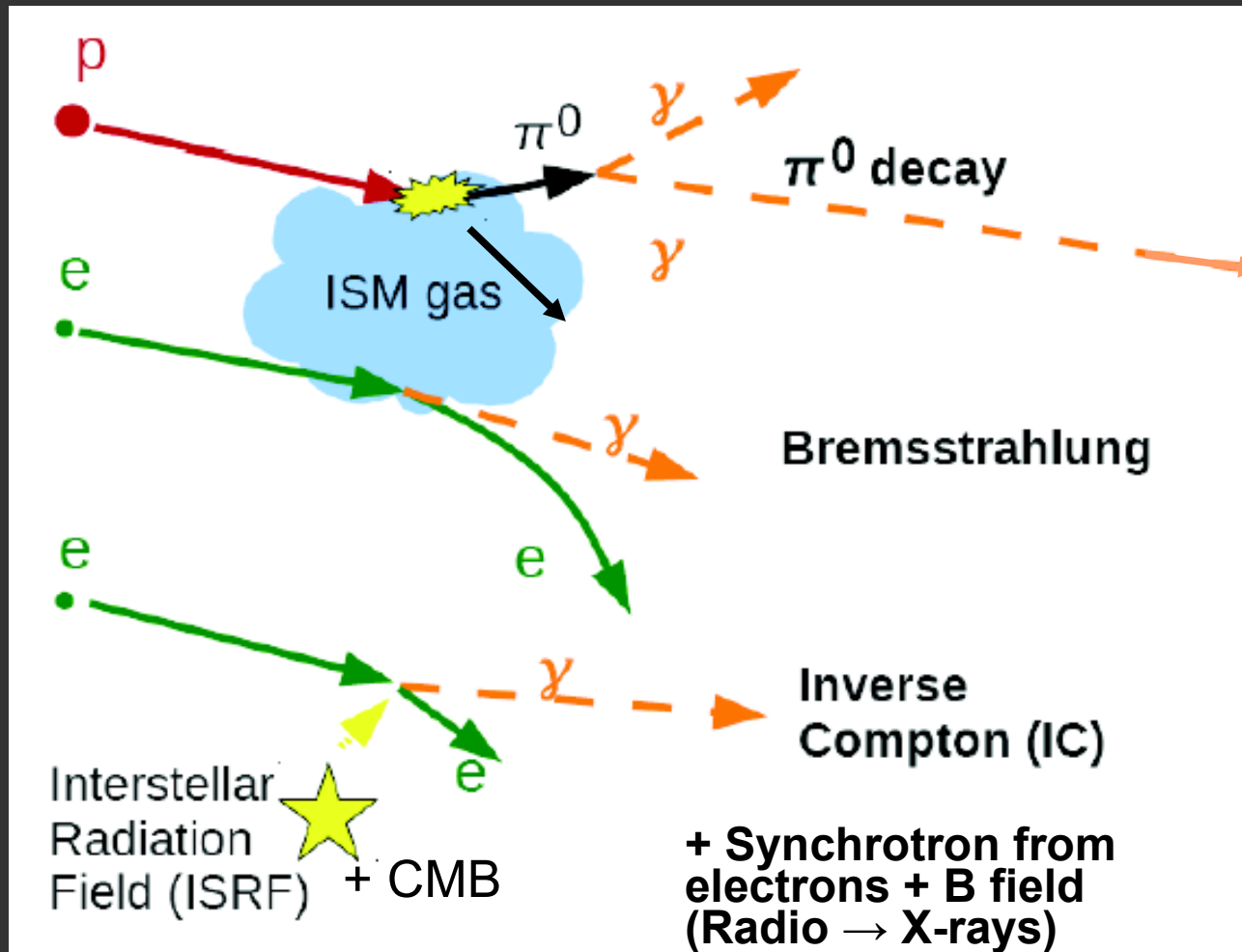
- PWN, BIN
- HBL, IBL, FSRQ, FRI, Blazar, BL Lac (class unclear), LBL
- Shell, SNR/Molec. Cloud, Composite SNR
- Starburst, Superbubble
- UNID, DARK
- Binary, Gamma BIN, PSR
- Extended TeV halo, UNID
- Massive Star Cluster, Globular Cluster

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



Great success with HESS, VERITAS, MAGIC, HAWC, building on previous generations  
Continued operations of HESS/VERITAS/MAGIC/HAWC 2025+  
Next generation → CTA, SWGO...

# Gamma Rays from multi-TeV particles



“ISM” gas  
Interstellar Medium

→ molecular +  
atomic + ionised gas  
in the Milky Way

+ Neutrinos from  
charged pions (2/3)

Protons: Gamma-rays and ISM are generally spatially correlated  
(require **atomic and molecular ISM** → **mm radio astronomy**)  
+ neutrino astronomy

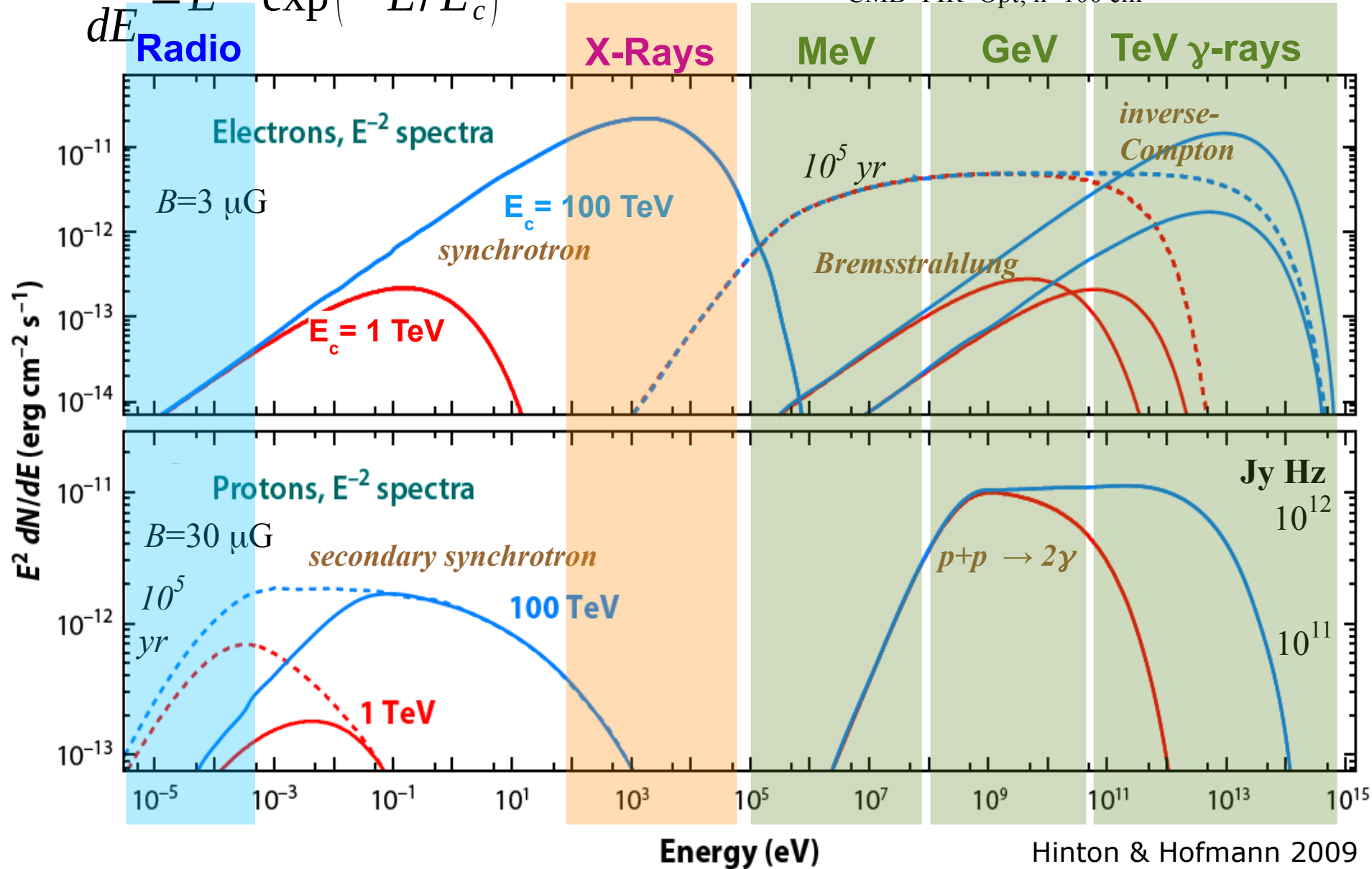
Electrons: **Gamma-ray** (IC) + **non-thermal X-ray, radio emission** (synchrotron)  
→ radio, X-ray, gamma-ray connections

# Non-Thermal Photon Energy-fluxes (hypothetical particle accelerator)

Particle Spectrum

$$\frac{dN}{dE} = E^{-2} \exp(-E/E_c)$$

$W_p = W_e = 10^{48}$  erg;  $d = 1$  kpc; Age =  $10^4$  yr,  
CMB+FIR+Opt;  $n = 100$  cm $^{-3}$



# Why study cosmic-rays (CRs) and electrons?

- Energy density of galactic CRs similar to that in starlight, magnetic fields, and gas kinetic energy

- these energy densities are all tightly connected.

- CRs carry energy throughout galaxies

- CRs intimately linked to evolution of stars and galaxies

- CRs are a signpost of massive stellar evolution

- death (supernova remnants)

- life (winds from massive stars)

- birth (perhaps) signalling onset of fusion/stellar winds

- catalyst for astro-chemistry → life!

- Where do magnetic fields come? Are they important?

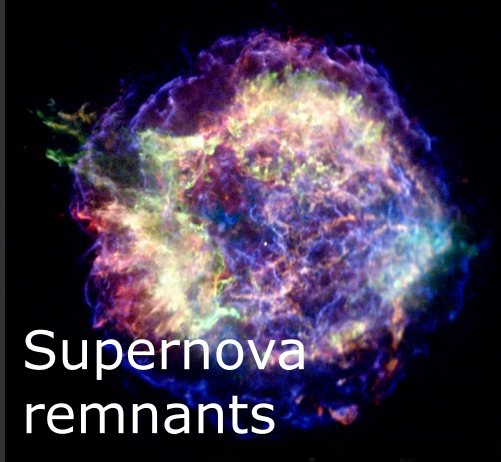
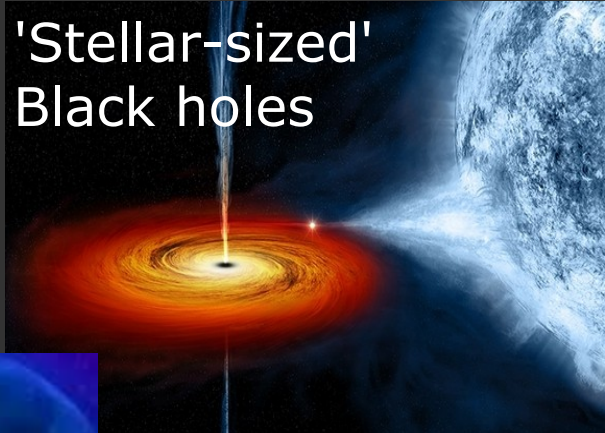
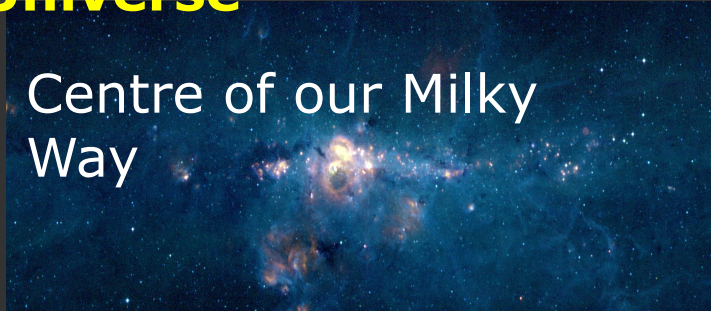
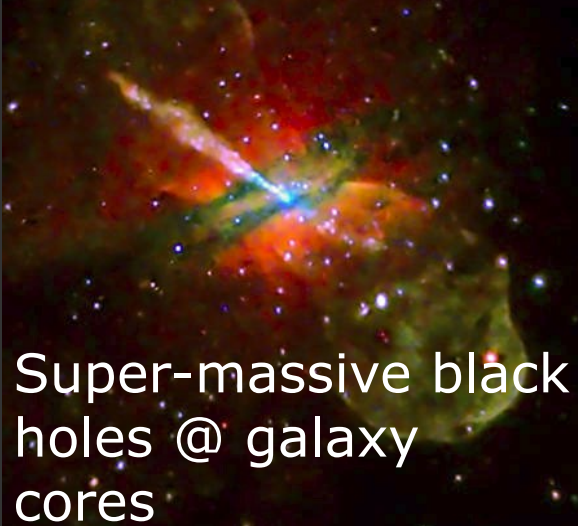
- Magnetic fields can greatly influence star formation!

- CRs can create magnetic fields - they ionise atoms

- CRs and electrons trace outflows and jets

- jets, pulsar winds, accretion, active Galaxies, GRBs, merger events.....

# Gamma rays provide insight into extreme particle accelerators in the Universe





# Gamma-rays (GeV to >PeV Energies)

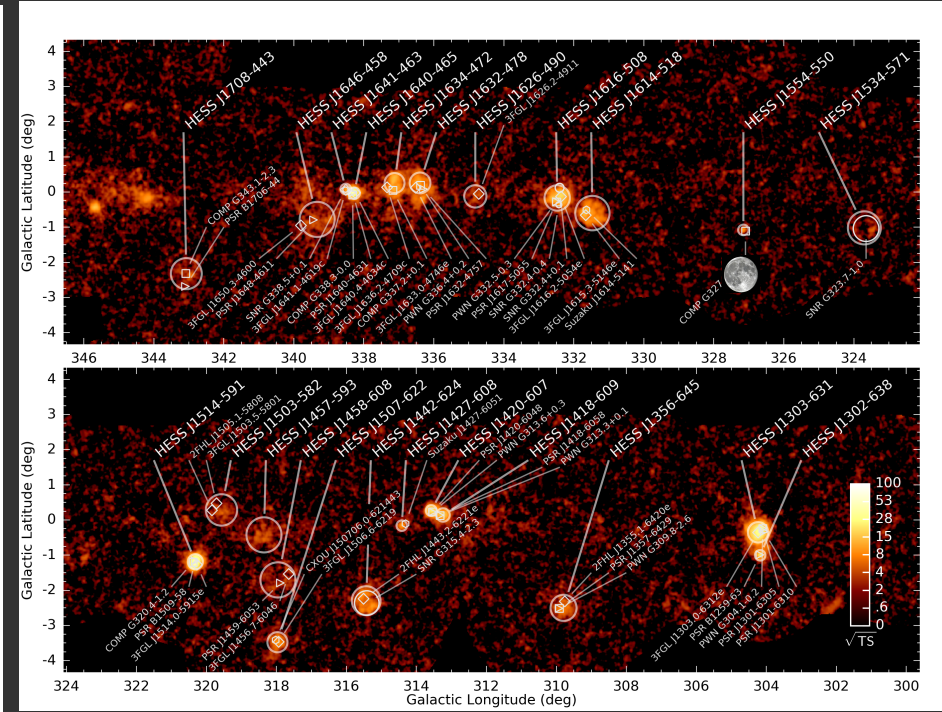
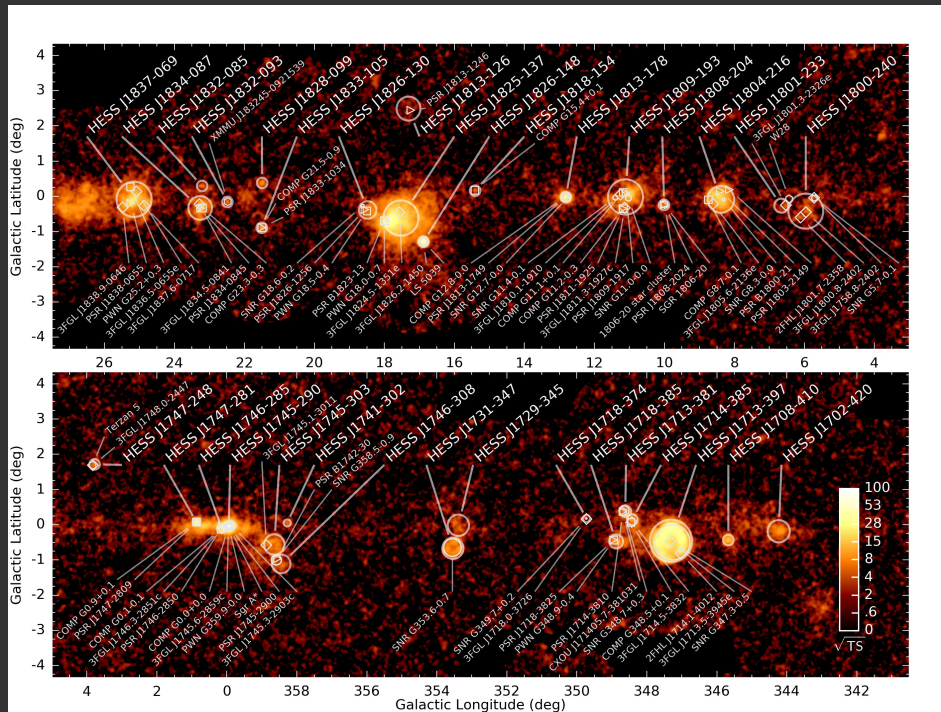
- **Gamma rays: Highly effective tracer of particle acceleration**
- **Many gamma-ray source types + astro/particle physics impact**
  - *Supernova remnants*
  - *Pulsars*
  - *Pulsar-wind nebulae & their halos*
  - *Compact binaries, stellar black holes*
  - *Gamma-ray bursts (hypernovae & compact mergers)*
  - *Novae*
  - *Galactic centre region*
  - *Massive stellar clusters*
  - *PeVatrons → our galaxy's extreme accelerators*
  - *Relativistic outflows; stellar winds; colliding wind interactions*
  - *ISM molecular & atomic gas; ISM magnetic fields*
  - *Unidentified & Dark TeV sources*
  - *Active Galaxy Cores; super-massive black holes*
  - *Star-burst galaxies*
  - *Globular clusters (millisecond pulsars and/or X-ray binaries?)*
  - *Extragalactic IR background constraints → cosmology*
  - *Indirect dark matter search, quantum gravity, axions, beyond SM physics*
  - *Cosmic ray electrons*

# The H.E.S.S. Galactic Plane Survey (2018)

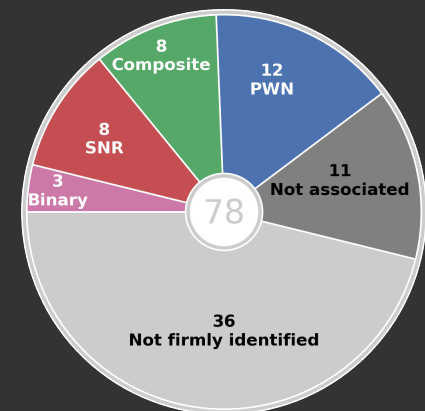
## HGPS - The Southern Milky Way in TeV Gamma-Rays



→ Major legacy survey (HESS A&A 2018)



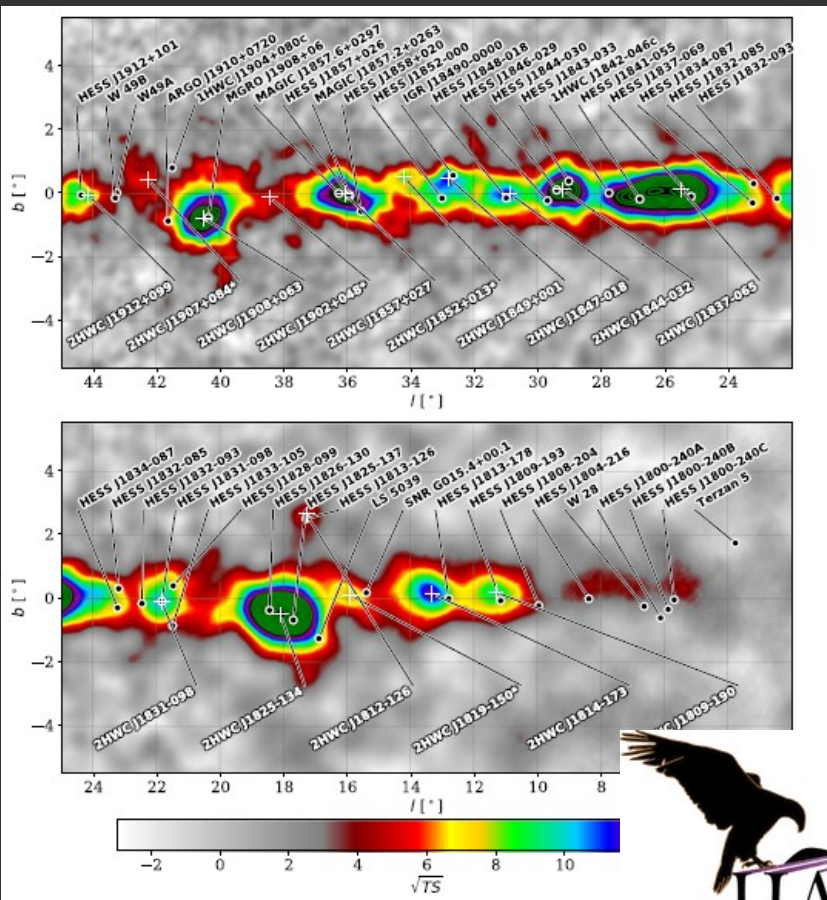
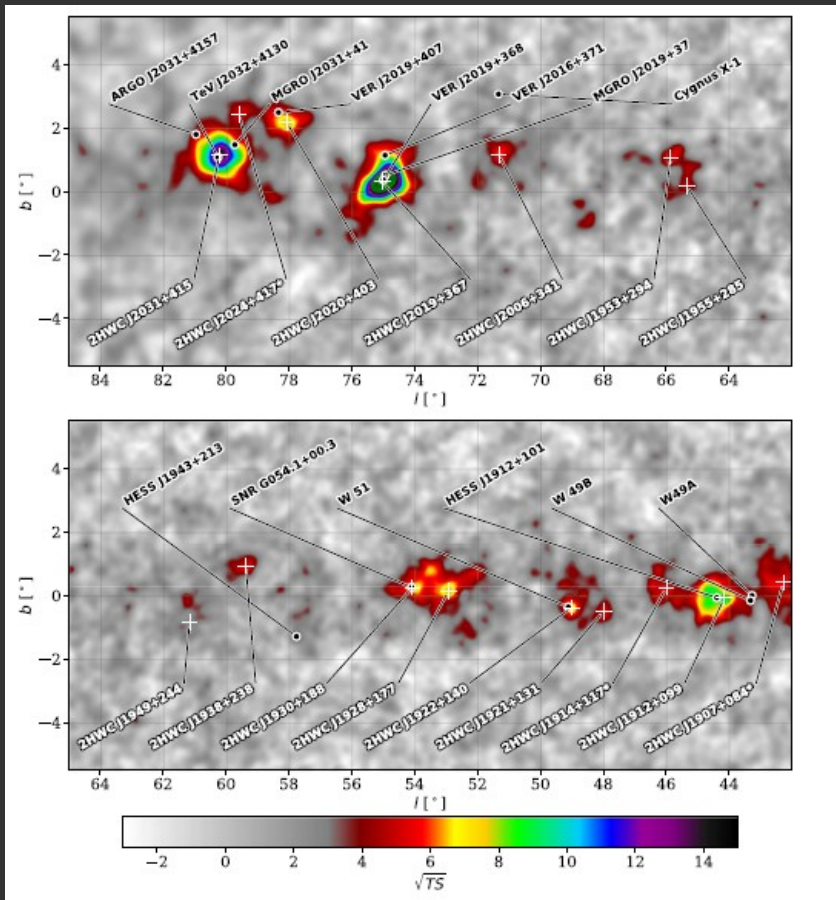
- Over 70 sources of Galactic TeV gamma-rays (>50% unidentified)
  - Model with discrete sources + diffuse emission (ad hoc)
  - Log N vs. log S studies for the first time
  - Three new TeV shells → gamma-ray bright supernova remnants?
  - TeV source assoc. massive stellar cluster/LBV star/magnetar
  - PeVatrons
- Data download <https://www.mpi-hd.mpg.de/hfm/HESS/hgps/>



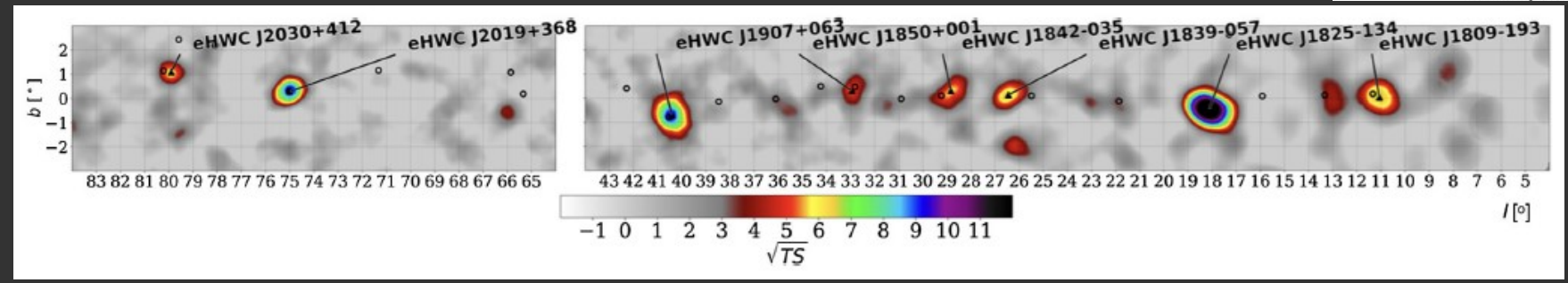
# HAWC Galactic Plane Survey (2HWC)

Abeyssekara et al. (HAWC) 2017, 2020

→ 39 sources (17 new sources)



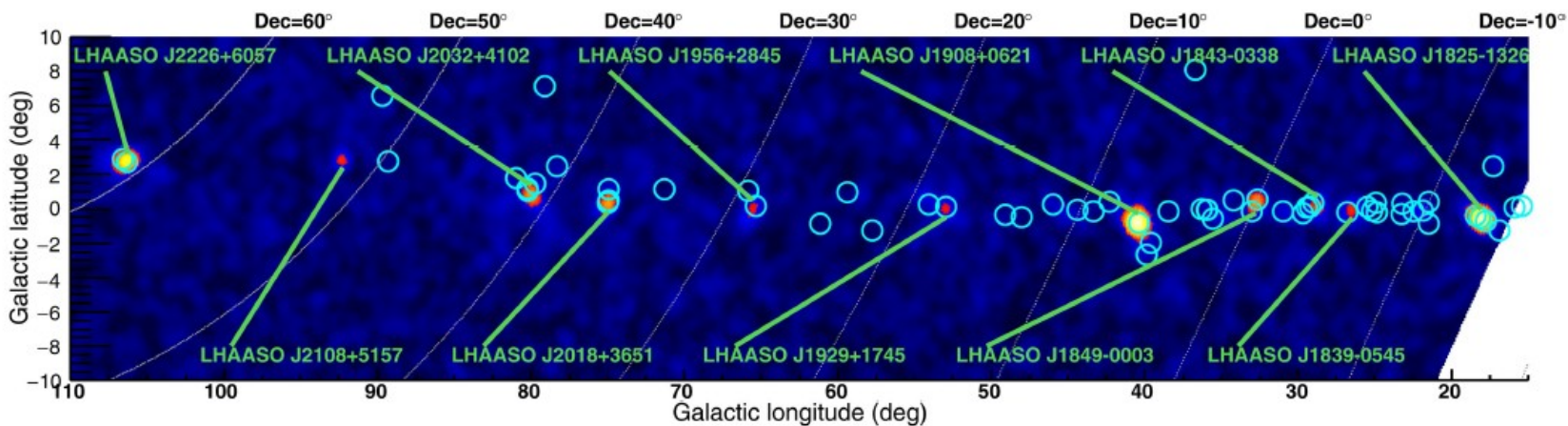
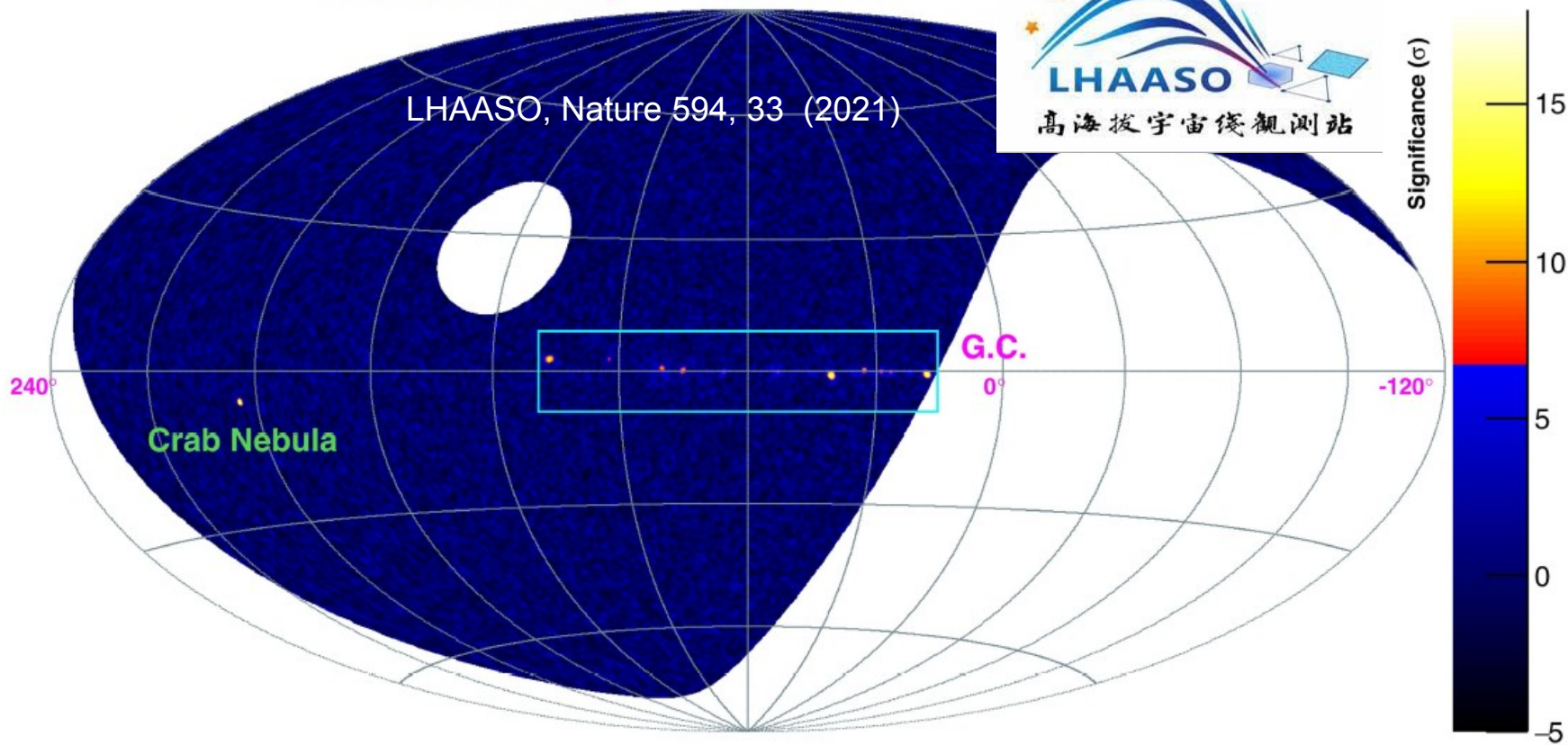
Sources >56 TeV → PeVatrons



# LHAASO Sky @ >100 TeV



LHAASO, Nature 594, 33 (2021)



Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy  $\gamma$ -ray sources.

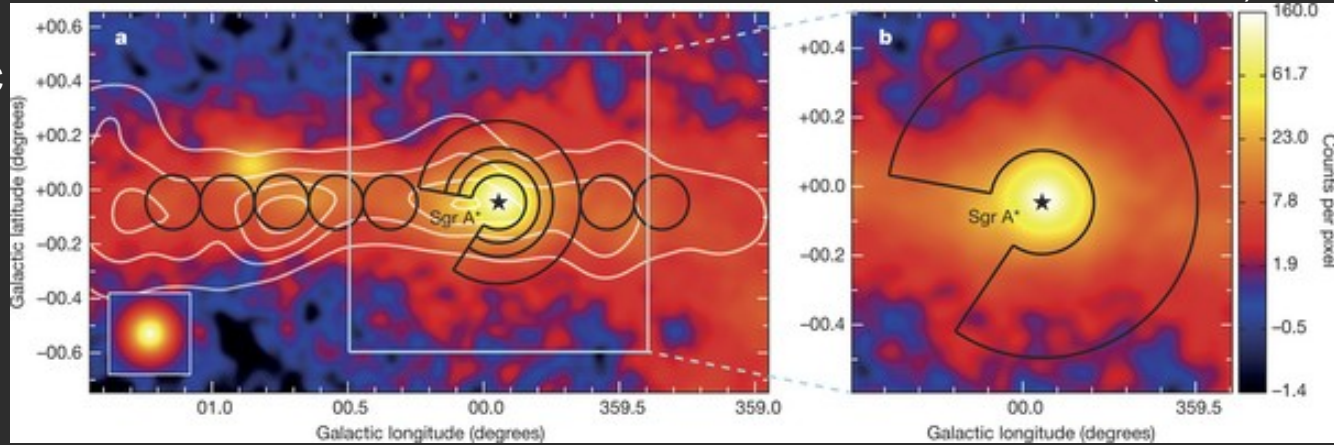
# PeVatrons: Particle acceleration to >PeV energies

- Inferred from hard gamma-ray spectra above ~50 TeV  $E_{\text{gamma}} \sim 10 E_{\text{particle}}$

HESS, Nature 531, 476 (2016)

## Galactic Centre Region

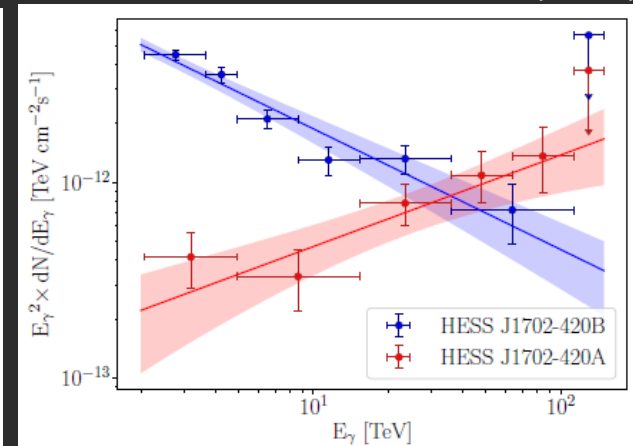
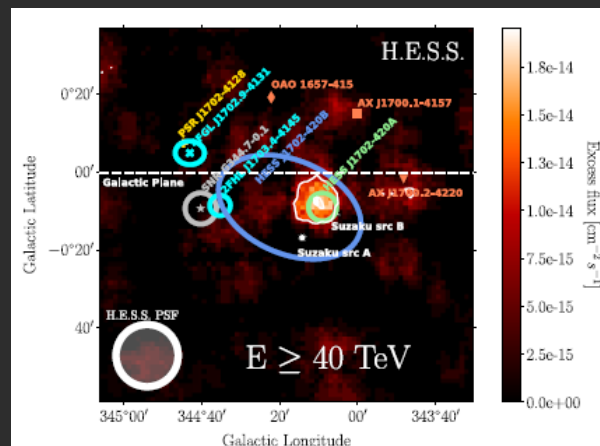
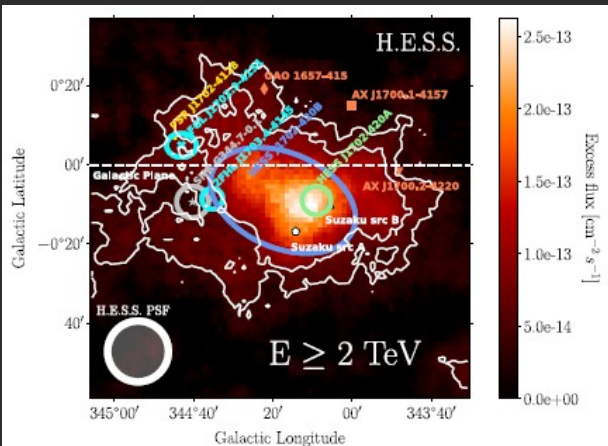
- Diffuse emission to 70pc
- Continuous CR injector over ~few1000yr
- Central BH most likely accelerator



## HESS J1702-420

- Resolved into two components A & B. Gamma rays from A > 100 TeV
- CR protons up to ~0.5 PeV, but leptonic scenario not ruled out.

HESS, A&A 653, A152 (2021)



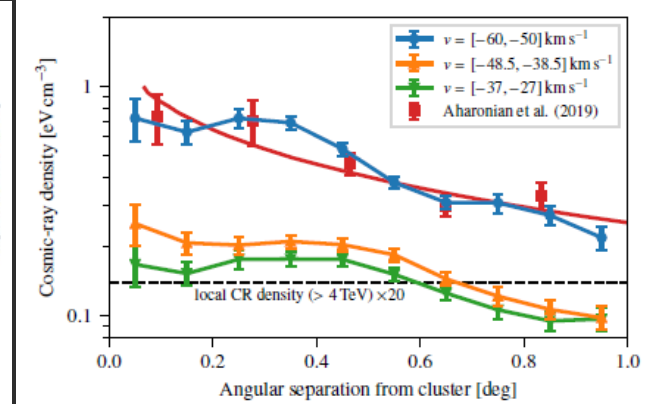
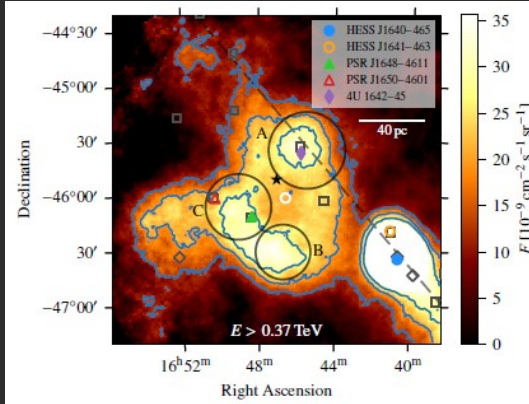
# PeVatrons: Particle acceleration to >PeV energies

- Inferred from hard gamma-ray spectra above  $\sim 50$  TeV  $E_{\text{gamma}} \sim 10 E_{\text{particle}}$

HESS, A&A 666, A124 (2022)

## Westerlund1 stellar cluster

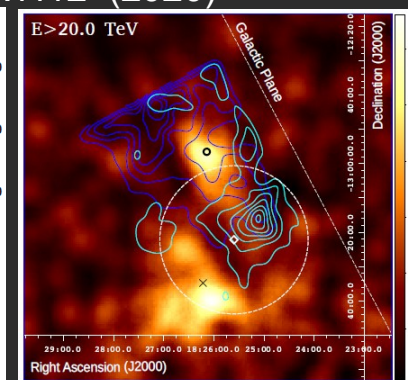
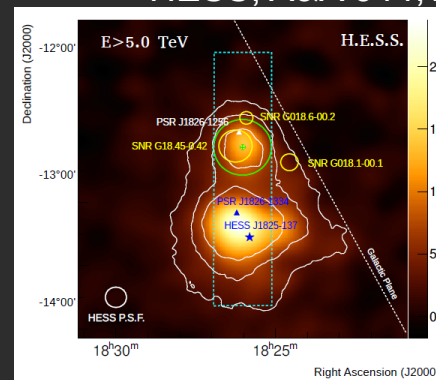
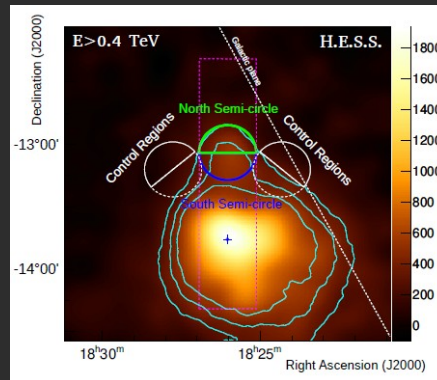
- >20 WR stars;  $L \sim 10^{39}$  erg/s
- TeV emission 2 deg diam.
- TeV spectrum >50 TeV
- Deeper HESS obs reveal no spectral change with location.
- Shell-like structure centred on Cluster. TeV+ISM comparison compatible with continuous CR injector.



HESS, A&A 644, A1112 (2020)

## HESS J1826-130

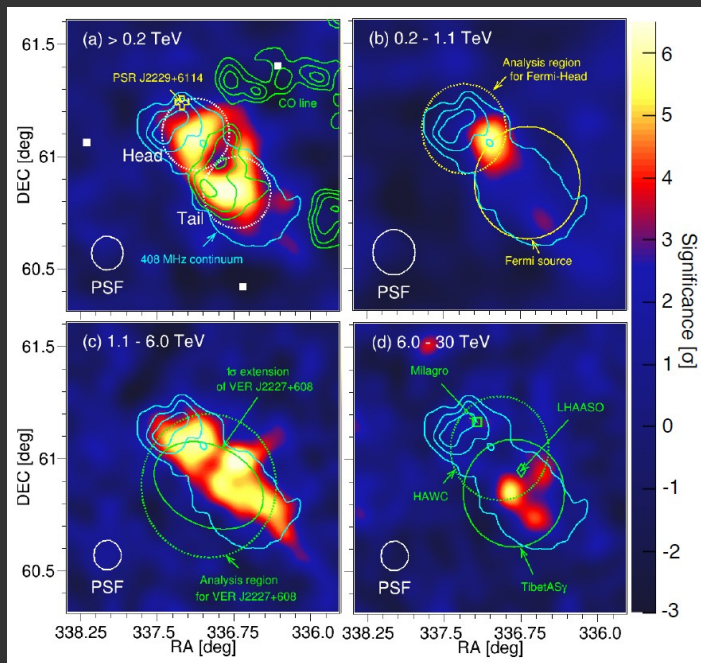
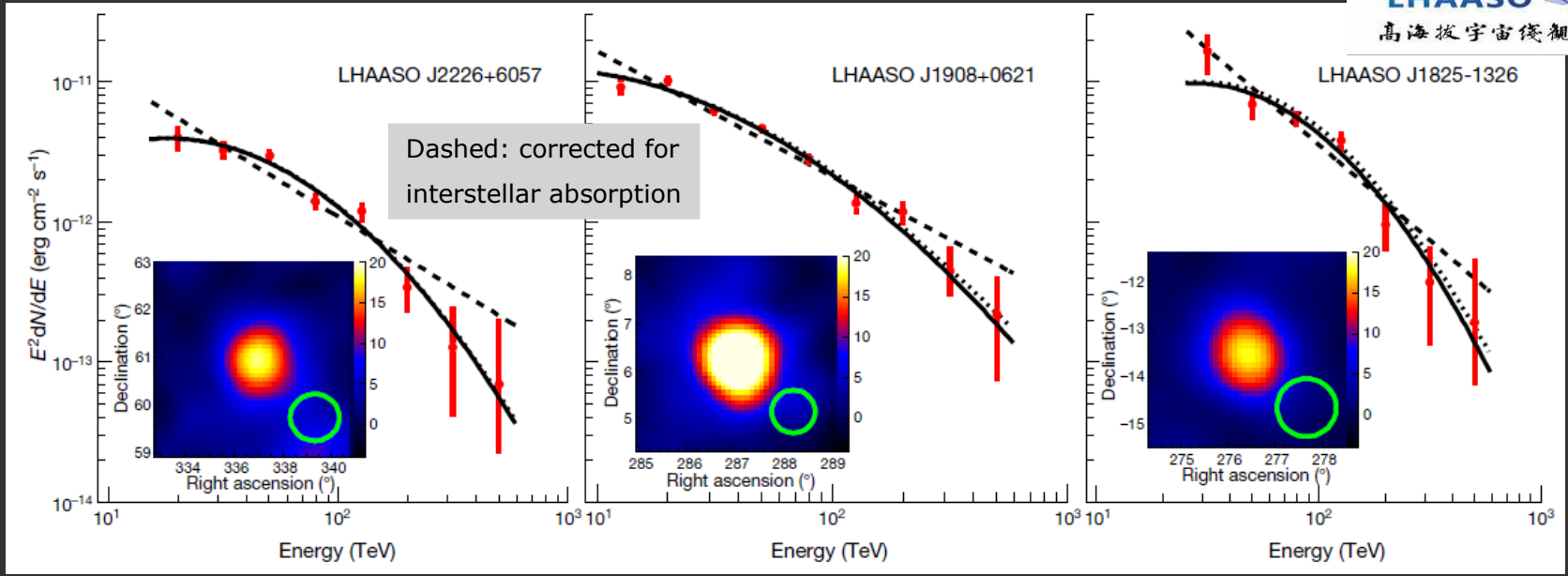
- Adjacent to TeV PWN HESSJ1825
- TeV flux to  $\sim 50$  TeV
- Overlaps dense ISM
- CRs escaping J1825 or PSR J1826-1256



## Some other examples

HESS J1809-193, HESS J1831-098, and HAWC, LHAASO discoveries >1 PeV

# LHAASO Gamma-Ray Spectra → 1 PeV



**Table 1 | UHE  $\gamma$ -ray sources**

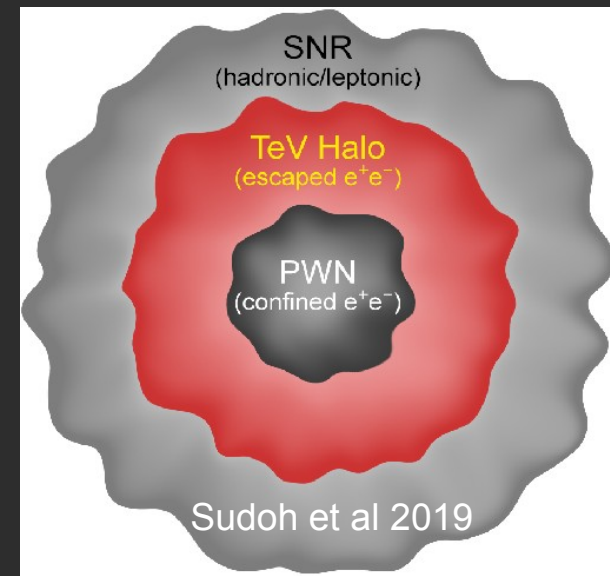
Source name	RA (°)	dec. (°)	Significance above 100 TeV ( $\times\sigma$ )	$E_{\max}$ (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55 ± 22.05	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	-13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	-5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	-3.65	8.5	0.26 - 0.10 <sup>+0.16</sup>	0.73(0.17)
LHAASO J1849-0003	282.35	-0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	0.71 - 0.07 <sup>+0.16</sup>	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimated as the boundary values of the area that contains  $\pm 34.14\%$  of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the error is 1 $\sigma$ .

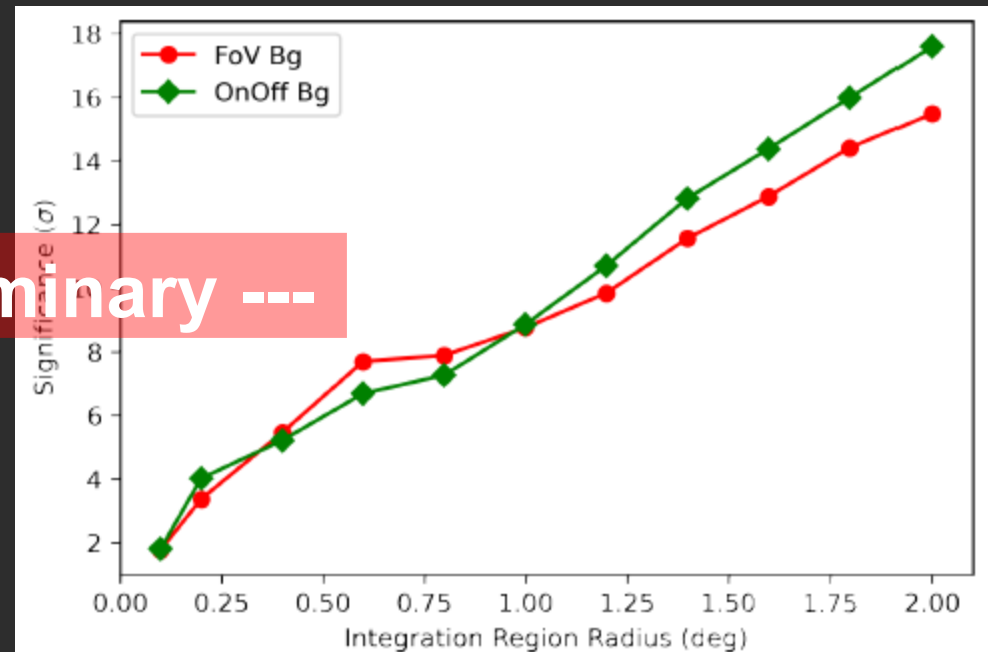
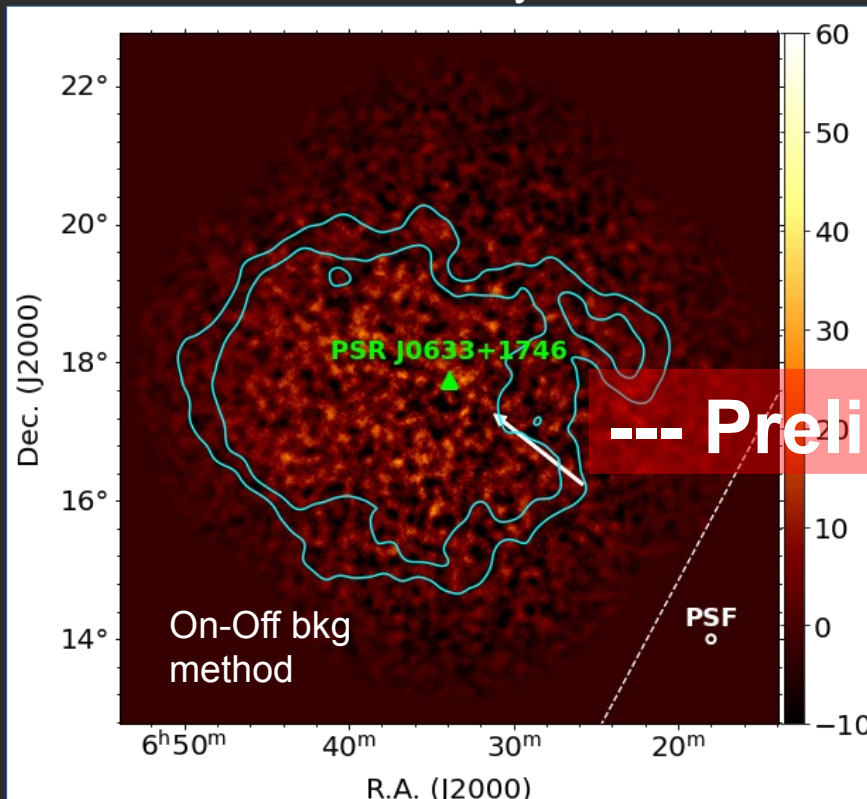
**LHAASO J2226+6057 assoc. with SNR G106.3+2.7**  
MAGIC, A&A in press 2022 arXiv:2211.1532

# Pulsar Wind Nebula Halos e.g. Geminga

- Old ( $\tau_c = 342\text{kyr}$ ) nearby pulsar (250 pc).
- HAWC: Extended TeV emission around PWN  
Abeysekara et al 2017
- Also seen by HESS but a challenge for its FoV.  
HESS ICRC2021
- Largest HESS TeV source (5deg diam;  $\sim 20\text{pc}$ )
- Requires slow diffusive transport of electrons, 100x lower the Galactic expectation (as per HAWC conclusion).
- PWN TeV halos may be considerable sources of PeV particles.



e.g. Martin et al 2022



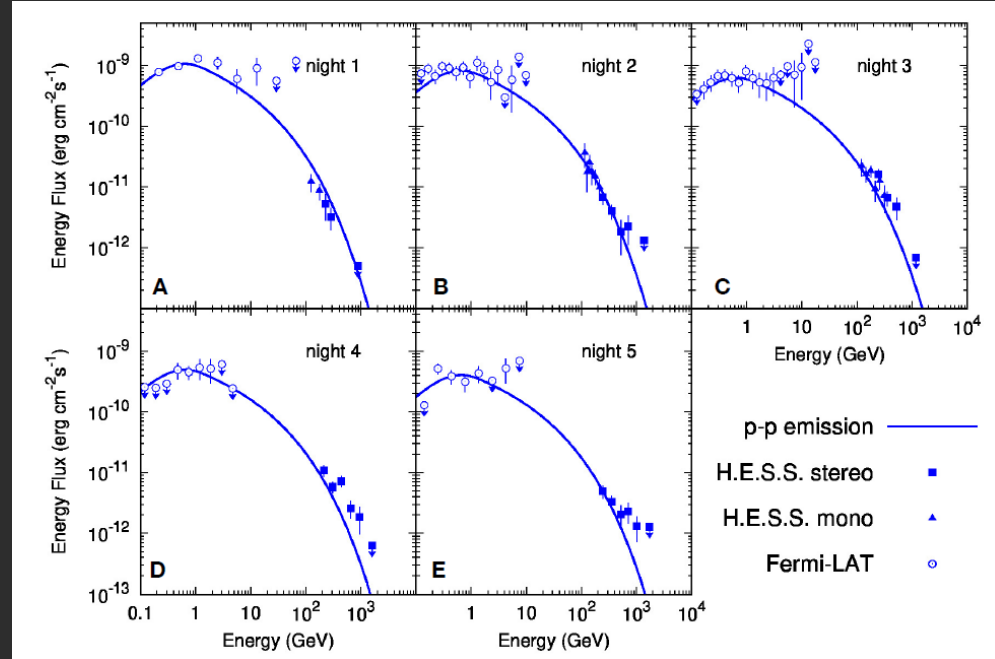
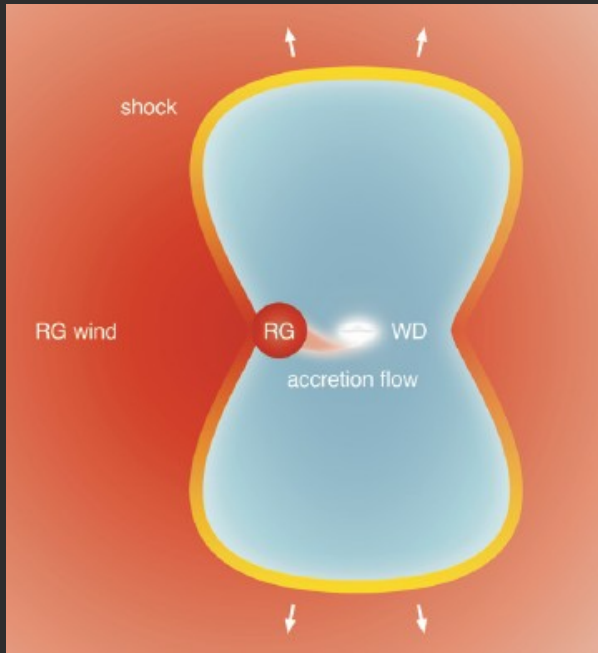
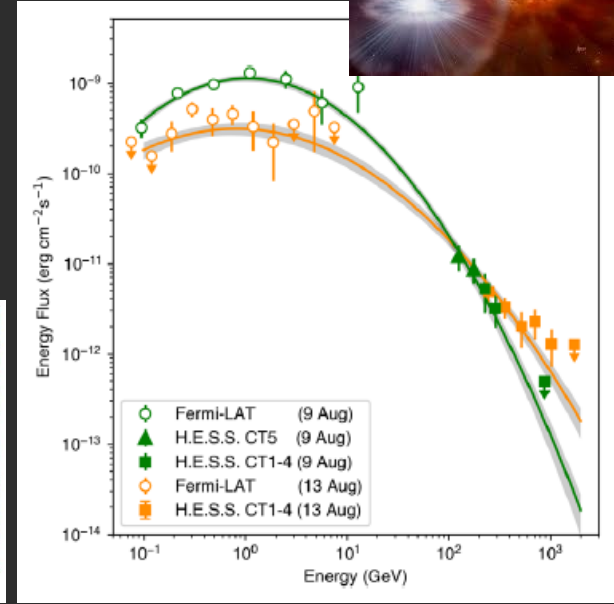
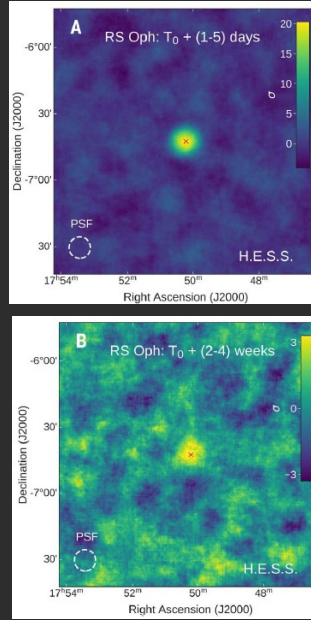


# RS-Oph Recurrent Nova – First Galactic TeV Transient

HESS, Science 376, 6588 (2022)

MAGIC, Nature Astron 6, 689 (2022)

- WD and massive companion RG star
- Flaring via thermonuclear detonation and particle acceleration.
- GeV emission from Fermi-LAT
- HESS obs. of 2021 outburst triggered by optical flare (prev. outburst ~9-26 yrs)
- >6sigma/day in first 5 nights with HESS (also seen by MAGIC Acciari et al 2022)
- Hadronic model preferred.



# PKS1510-089 FSRQ $z=0.361$

HESS, MAGIC, A&A 648, A25 (2021)

## TeV & optical intra-day variation (May 2016)

HESS+MAGIC+Fermi-LAT (gamma)

ATOM (optical R-band)

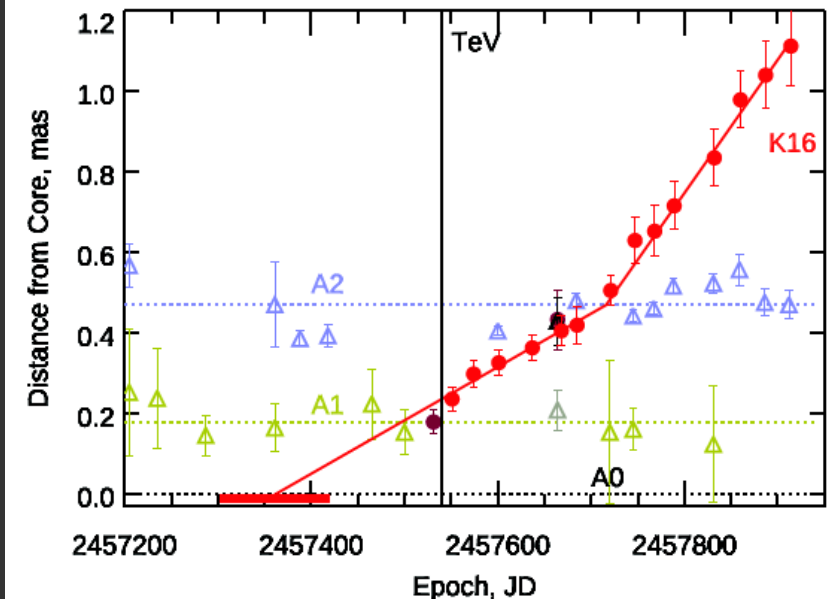
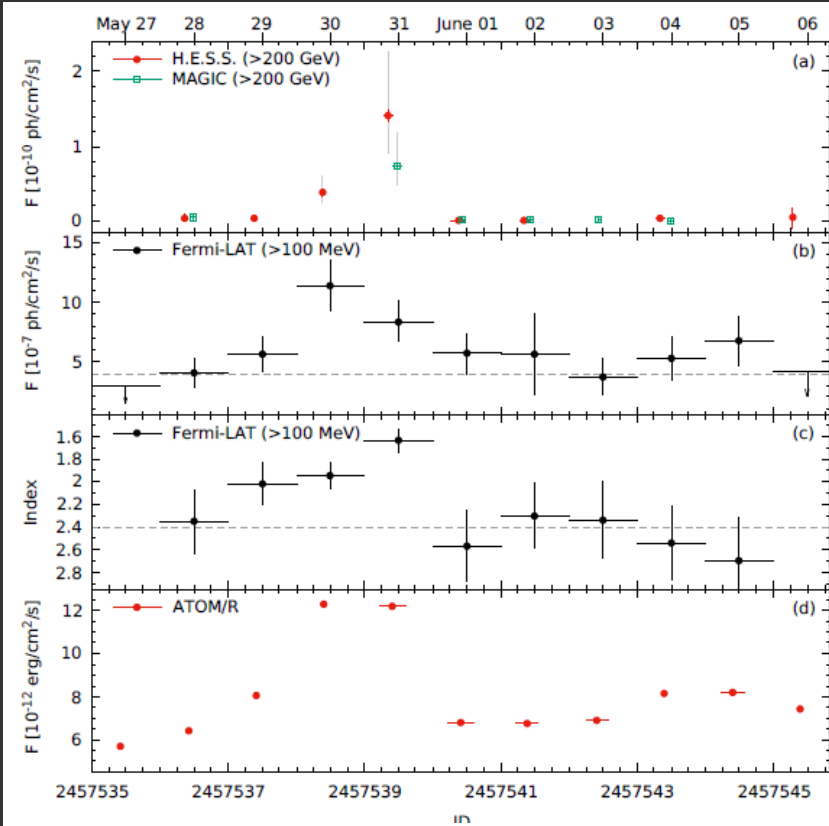
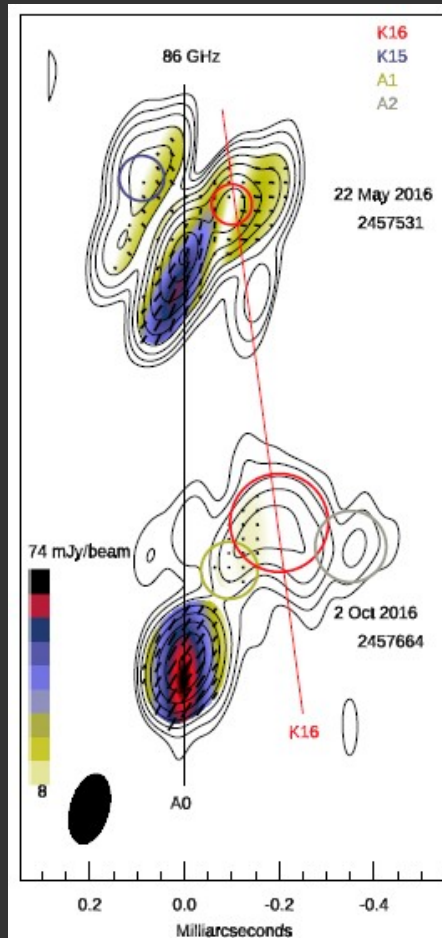
VLBA + GMVA (radio 43 & 83 GHz)

- Rapid cessation of TeV and optical flaring on sub-day timescale

- GeV+TeV spectral curvature  $\rightarrow$  absorption from EBL, not BLR.

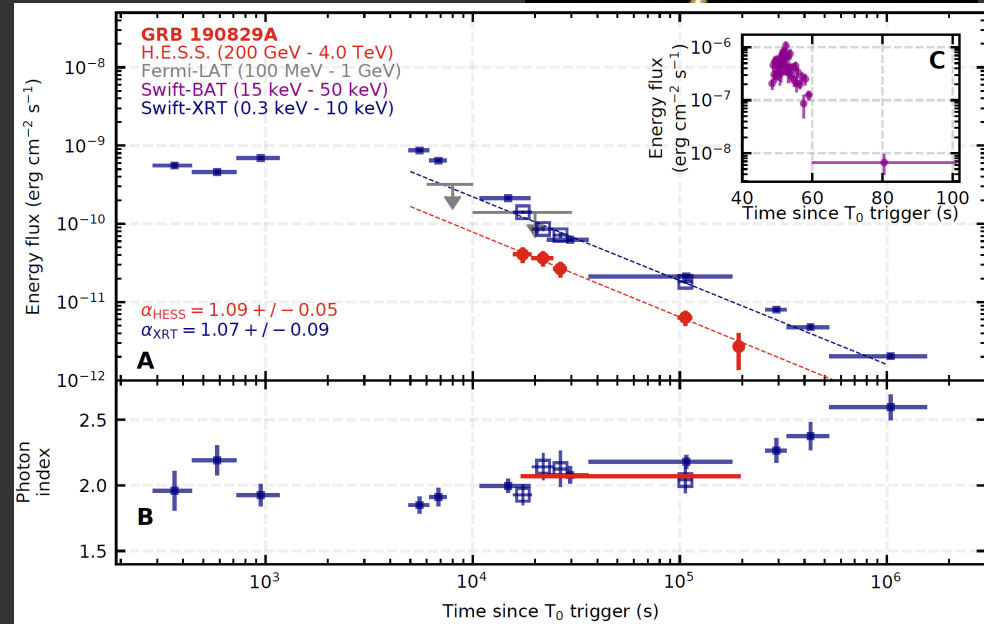
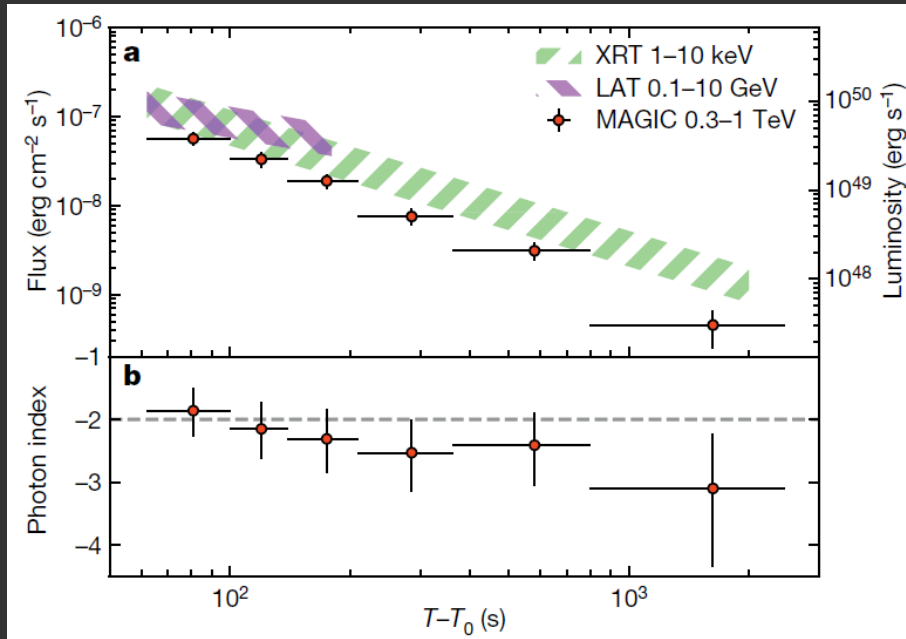
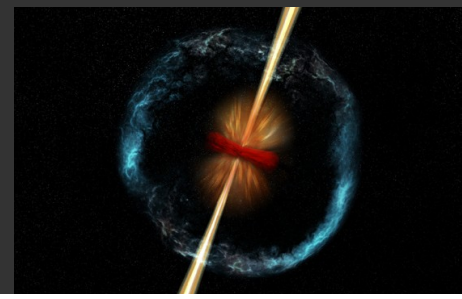
- Gamma emission  $>2.6R_{\text{BLR}}$  from BH

- Flare associated with rapidly moving radio knot K16?



# TeV Gamma Ray Bursts : A New Era Begins

(MAGIC 2019, 2021, HESS 2019, 2021)



- Three Long GRBs GRB180720B, GRB190114C, GRB1900829A

z=0.653 0.424 0.079

- One Short GRB GRB160821B (z=0.162) marginal!

- GRB190114C seen at >300 GeV at low elevation during moonlight!

- GRB1900829A seen T+2 days

> 1000's photons > 50 GeV → gamma-ray spectra on hourly timescales

- Rapid radio follow-up in place (HESS+ATCA; e.g. Anderson et al 2022 submitted)

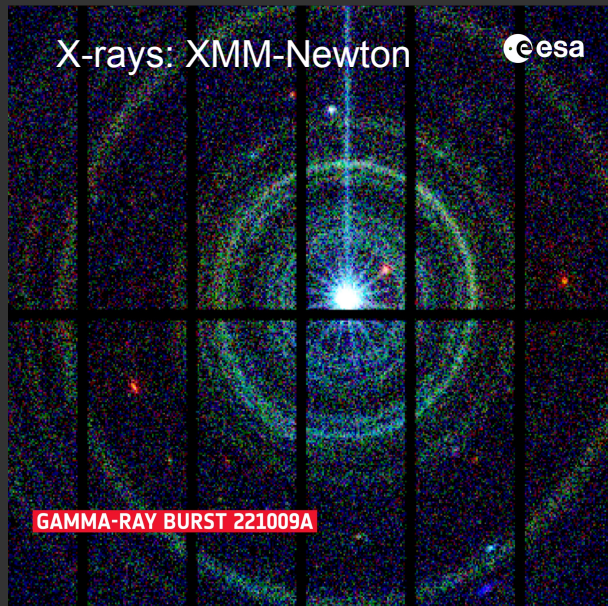
# TeV Gamma Ray Bursts: The Extraordinary GRB221009A

- Originally classified as X-ray + optical transient Swift J1913.1+1946
- Later confirmed as a GRB with Fermi GBM + LAT detections up to 99 GeV

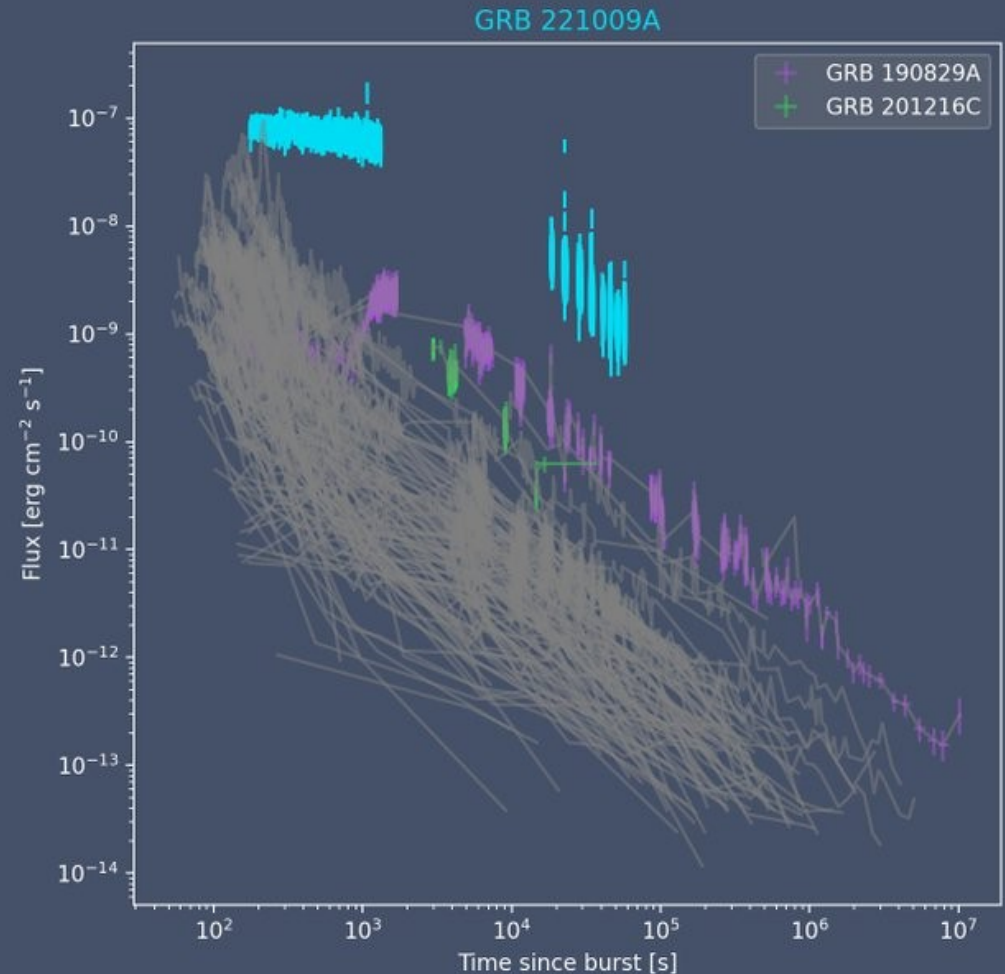
- Seen by >10 facilities ( $z=0.151$ )  
→ One of brightest ever GRBs

- LHASSO detection GCN32677  
 $E > 500 \text{ GeV} > 100\sigma$   
 $E_{\text{max}} = 18 \text{ TeV}$

→ Axions or Neutrino origin?  
(7 arXiv papers)

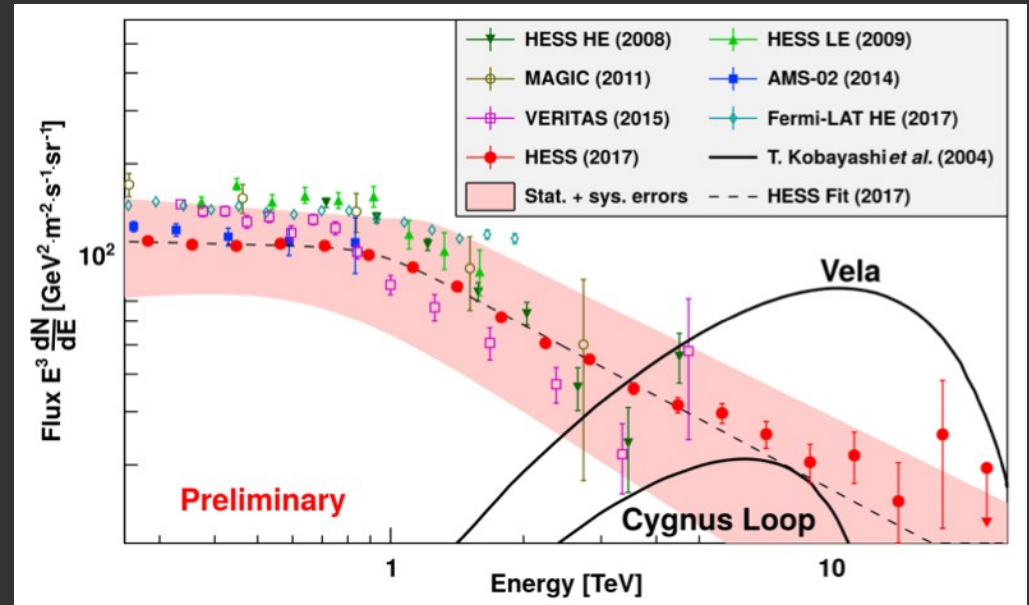
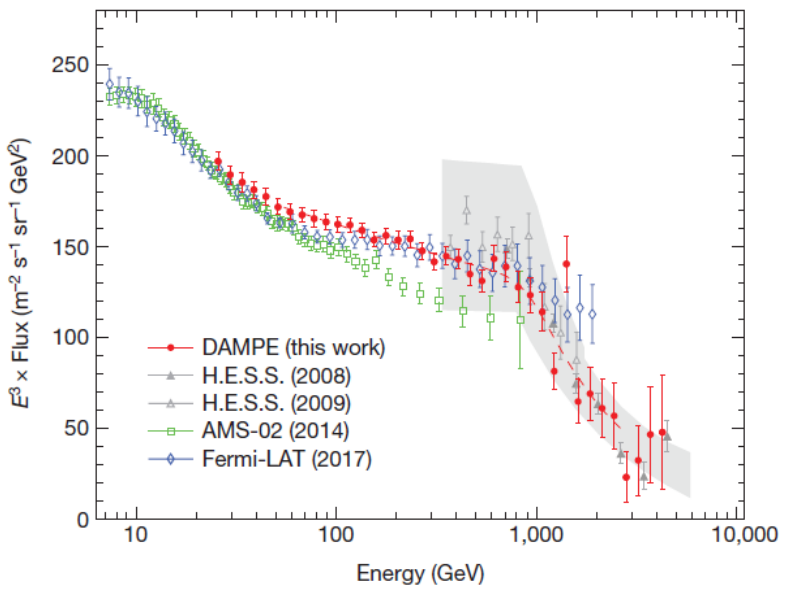
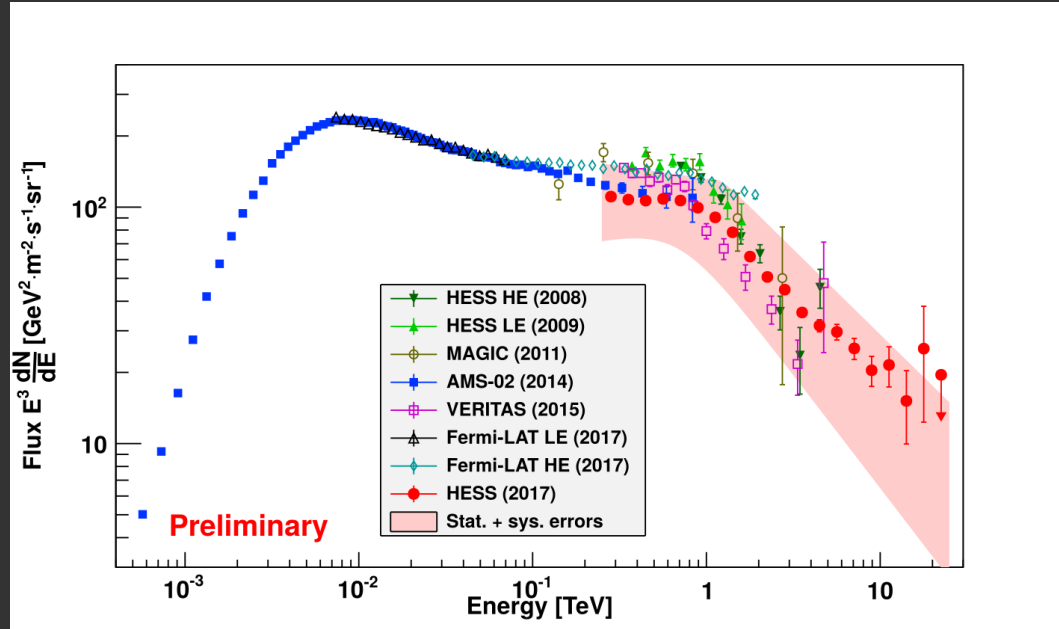


<https://twitter.com/astrocolibri/status/1579478412678561792>



# Electron Spectrum as seen by HESS

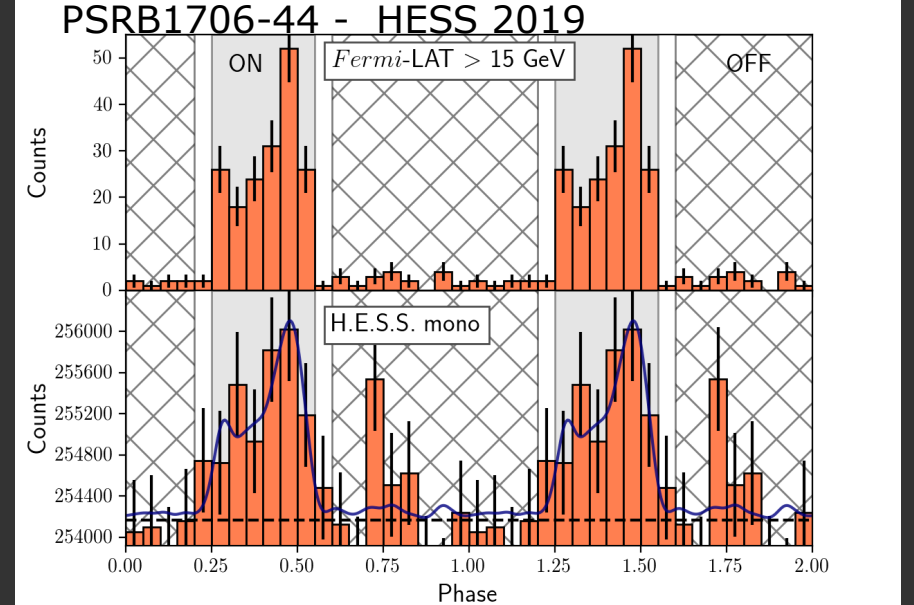
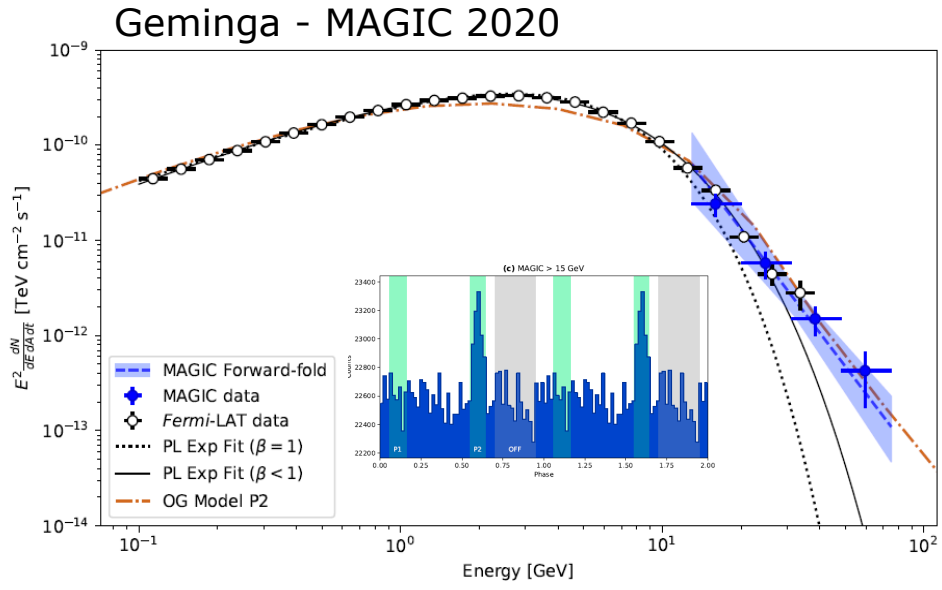
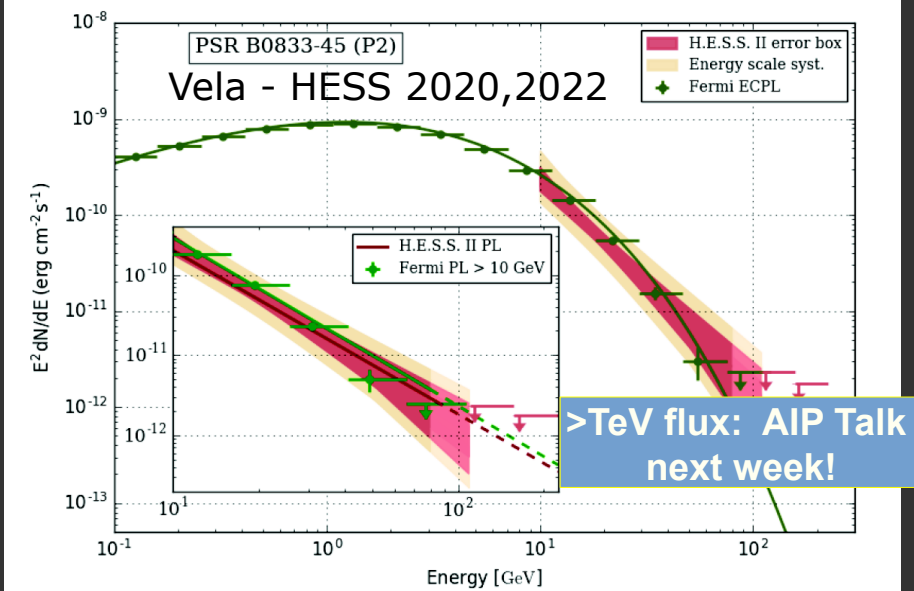
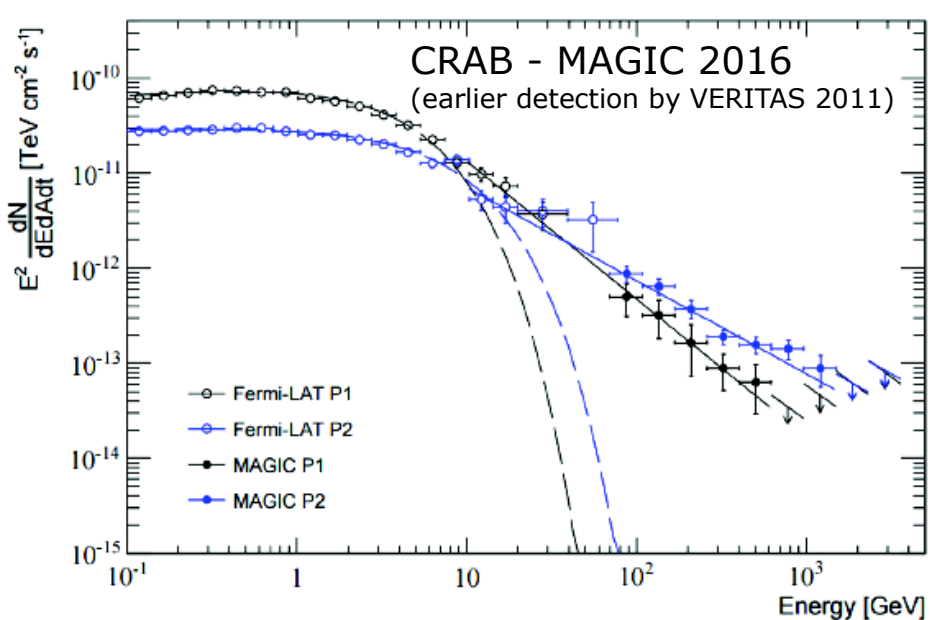
- HESS pushes electron spectrum up to ~20 TeV HESS (2017)
- Spectral break at ~1 TeV
- Spectral break also reveal by DAMPE (2017)
- Electron spectrum >1 TeV constrains local accelerators



# Now Four Pulsars Detected with Ground-Based Gamma-Ray Telescopes

– Crab, Vela, PSR B1706-44, Geminga (brightest pulsars in Fermi-LAT 2PC)

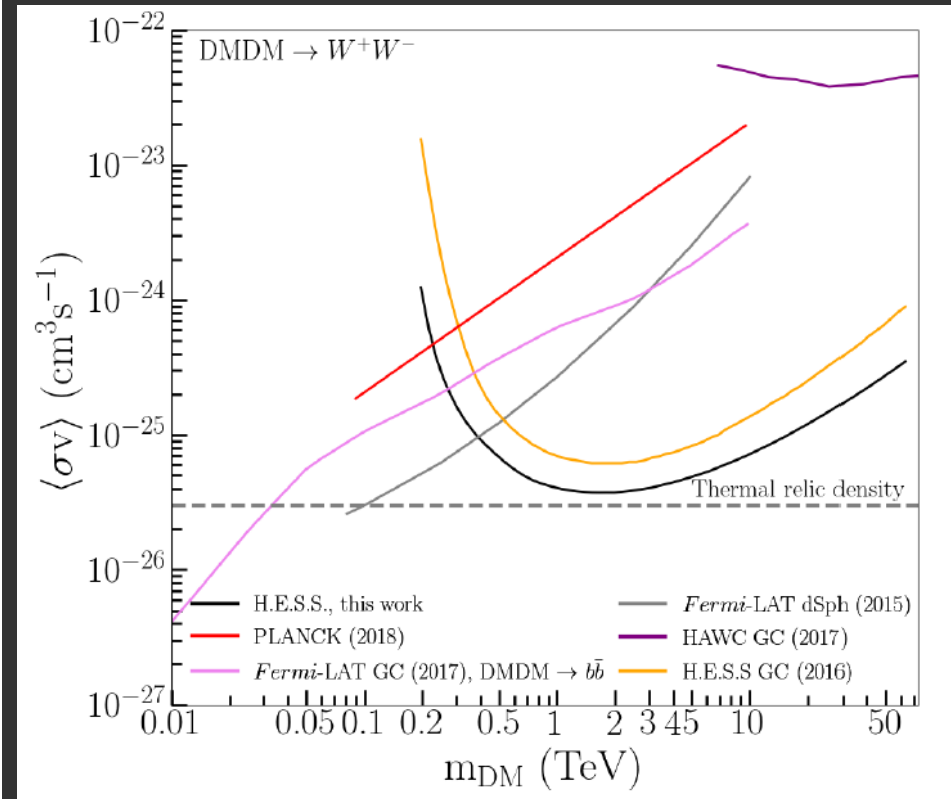
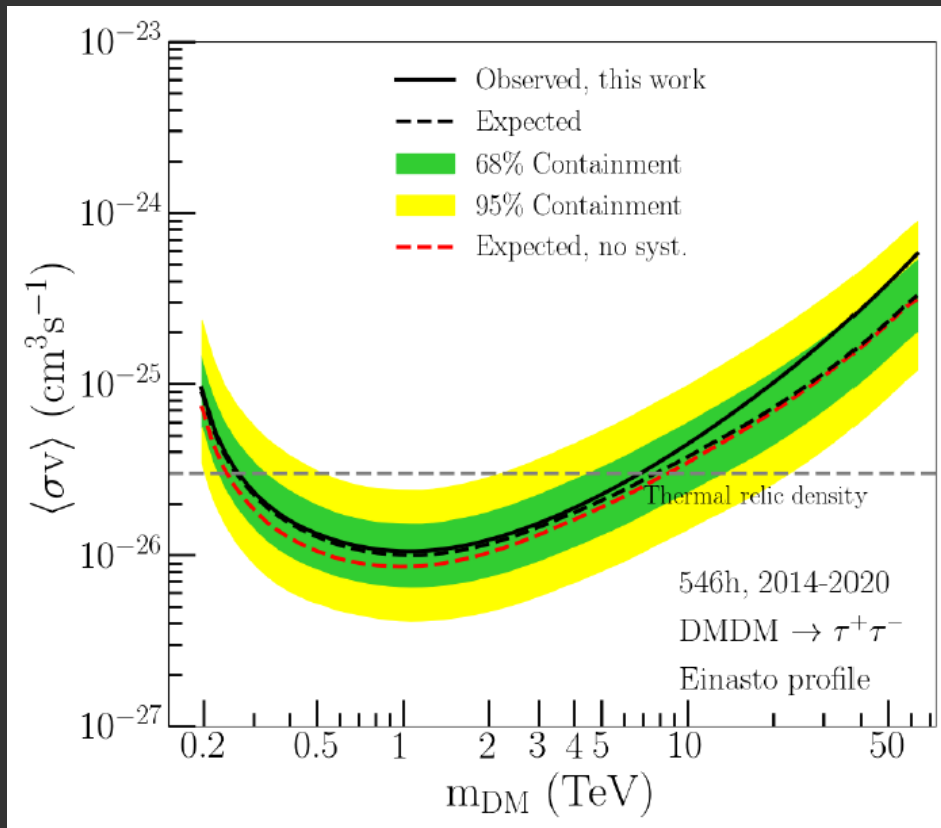
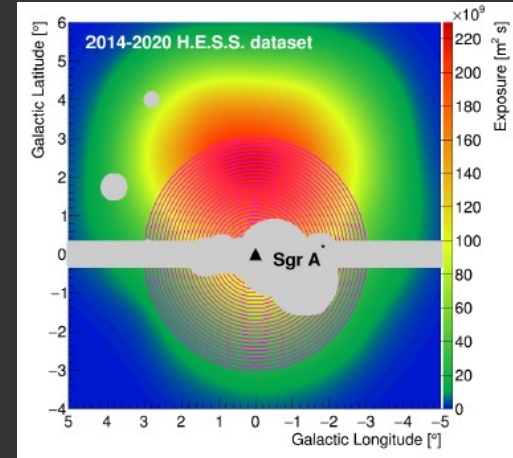
→ New electron components (e.g. inv-Compton) beyond curvature radiation...



# Dark Matter Search – Inner Galaxy Survey

HESS, PRL 129, 111101 (2022)

- 546 hr obs. of inner Galaxy region (2014 - 2020)
- Testing WIMP self-annihilation into quark, lepton, gauge boson and Higgs channels.
- Lowest constraints for  $\tau^+\tau^-$ 
  - below thermal relic density
- All other channel v.close to thermal relic.
- HESS most sensitive constraints  $>0.5$  TeV from gamma





# CTA- The next step in TeV gamma-ray astronomy

- Building on HESS, MAGIC, VERITAS...

~ 0.03 to 100 TeV

~ 330 MEuro for construction (cash+in-kind) **funds available**

## CTA Arrays "alpha" Configuration

- **Northern Array: 4 LSTs + 9 MSTs (La Palma, Spain)**

1<sup>st</sup> telescope in operation!

- **Southern Array: 14 MSTs + 37 SSTs (Paranal, Chile)**

site prep. work underway

- CTA HQ, Bologna

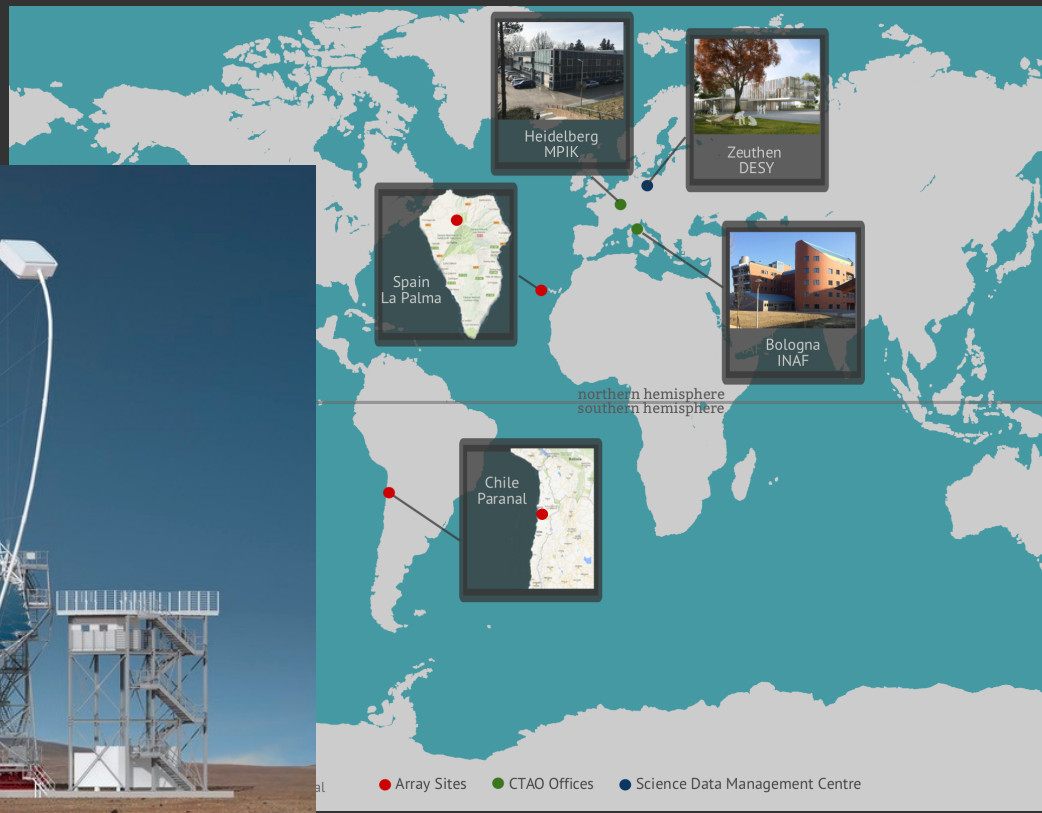
- CTA Data Centre, Berlin

<https://www.cta-observatory.org/>

SST – small sized telescopes

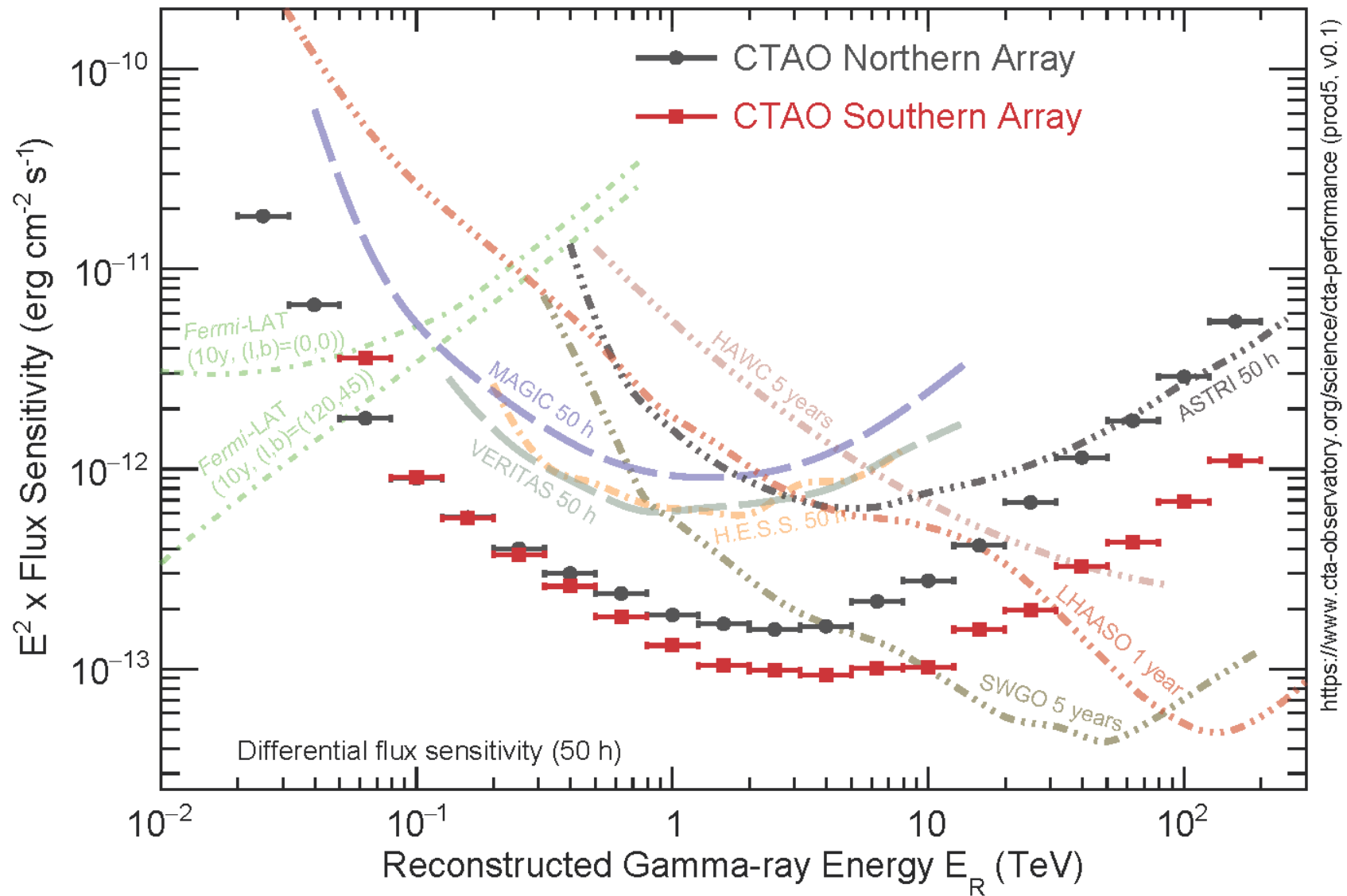
MST – mid-sized

LST – large sized



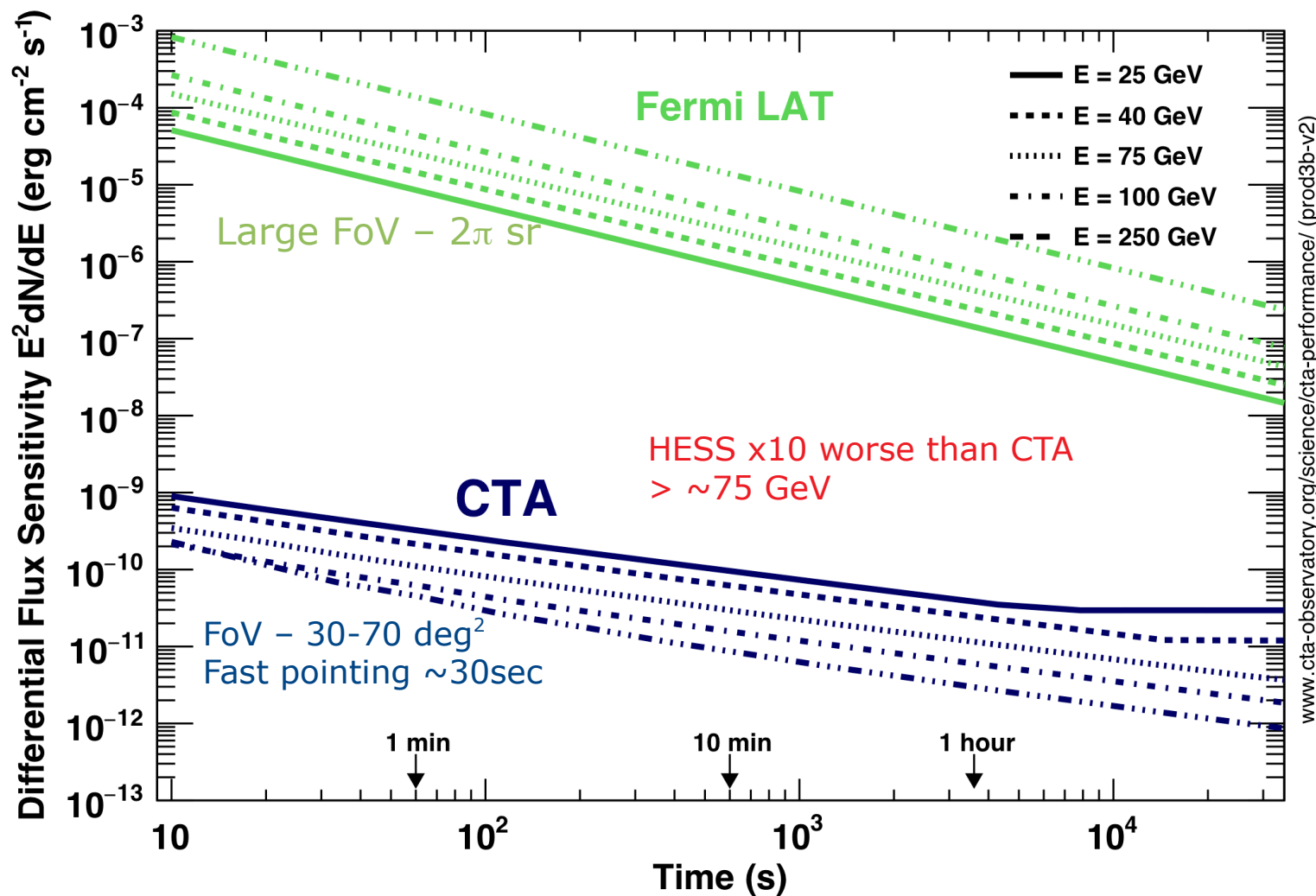


# CTA Flux Sensitivity (50hr) vs. Others



# Transients & Variable Sources: CTA Sensitivity vs. Time

(CTA Collab 2019)

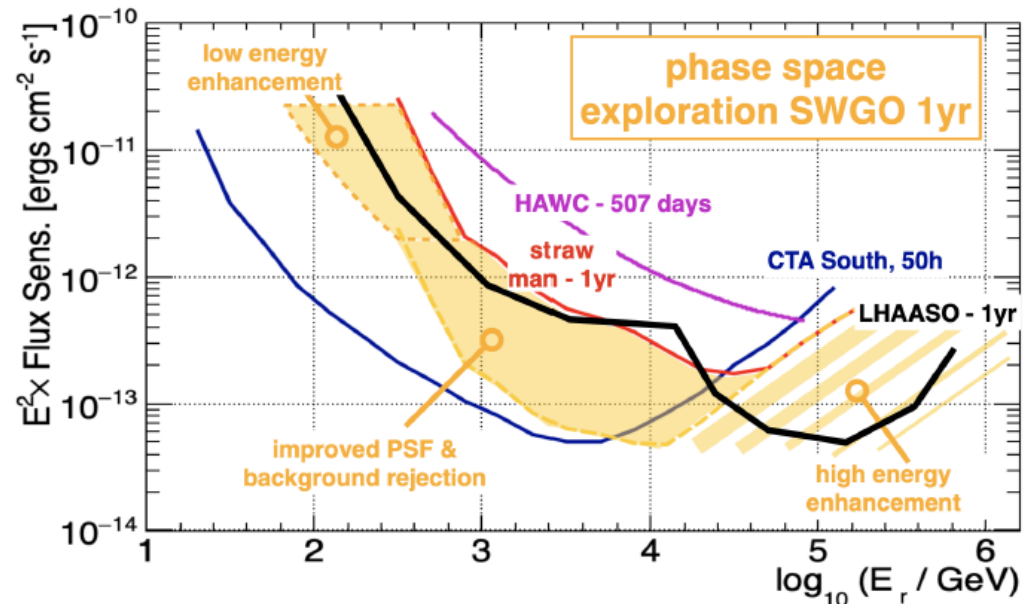
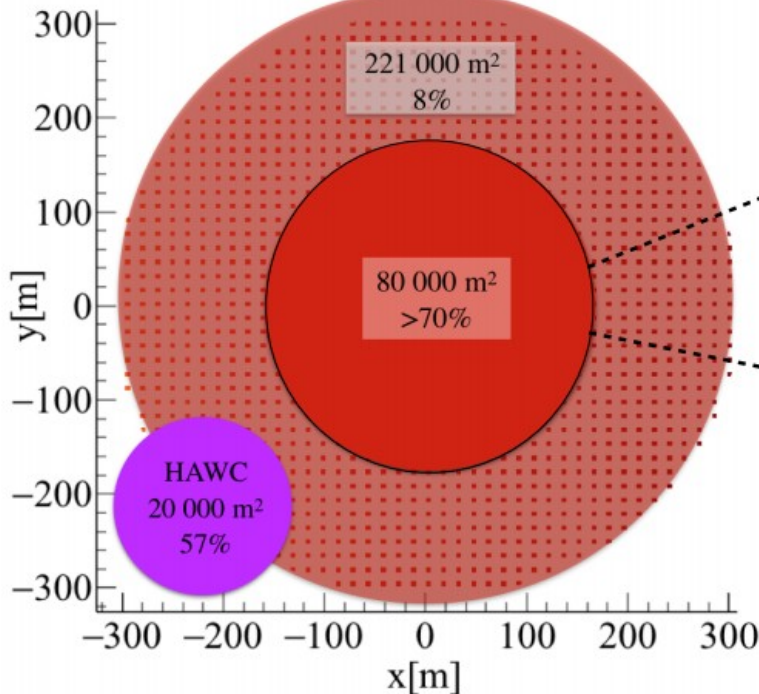


CTA >10,000 times more sensitive than Fermi-LAT in multi-GeV range  
→ GRBs, AGN, giant pulses, FRBs, GW, SGR bursts.....

# SWGGO – Southern Widefield Gamma ray Observatory

- Building on experience from HAWC and LHAASO
- Array of >6000 tanks or array of bags/bladders in a lake?
- Potential sites in Peru, Bolivia, Chile, Argentina (5000m a.s.l.)
- Australian (Adelaide) company identified to supply tanks & bags >A\$30M

https://  
www.swgo.org



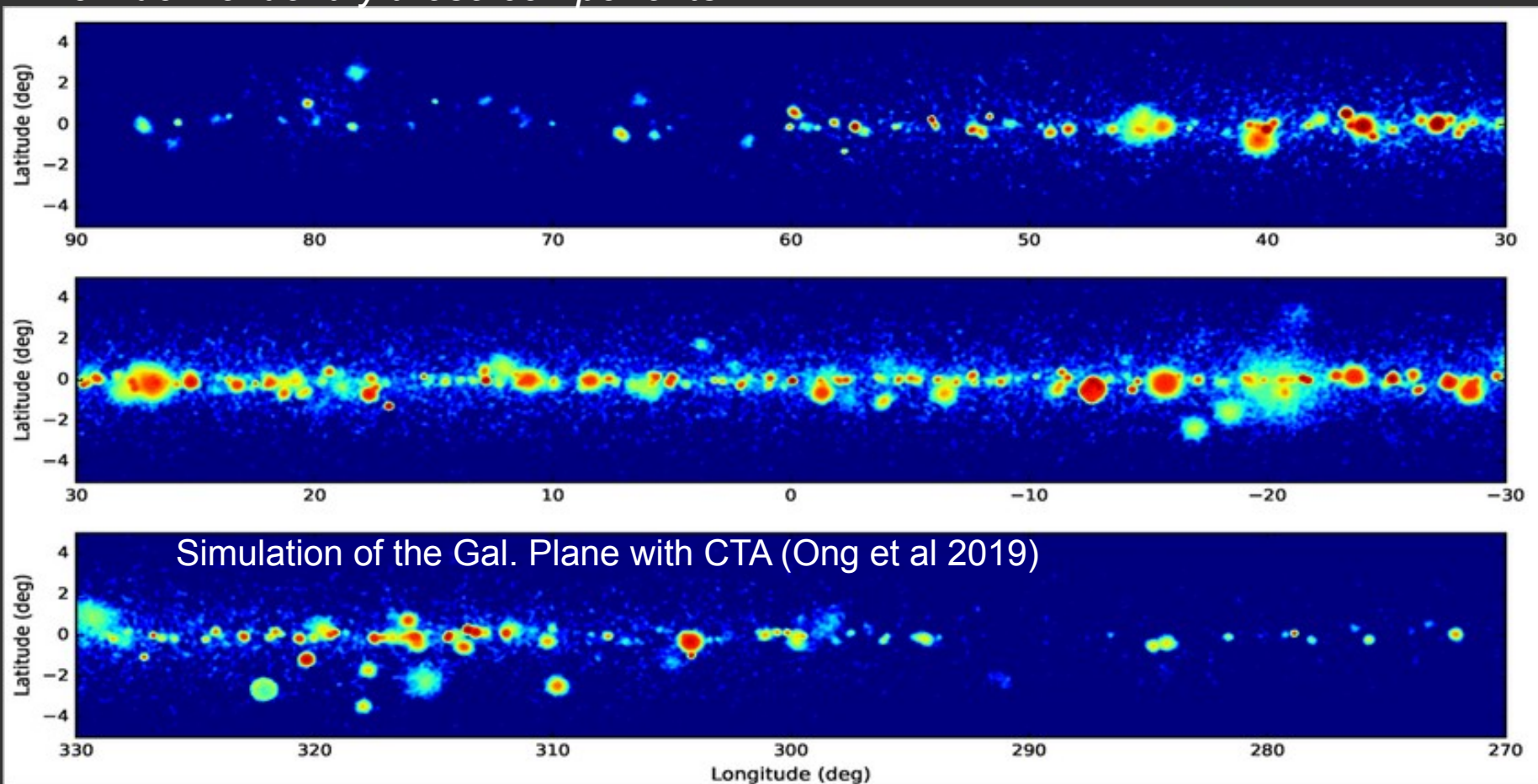
# Galactic Plane: A major astrophysical challenge for CTA

CTA will see a confusing mix of:

- local emission from discrete sources
- local diffuse surrounding discrete sources
- large-scale diffuse emission from particle permeating the Milky Way

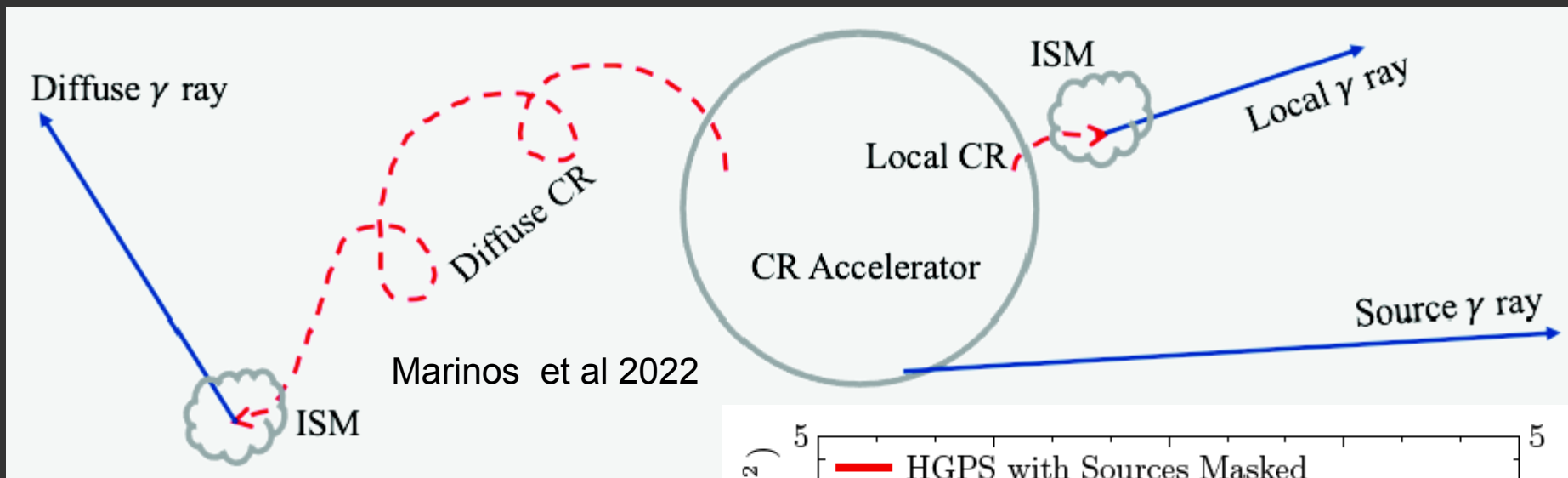
Already hints for TeV & PeV diffuse emission from HESS (2014) and Tibet ASgamma (2021), but maybe from unresolved sources Vecchiotti et al 2022

*How do we identify these components?*



# Galactic Plane: A major astrophysical challenge for CTA

The 'large-scale diffuse' component: Cosmic rays permeating the Milky Way after travelling  $>100$ s pc from their accelerators  $\rightarrow$  interacting with ISM  $\rightarrow$  gamma rays



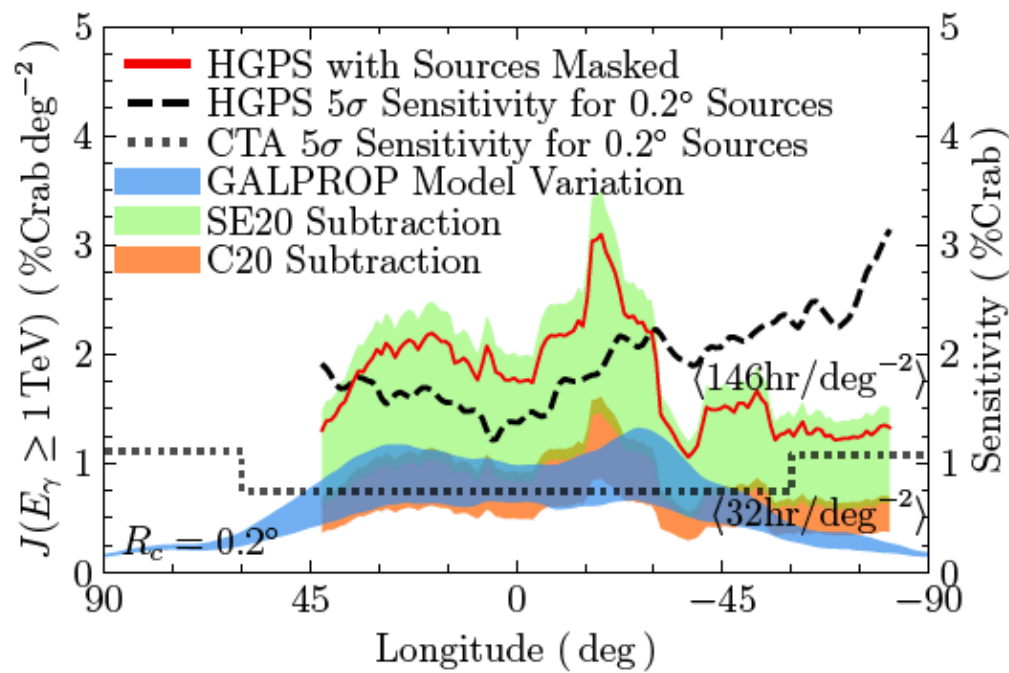
## GALPROP predictions $>1$ TeV

- Subtract discrete sources from HESS Gal. Plane Survey & estimates of unresolved sources.

$\rightarrow$  estimate of TeV diffuse emission

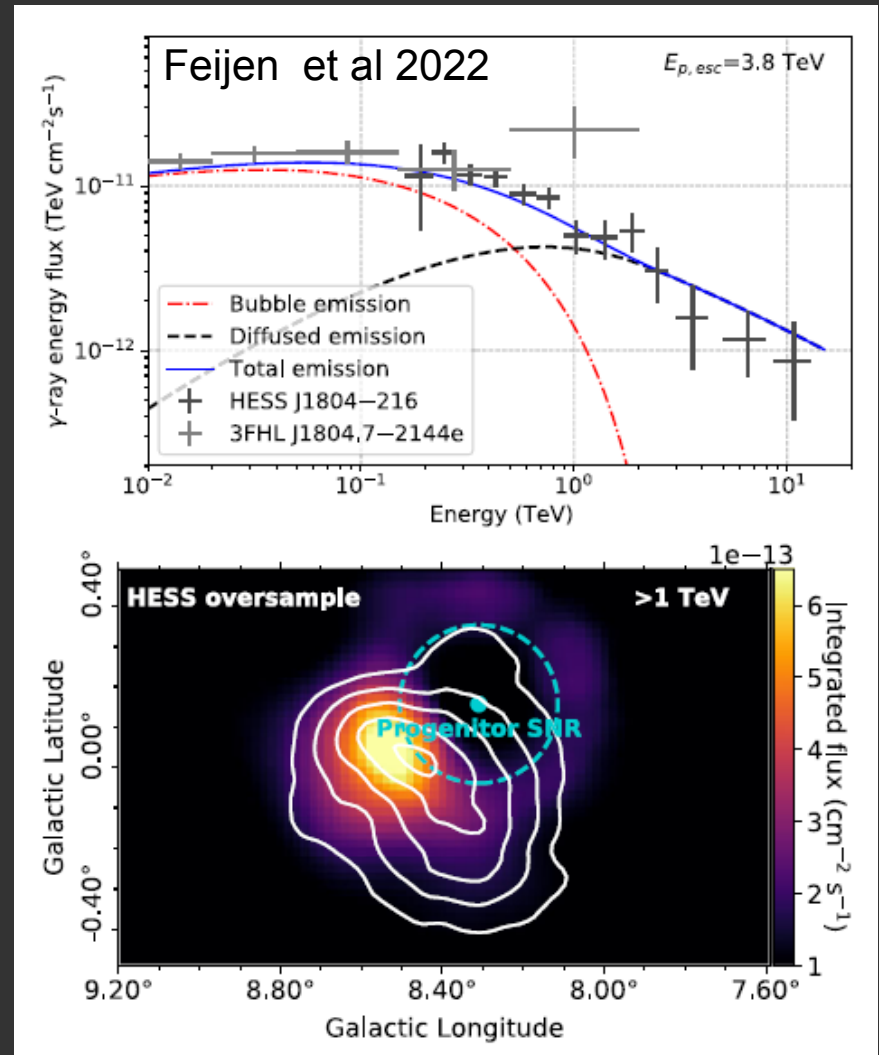
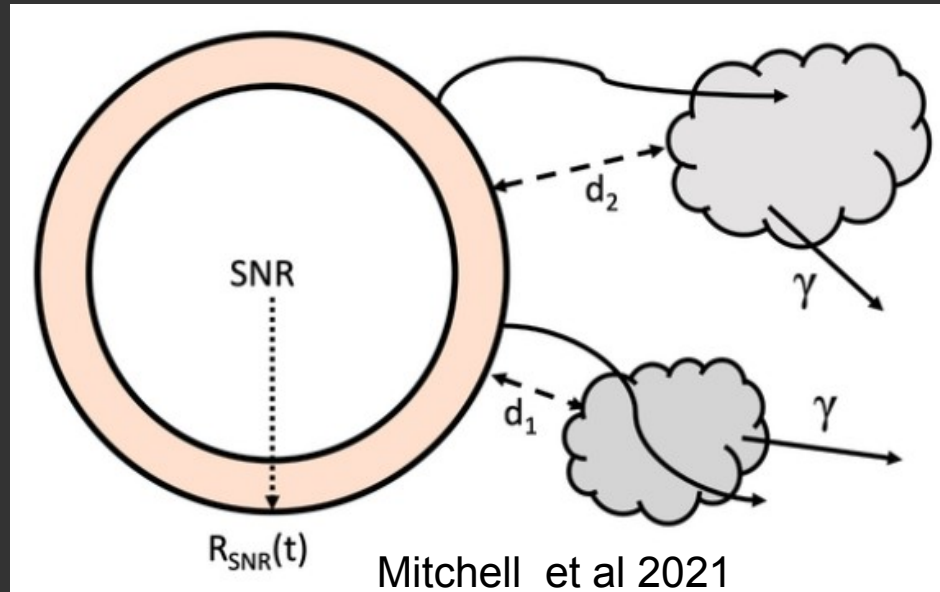
- Compare to GALPROP under variety of inputs (blue region)

$\rightarrow$  **CTA will detect this emission**



# Galactic Plane: A major astrophysical challenge for CTA

The 'local diffuse' component: Cosmic rays escaping accelerators (e.g. SNRs) and interacting with ISM clouds at nearby distances (<100 pc) to produce gamma rays



## Physics we need to know:

- Time-history of particle acceleration and 'escape' into the ISM
- 3D ISM down to 30 arc-sec scales
- Particle diffusion, advection, and radiative loss properties
- B field strength and direction down to 30 arc-sec scales



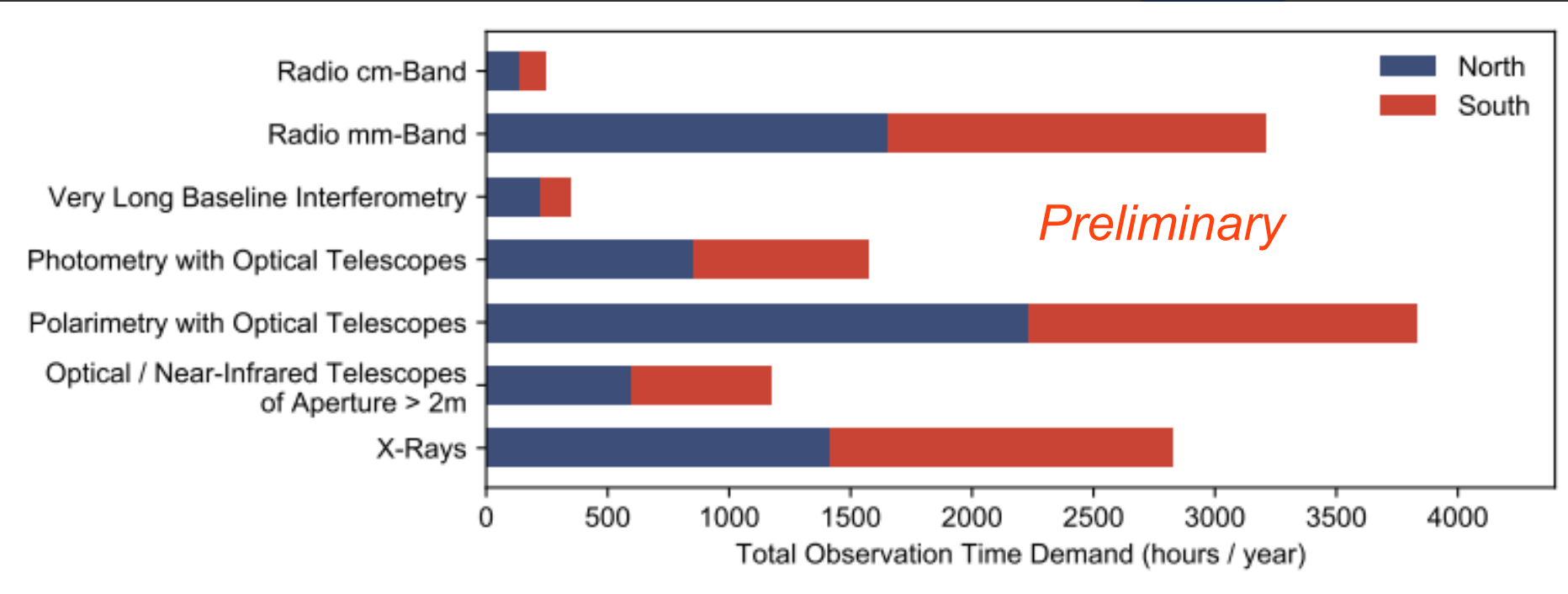
Thank you...

Backup....



# MWL Needs for CTA's Key Science Projects

Up ~1000 hr/yr for most radio to-optical coverage (huge potential for Australia)  
+ much more MWL needed for non-KSP time!



## MWL Needs for Key Science Projects++ (Survey Data)

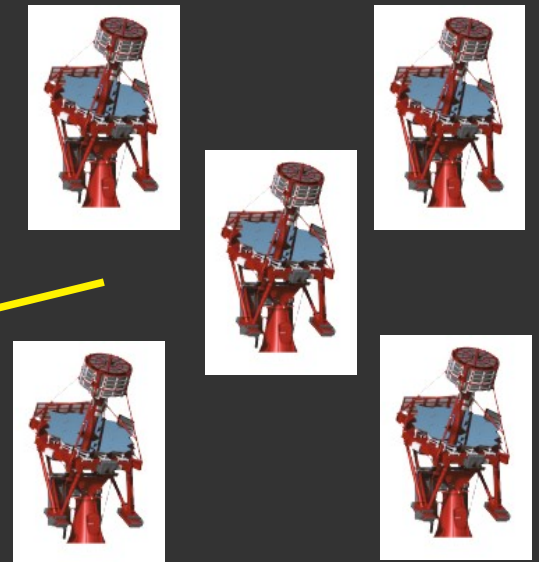
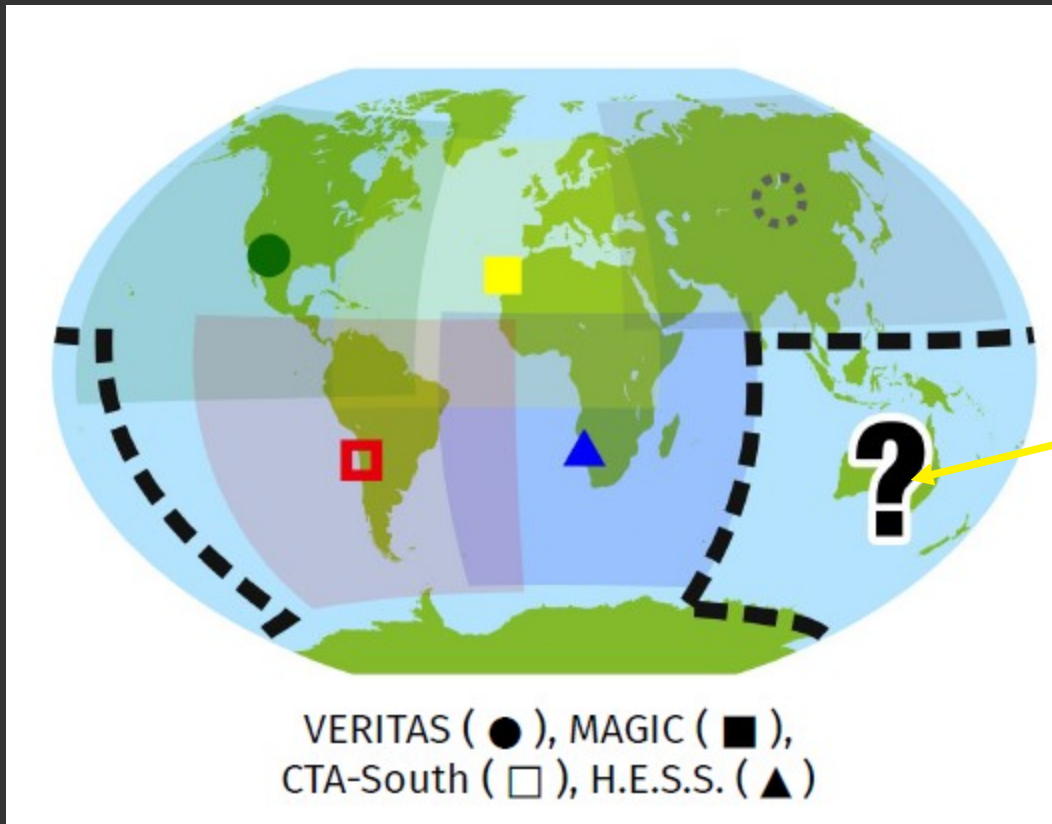
- ISM surveys                      arc-min or better resolution
- Radio/X-ray continuum              measure synchrotron component

**Linkages underpinned by fundamental physics of non-thermal emission**

# Cherenkov Telescope Ring (CTR)

Rohde et al 2017, Ruhe et al 2019  
+ Einecke, Rowell, Lee....

- Worldwide network of Cherenkov telescopes
- need to provide  $\geq 1 \text{ km}^2$  instantaneous collection area
- For transients and variable TeV sources:  
Rapid follow-up, discovery and monitoring
- Missing coverage in Australia! (& E-Asia)



Small array of CTA-type  
SSTs or MSTs?  
→ fully robotic!