High-Energy Astrophysics with Gamma-Ray Telescopes

(focus on >TeV energies)

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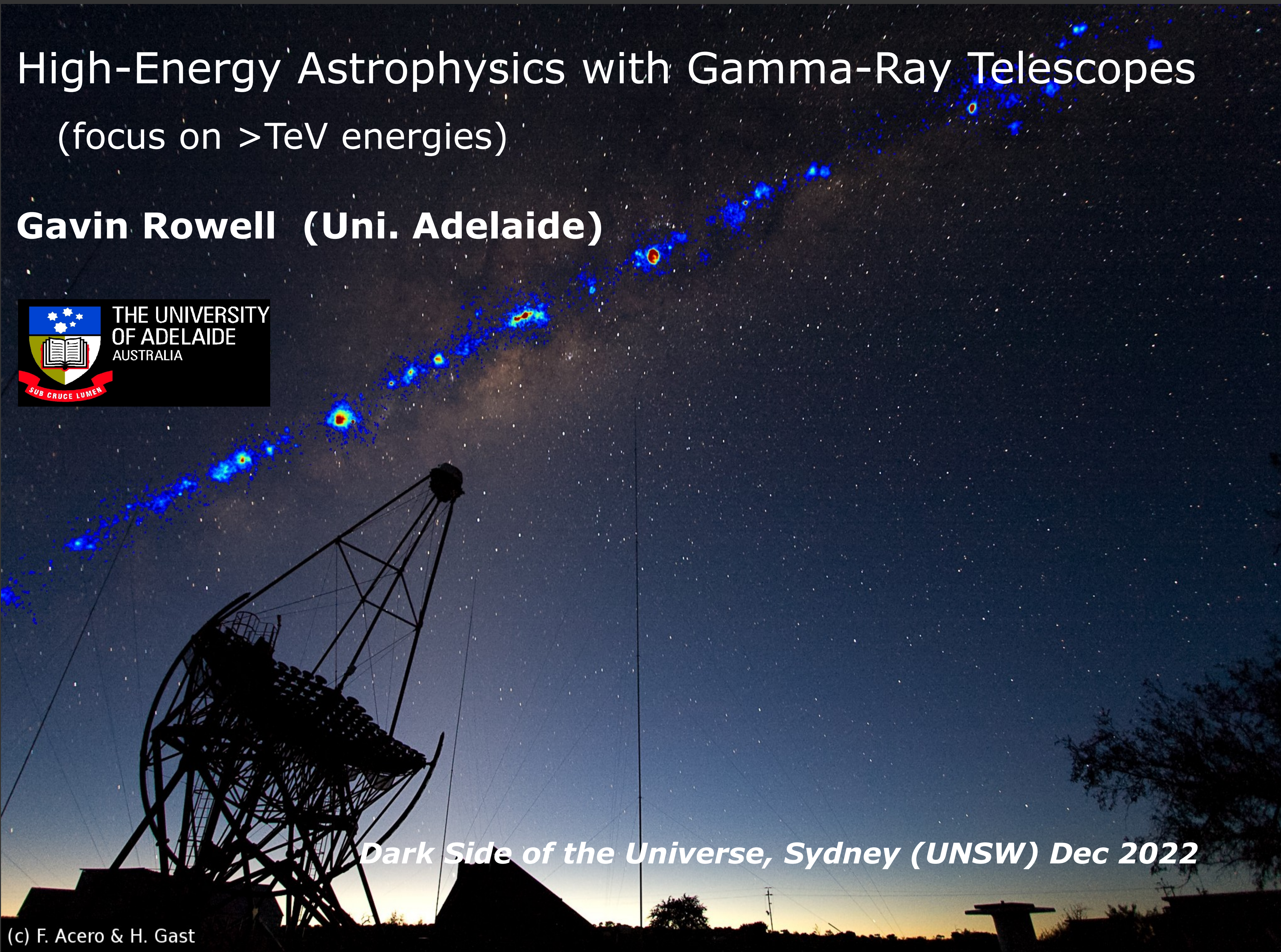
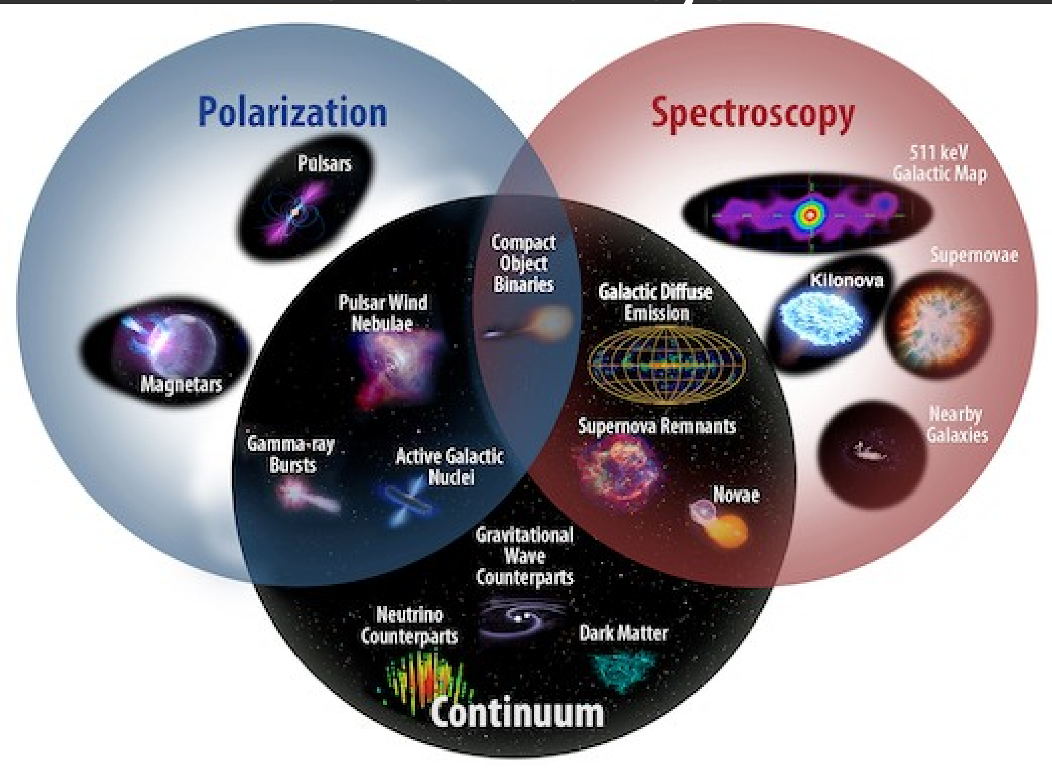
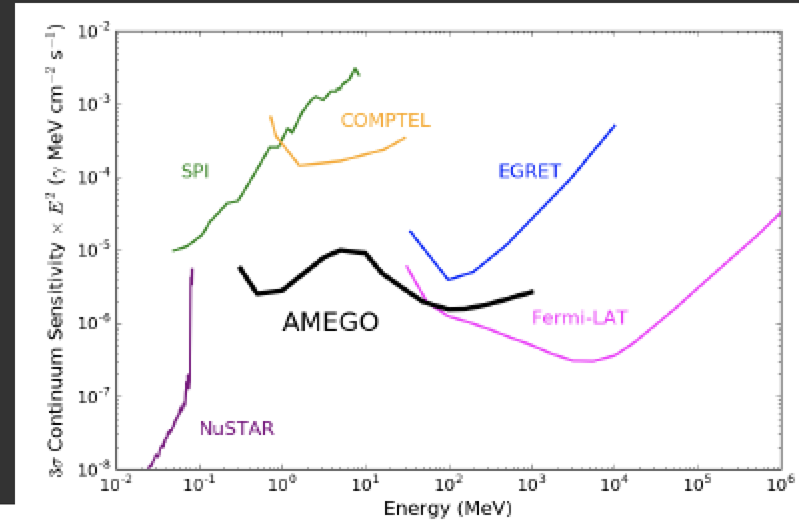
THE UNIVERSITY OF ADELAIDE AUSTRALIA
SUB CRUCE LUMEN

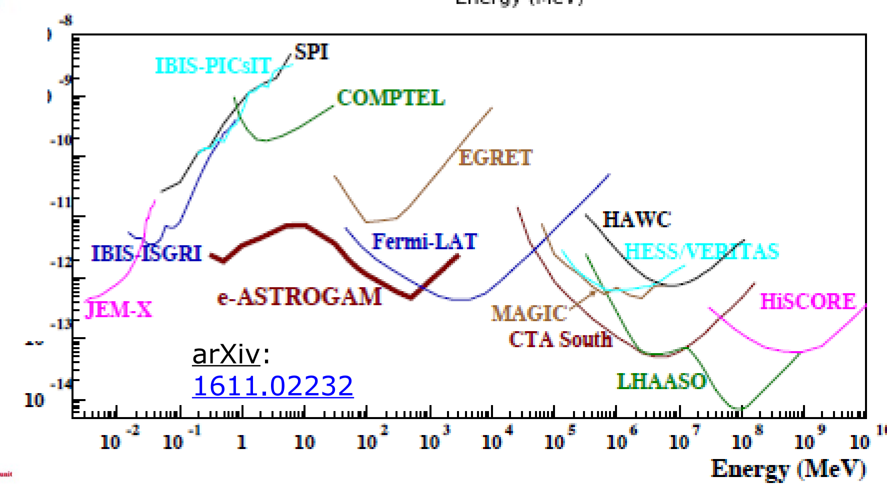
Dark Side of the Universe, Sydney (UNSW) Dec 2022



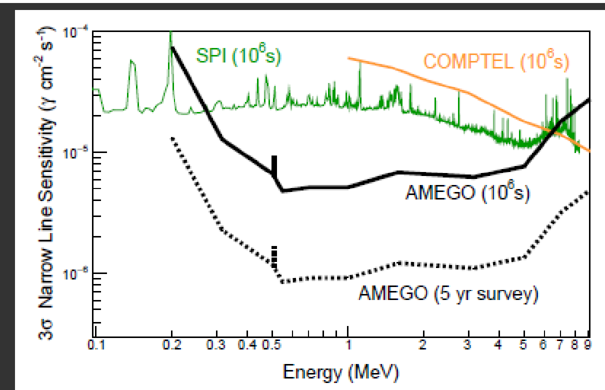
MeV Gamma Rays

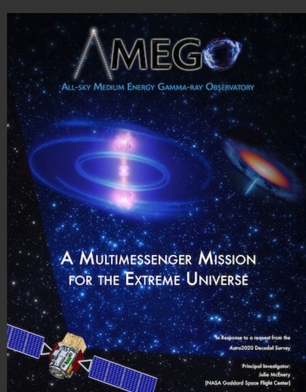


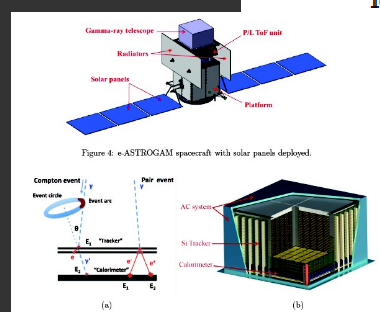




arXiv: [1611.02232](https://arxiv.org/abs/1611.02232)



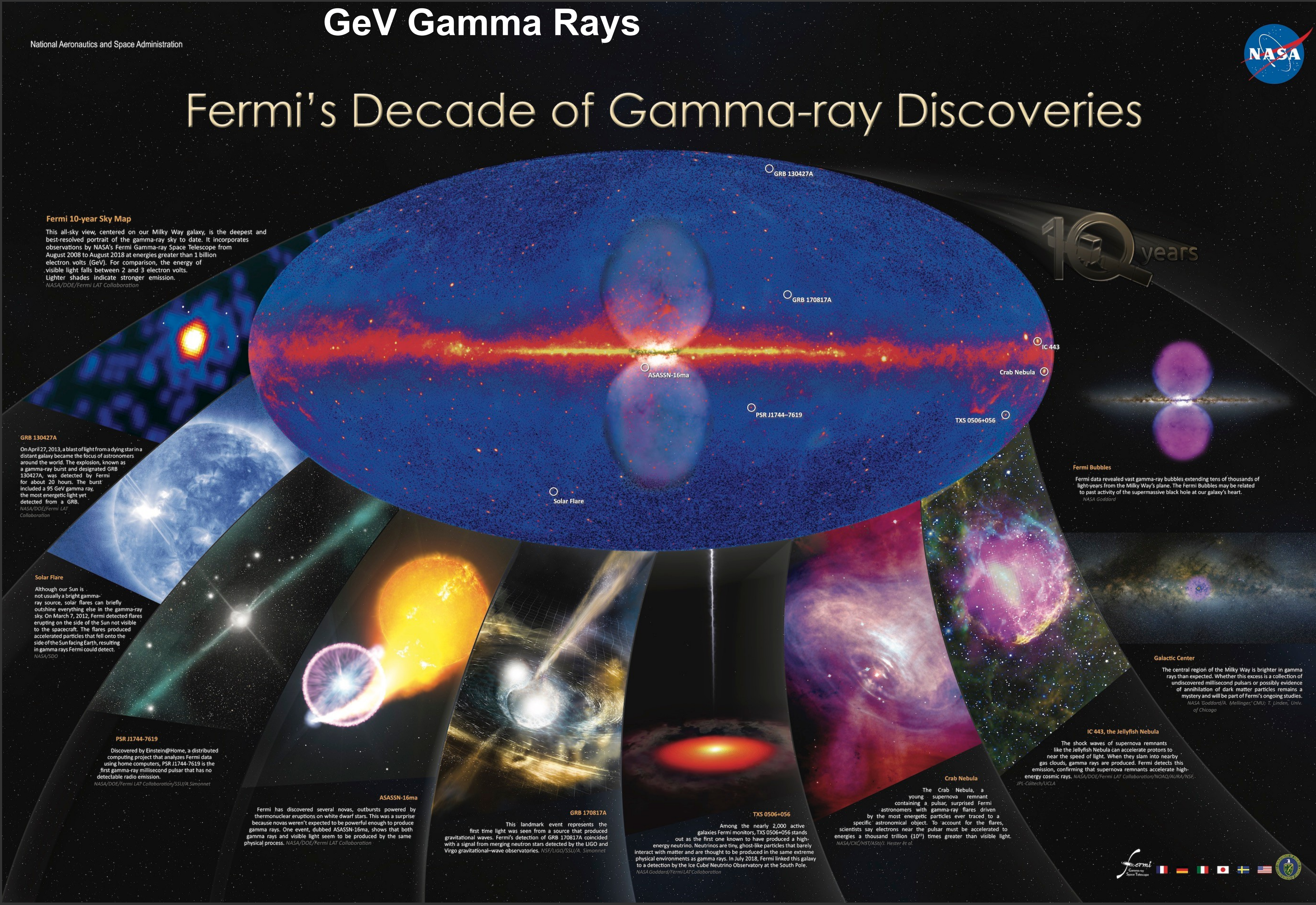




AMEGO & e-ASTROGAM

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

GeV Gamma Rays



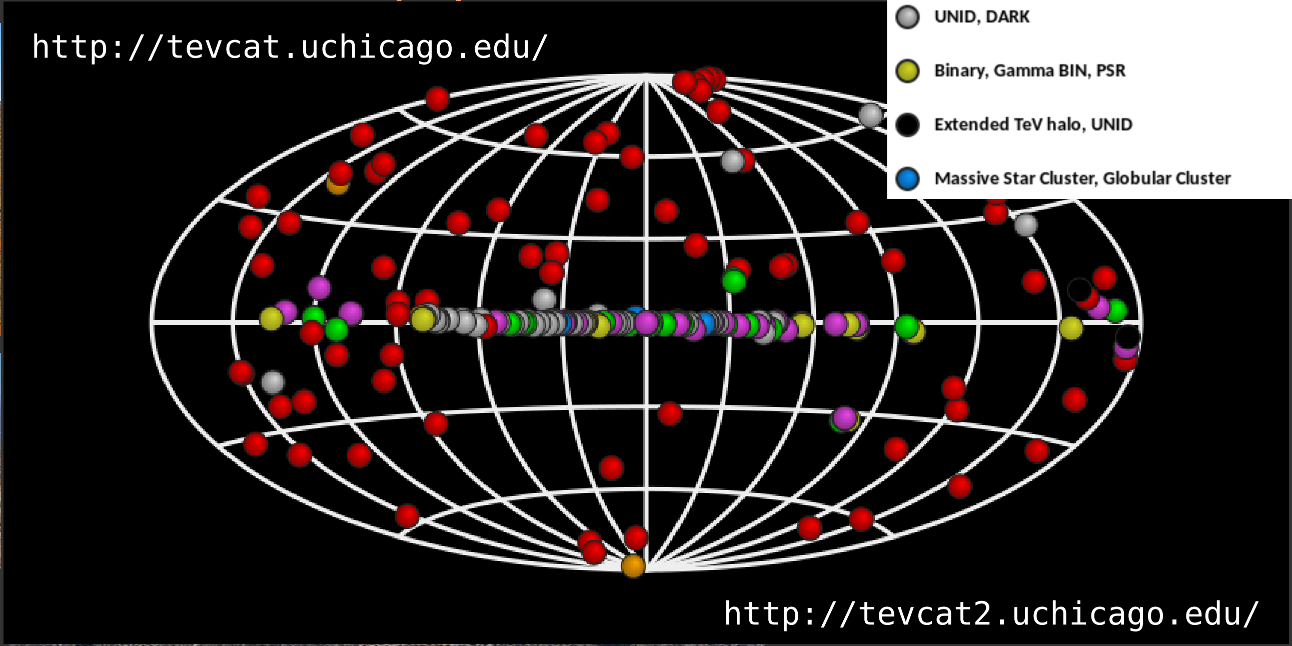
11 June 2018

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

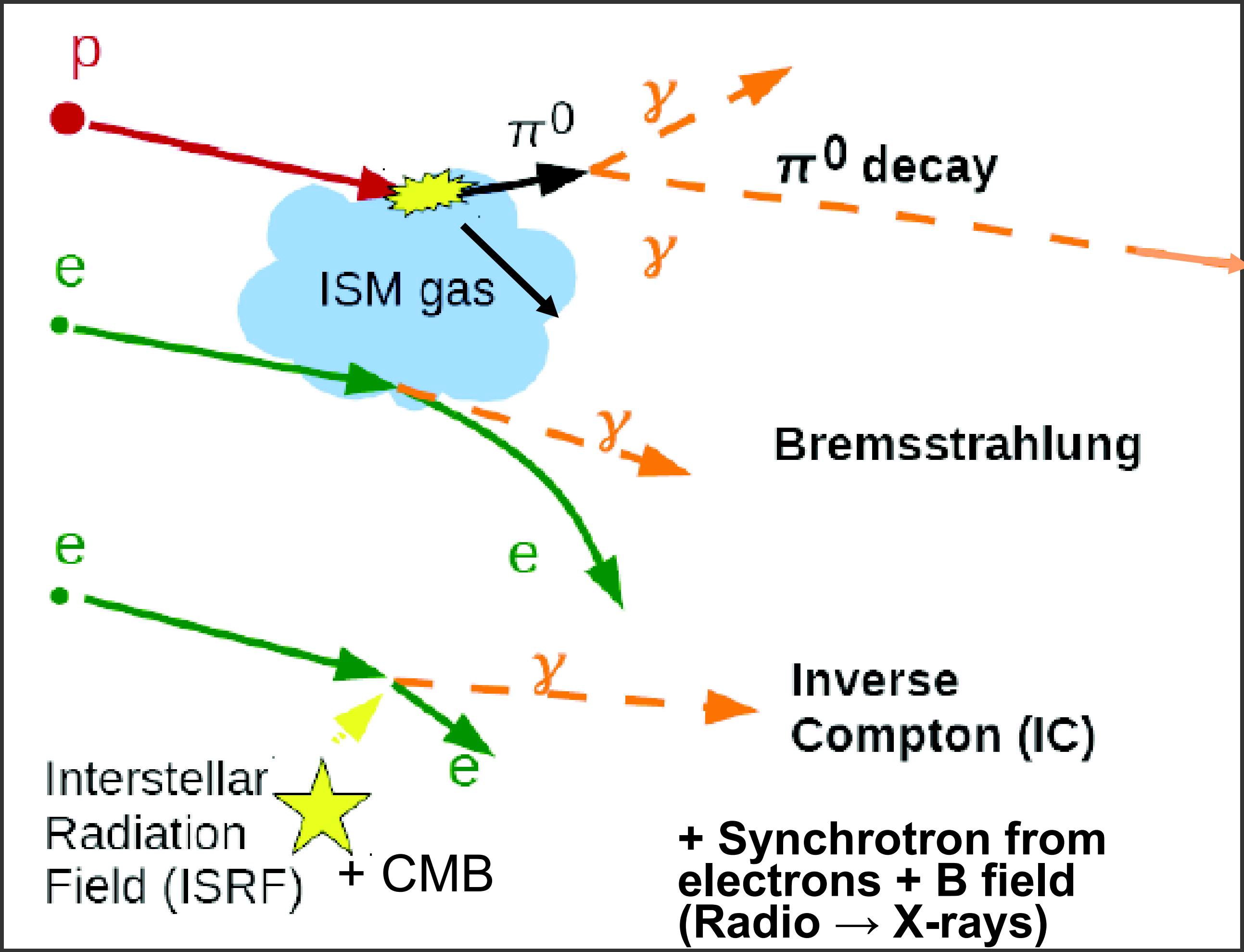


Great success with HESS, VERITAS, MAGIC, HAWC, building on previous generations

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

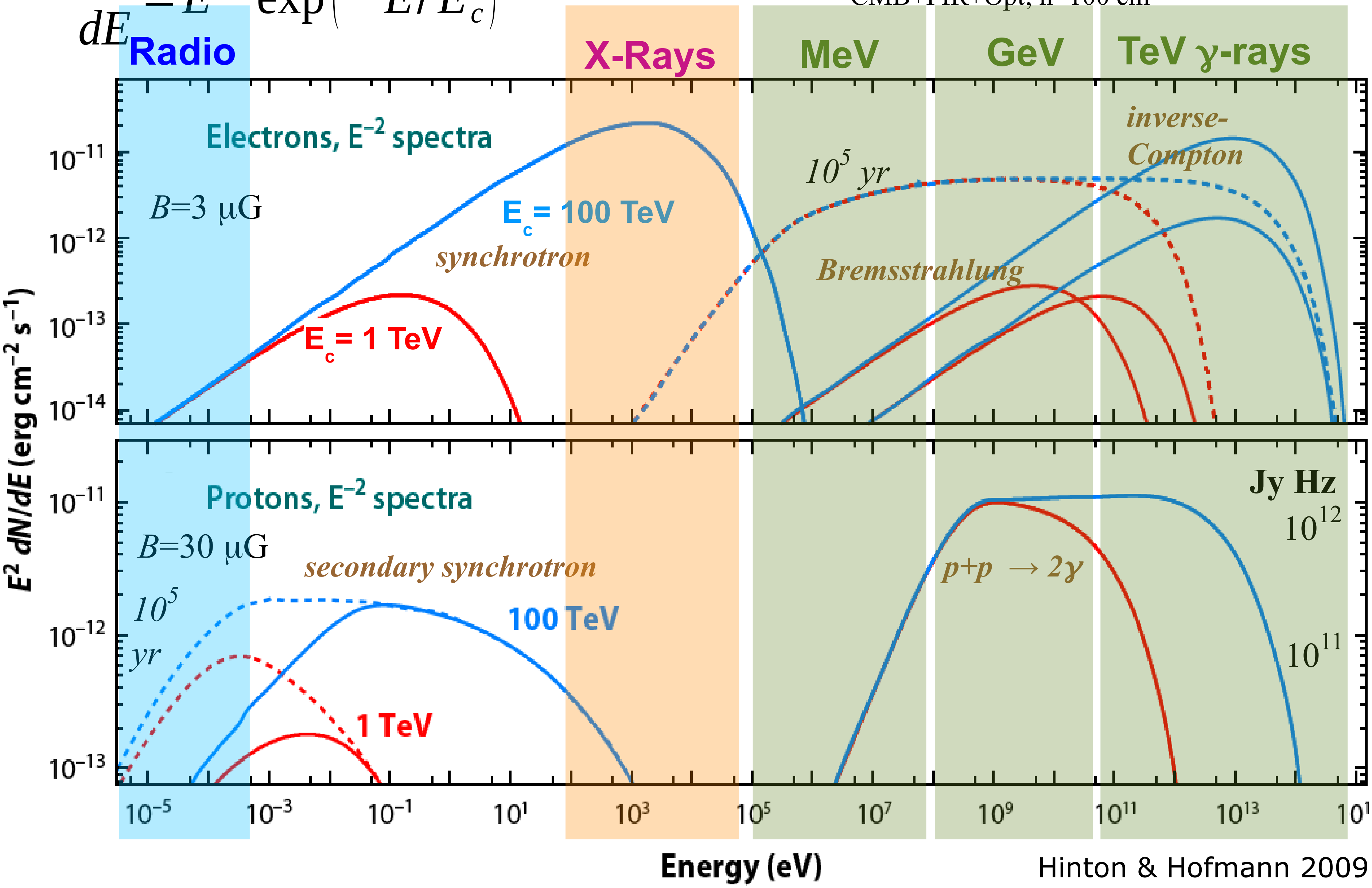
Electrons: Gamma-ray (IC) + non-thermal X-ray, radio emission (synchrotron)
→ radio, X-ray, gamma-ray connections

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

Particle Spectrum

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

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



Hinton & Hofmann 2009

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

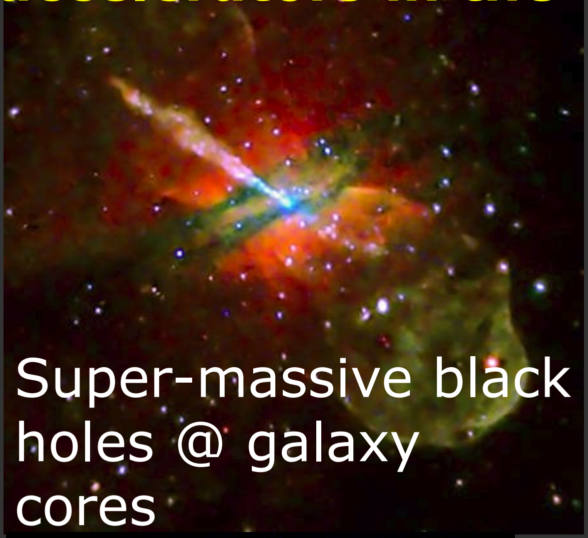
→ CRs intimately linked to evolution of stars and galaxies

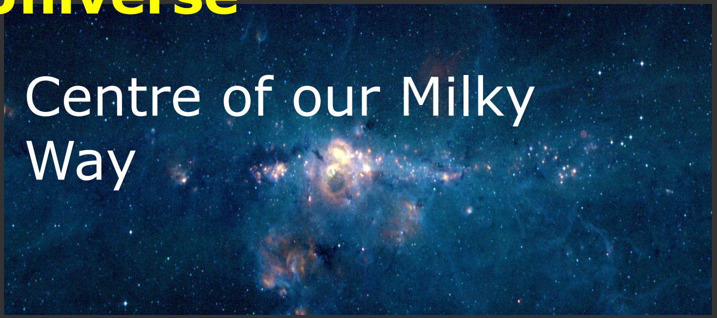
- CRs are a signpost of massive stellar evolution
  - – death (supernova remnants)
  - – life (winds from massive stars)
  - – birth (perhaps) signalling onset of fusion/stellar winds
  - – catalyst for astro-chemistry → life!

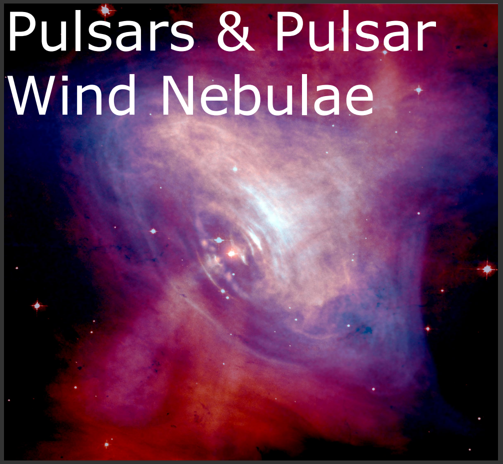
- Where do magnetic fields come? Are they important?
  - – Magnetic fields can greatly inflence star formation!
  - – CRs can create magnetic fields - they ionise atoms

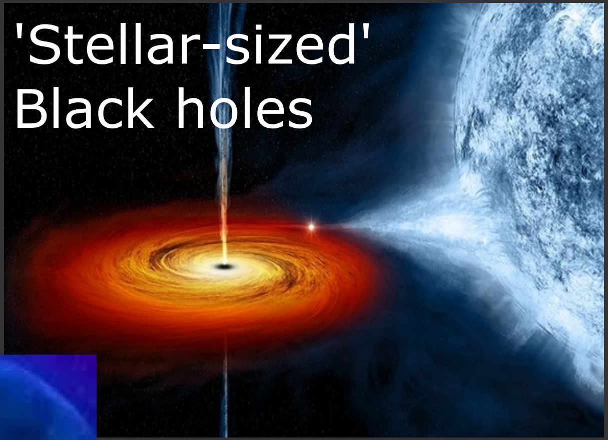
- CRs and electrons trace outflows and jets
  - – jets, pulsar winds, accretion, active Galaxies, GRBs, merger events......

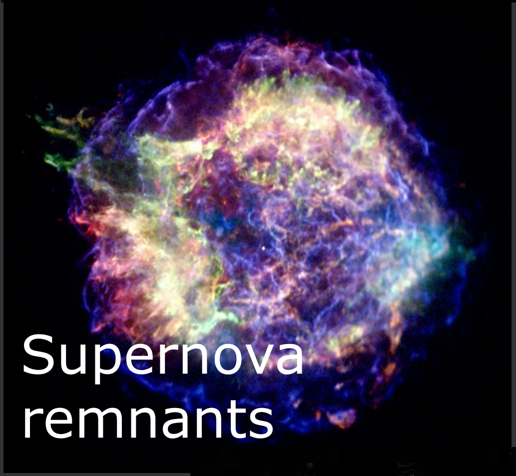
Gamma rays provide insight into extreme particle accelerators in the Universe











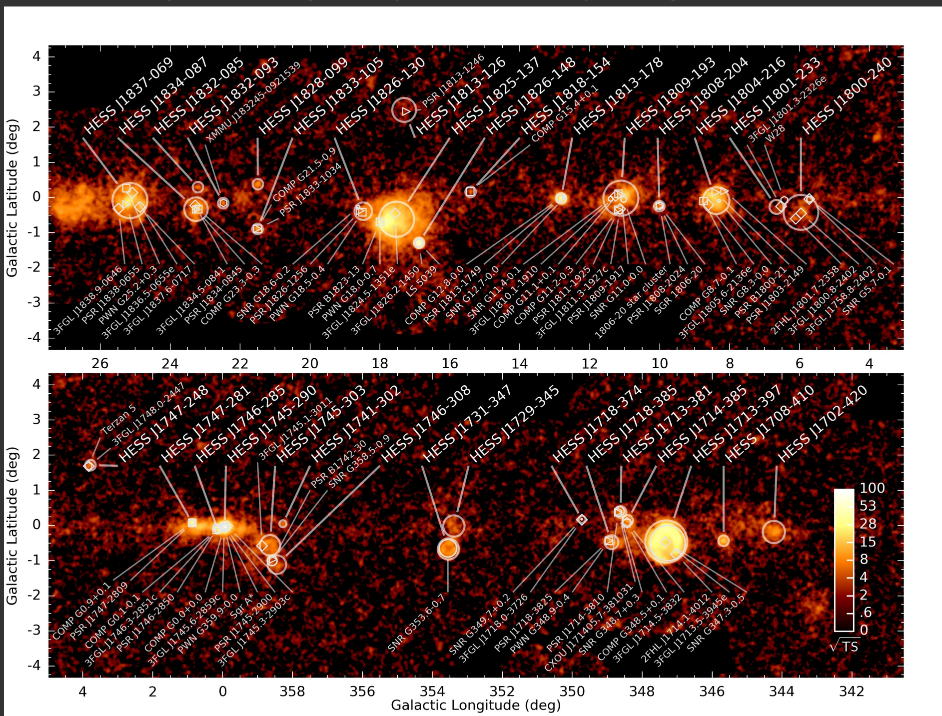
Gamma-rays (GeV to >PeV Energies)

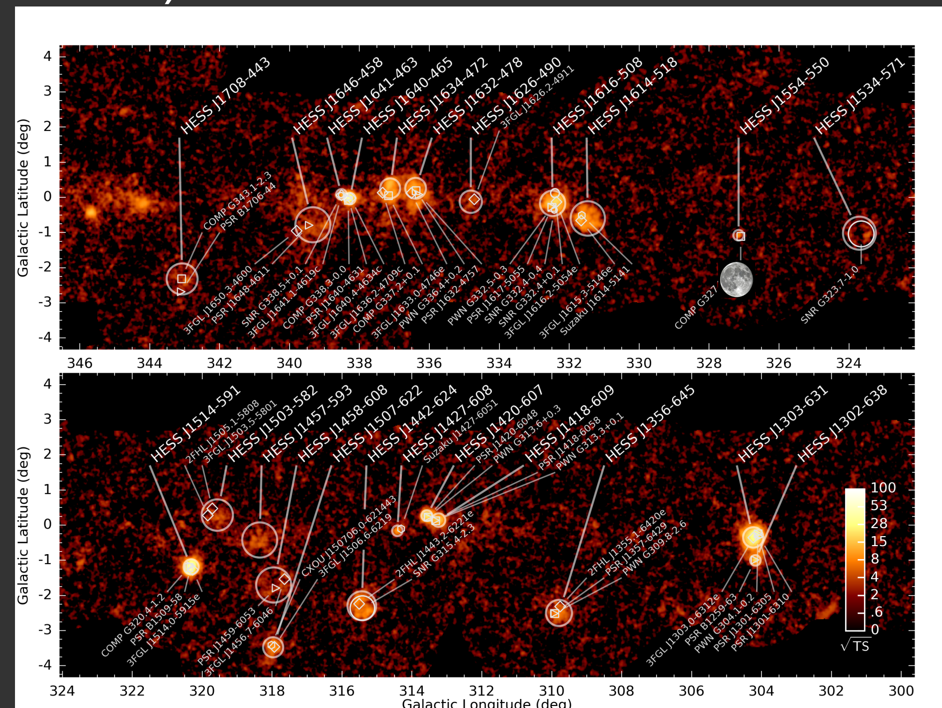
- **Gamma rays: Highly effective tracer of particle acceleration**
- **Many gamma-ray source types + astro/particle physics impact**
  - *Supernova remnants*
  - *Pulsars*
  - *Pulsar-wind nebulae & their halos*
  - *Compact binaries, stellar black holes*
  - *Gamma-ray bursts (hypernovae & compact mergers)*
  - *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)

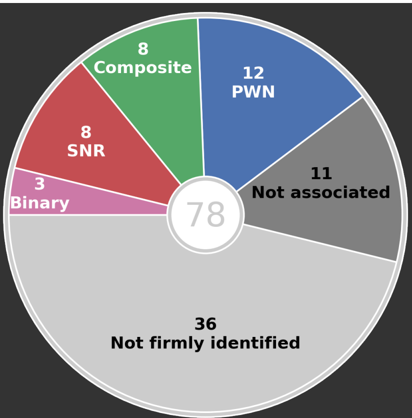
HGPS - The Southern Milky Way in TeV Gamma-Rays

→ 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

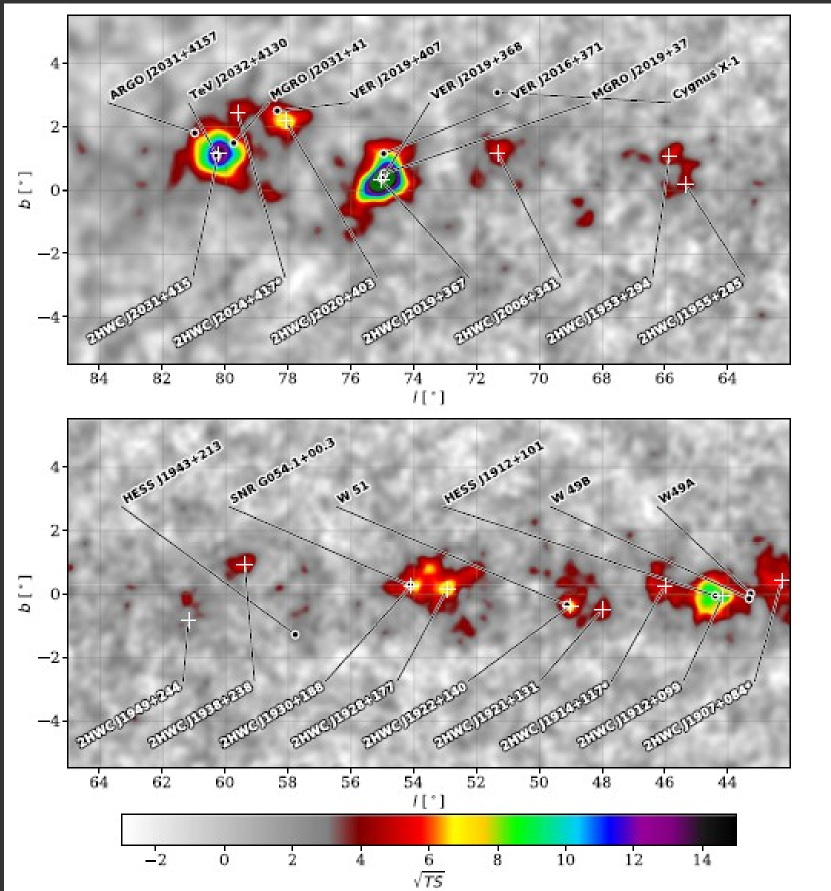


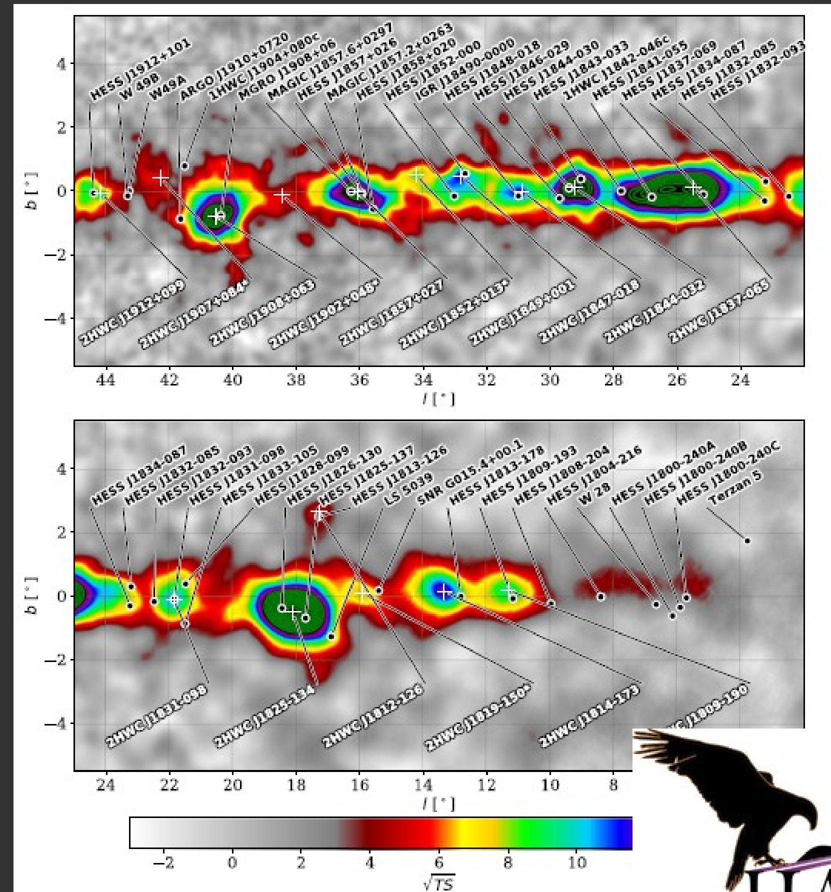
Data download `https://www.mpi-hd.mpg.de/hfm/HESS/hgps/`

HAWC Galactic Plane Survey (2HWC)

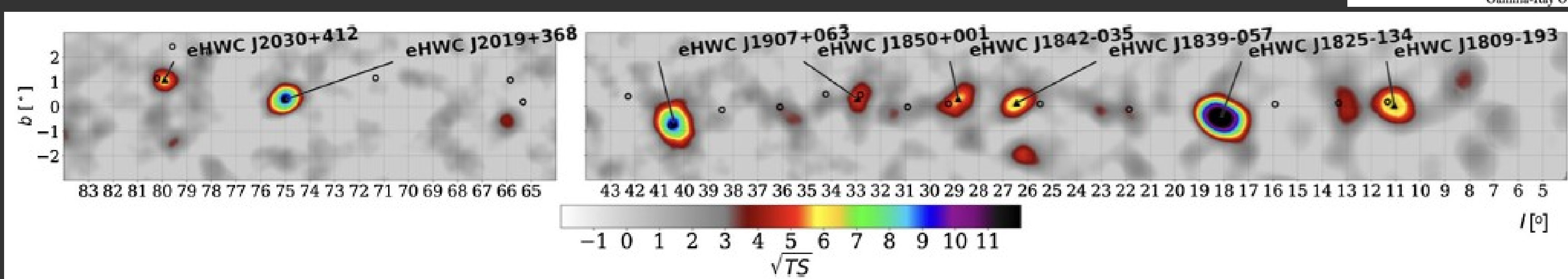
→ 39 sources (17 new sources)

Abeysekara et al. (HAWC) 2017,2020



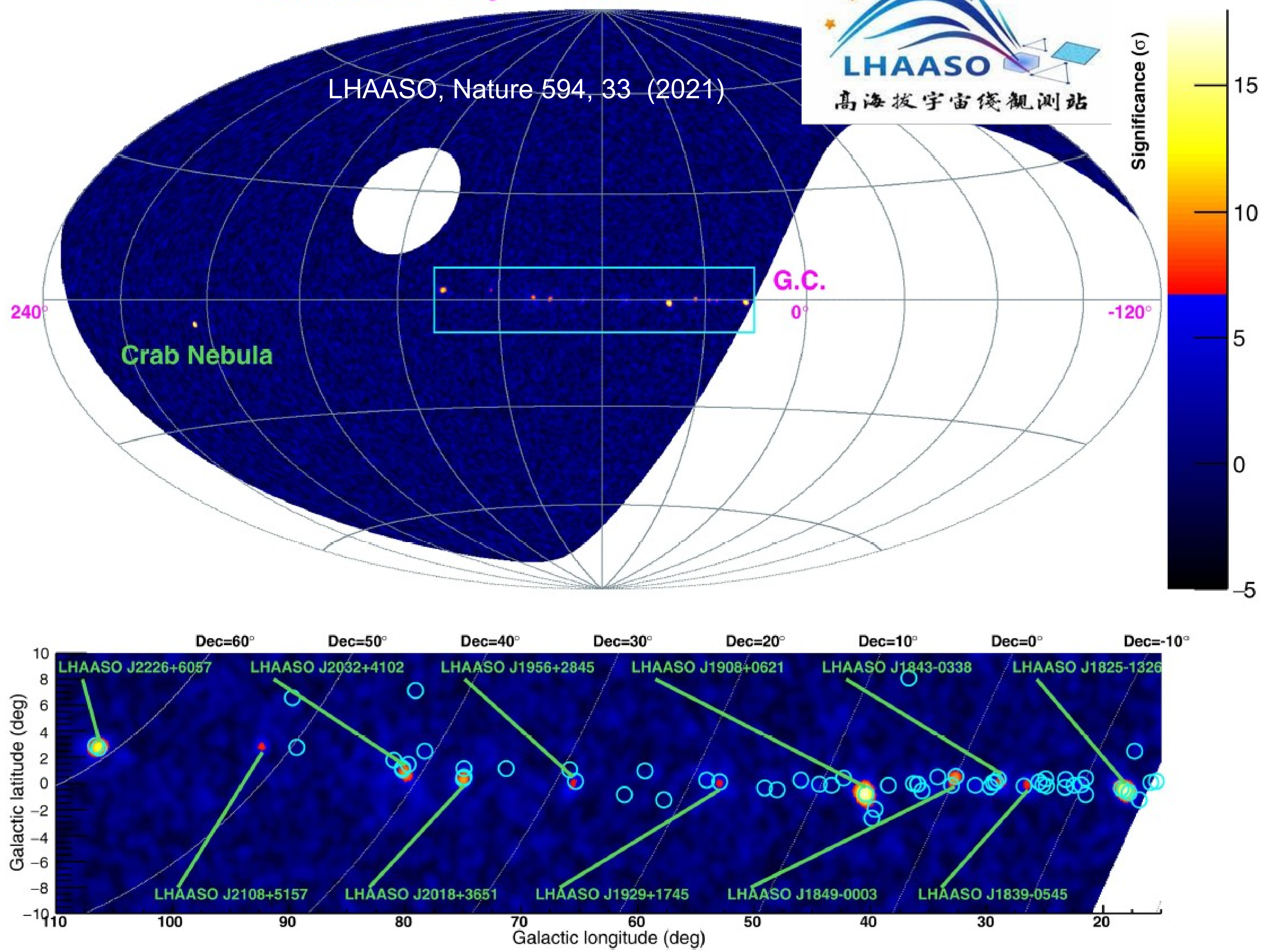


Sources >56 TeV → PeVatrons



High Altitude Water Cherenkov
Gamma-Ray Observatory

LHAASO Sky @ >100 TeV



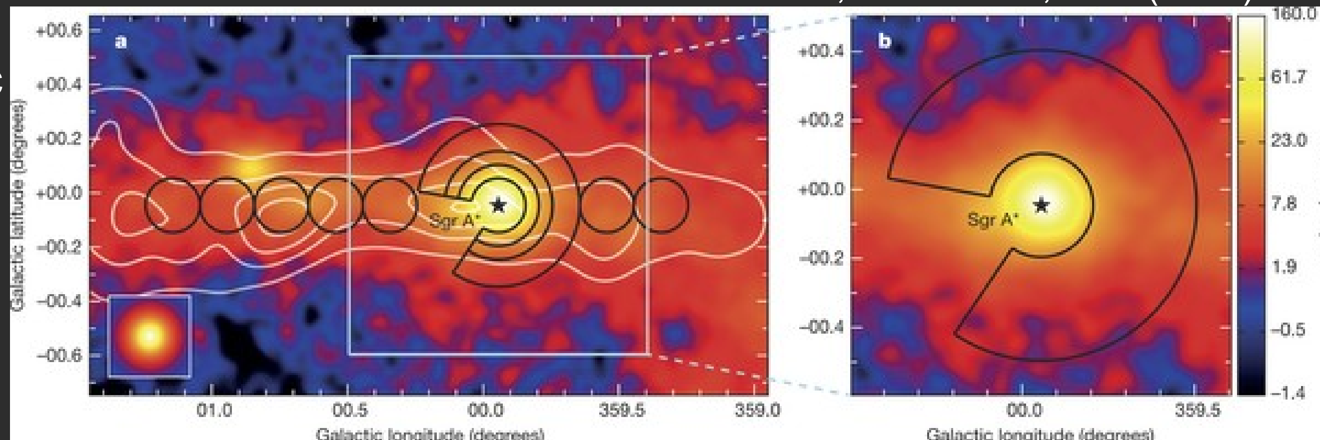
Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.

PeVatrons: Particle acceleration to >PeV energies

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

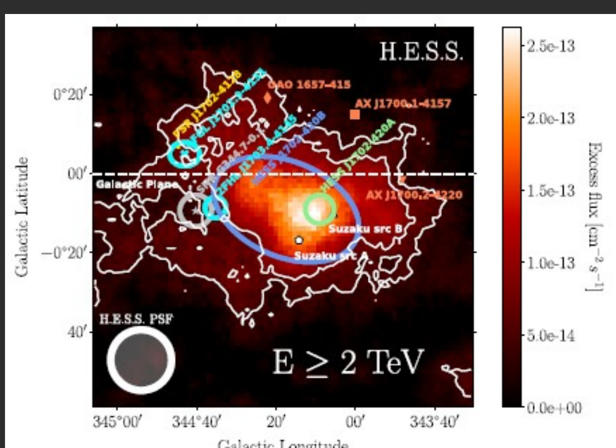
HESS, Nature 531, 476 (2016)

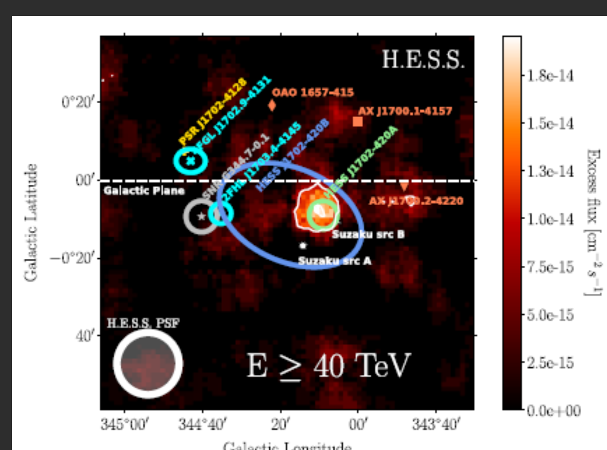
<u>Galactic Centre Region</u>
- Diffuse emission to 70pc
- Continous CR injector over ~few1000yr
- Central BH most likely accelerator

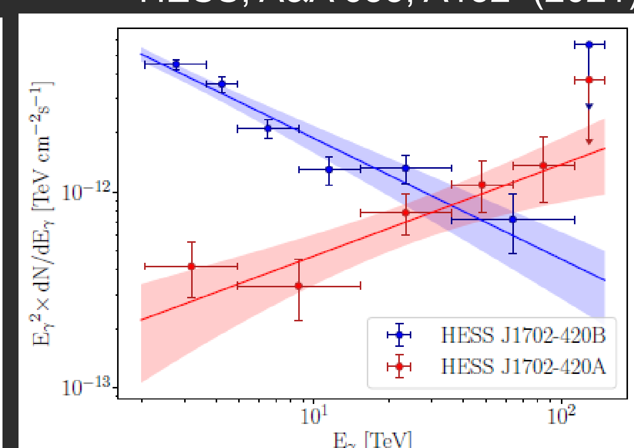


<u>HESS J1702-420</u>
- Resolved into two components A & B. Gamma rays from A > 100 TeV
- CR protons up to ~0.5 PeV, but leptonic scenario not ruled out.

HESS, A&A 653, A152 (2021)



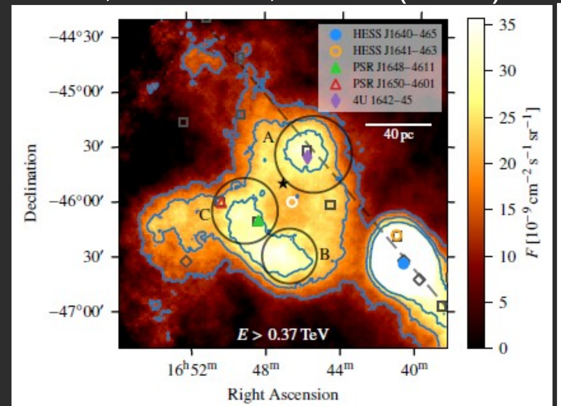


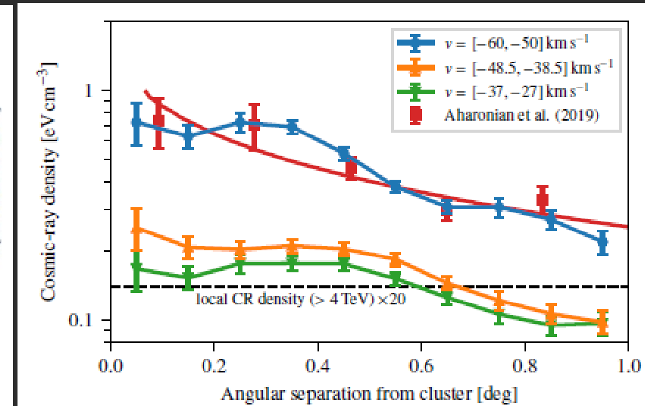


PeVatrons: Particle acceleration to >PeV energies

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

HESS, A&A 666, A124 (2022)





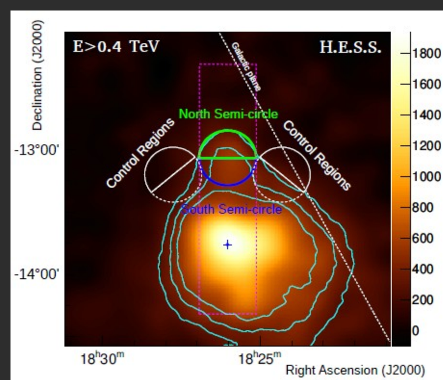
<u>Westerlund1 stellar cluster</u>

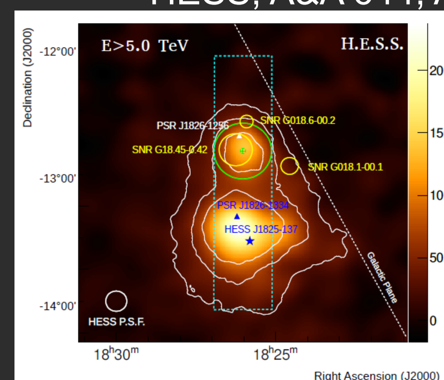
- >20 WR stars; $L \sim 10^{39}$ erg/s
- TeV emission 2 deg diam.
- TeV spectrum >50 TeV
- Deeper HESS obs reveal no spectral change with location.
- Shell-like structure centred on Cluster. TeV+ISM comparison compatible with continuous CR injector.

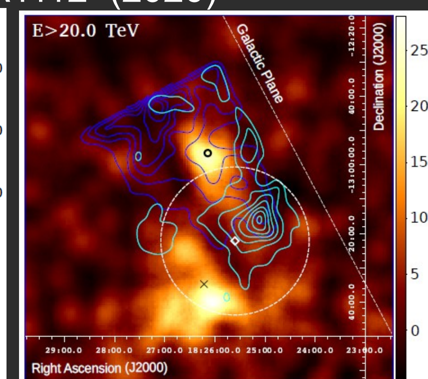
HESS, A&A 644, A1112 (2020)

<u>HESS J1826-130</u>

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



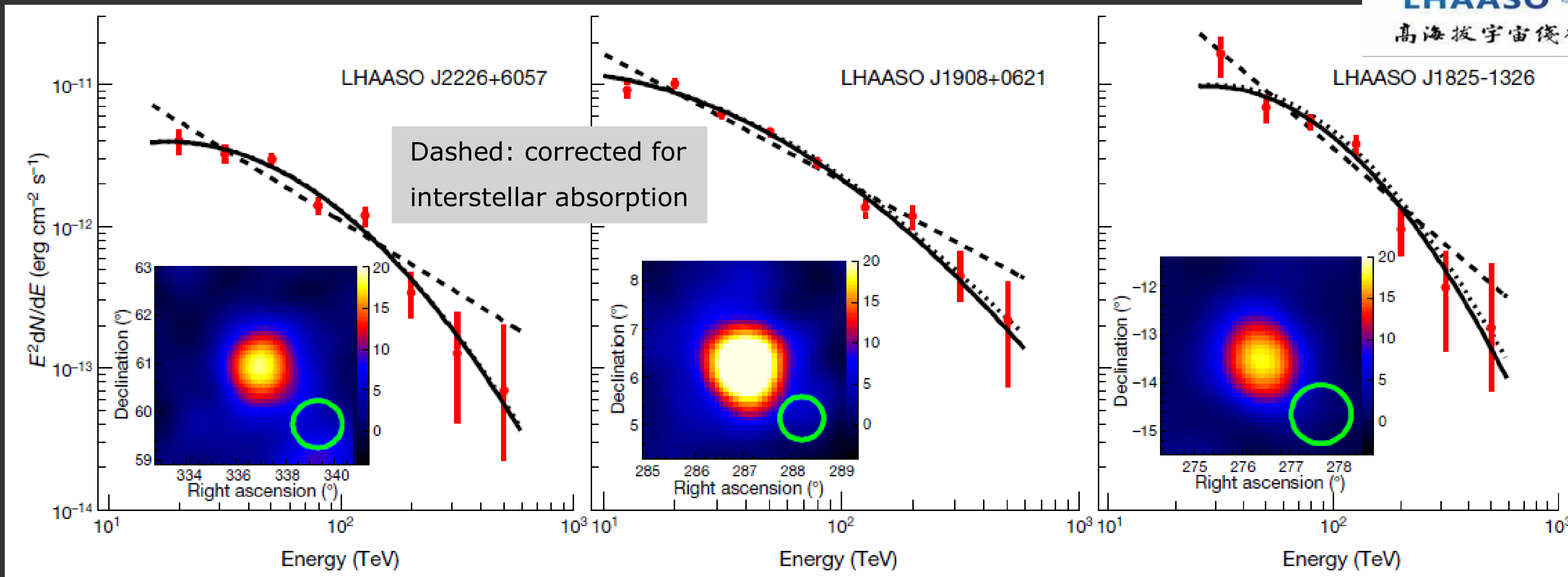




<u>Some other examples</u>

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

LHAASO Gamma-Ray Spectra → 1 PeV



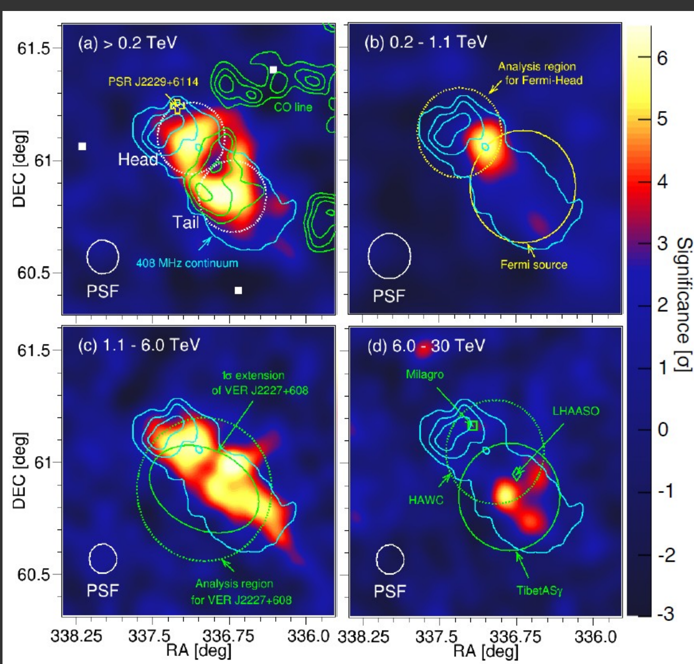


Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	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	$0.26^{+0.16}_{-0.10}$	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	$0.71^{+0.16}_{-0.07}$	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 tha contains ±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 1σ.

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

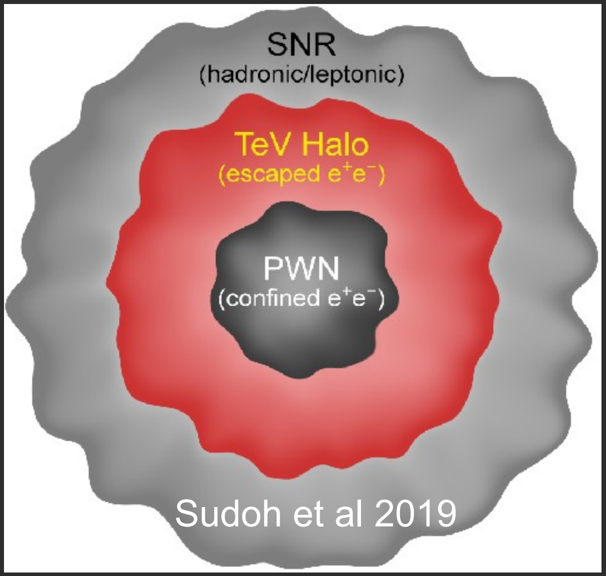
- Old (τ_c=342kyr) nearby pulsar (250 pc).
- HAWC: Extended TeV emission around PWN

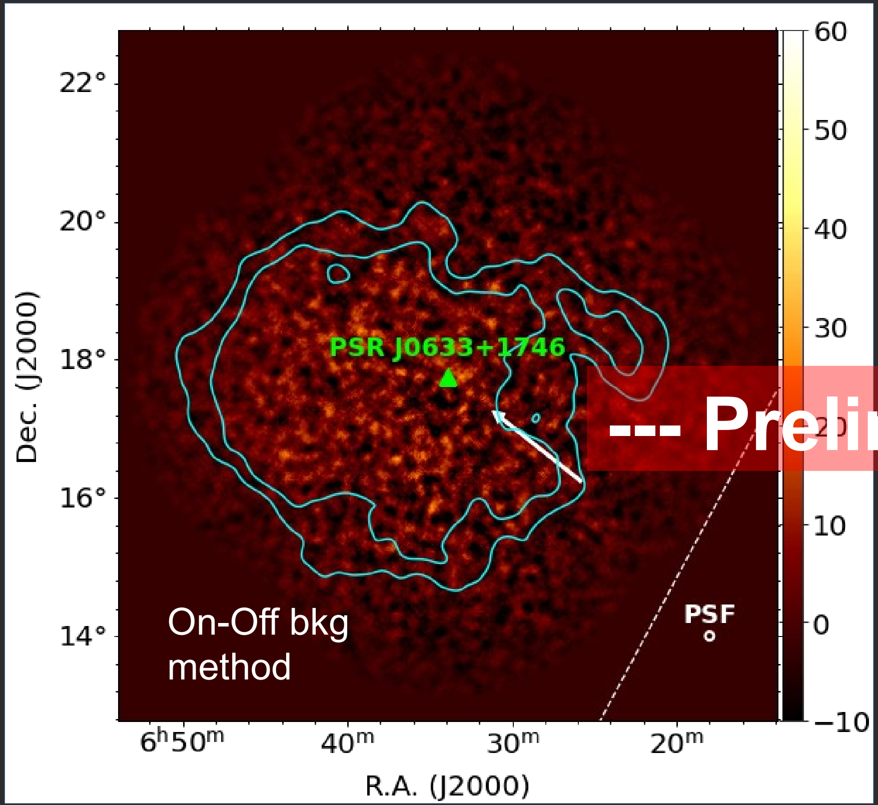
  Abeysekara et al 2017
- Also seen by HESS but a challenge for its FoV.

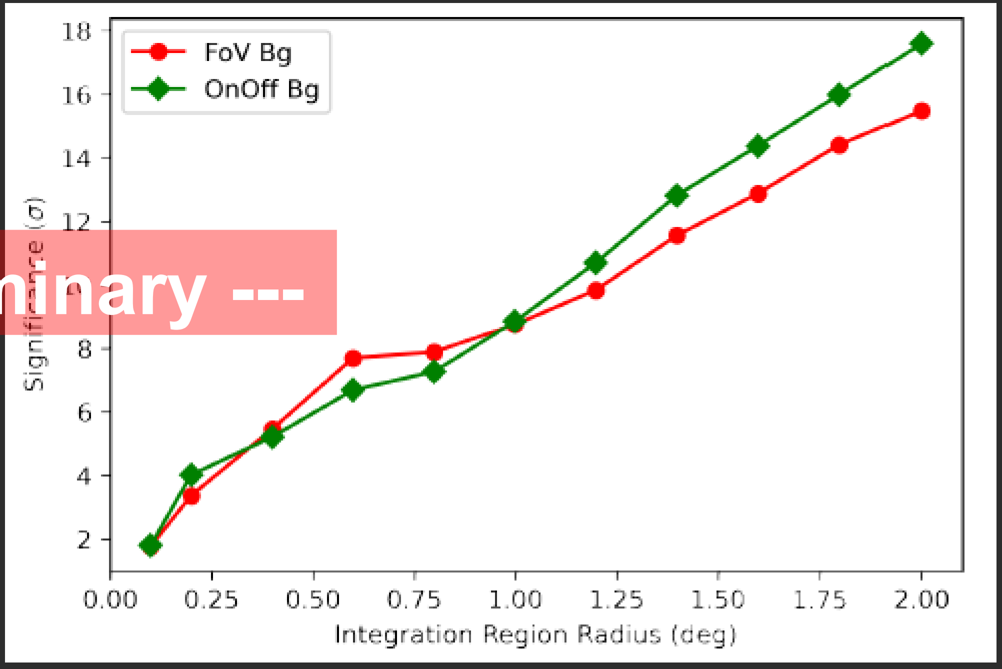
  HESS ICRC2021
- Largest HESS TeV source (5deg diam; ~20pc)
- Requires slow diffusive transport of electrons, 100x lower the Galactic expectation (as per HAWC conclusion).

  → PWN TeV halos may be considerable sources of PeV particles.

  e.g. Martin et al 2022



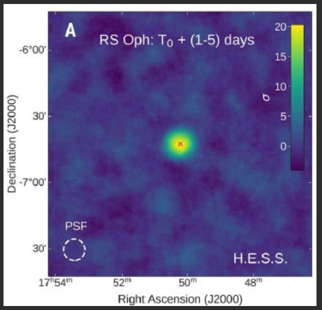


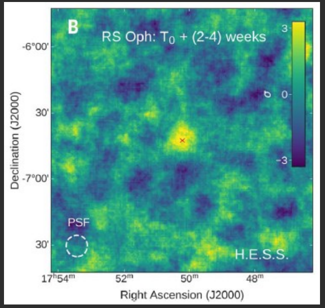


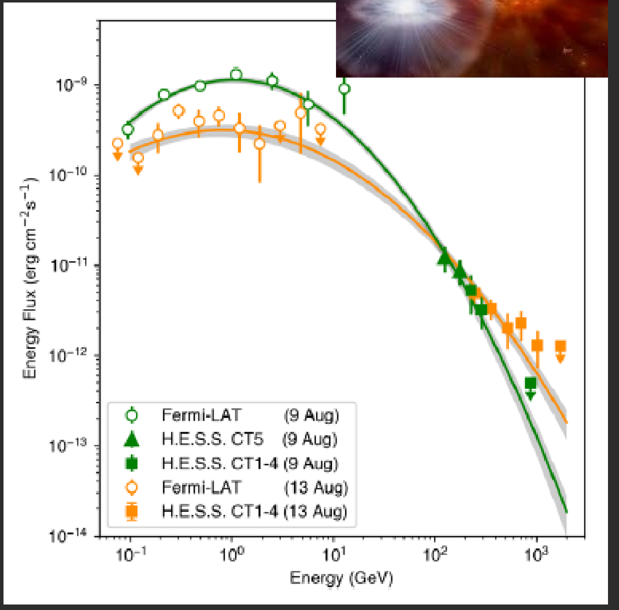
RS-Oph Recurrent Nova – First Galactic TeV Transient

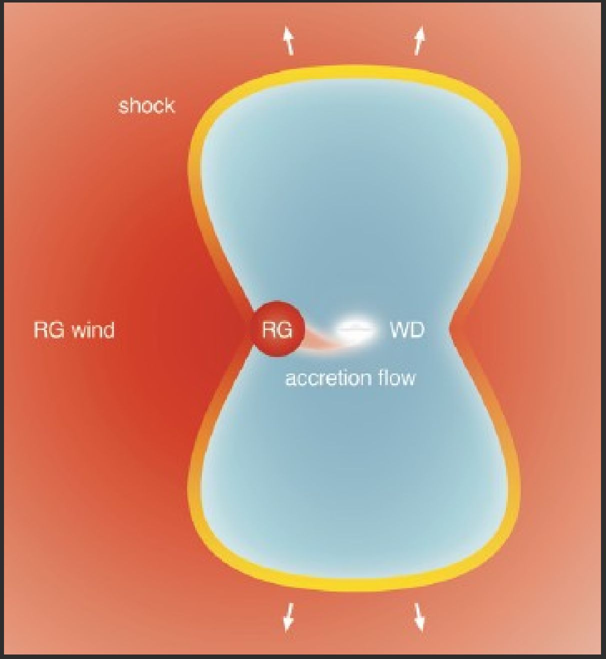
HESS, Science 376, 6588 (2022)
MAGIC, Nature Astron 6, 689 (2022)

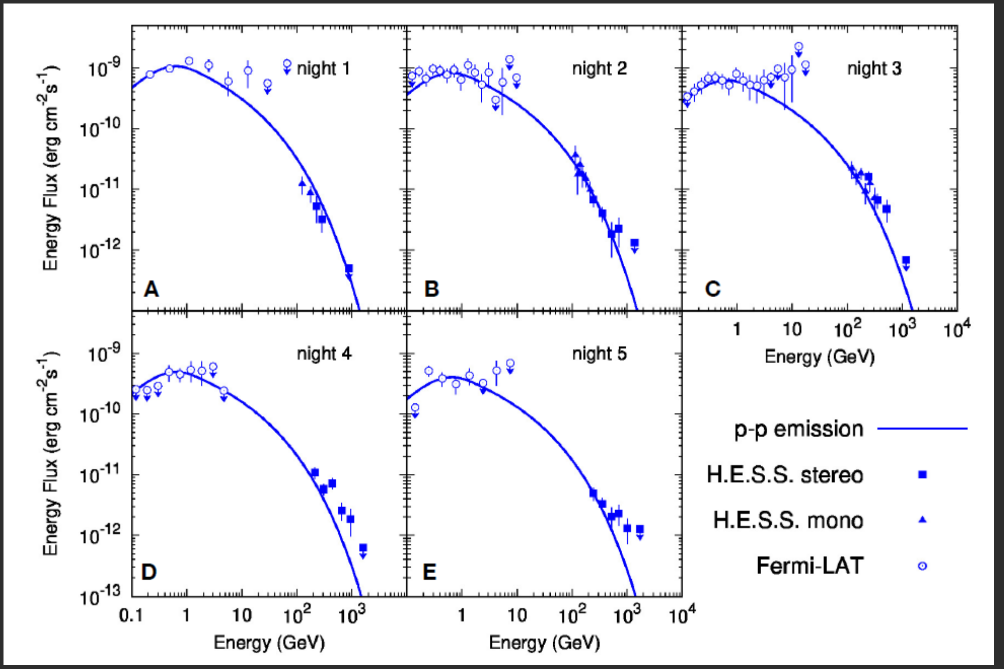
- WD and massive companion RG star
- Flaring via thermonuclear detonation and particle acceleration.
- GeV emission from Fermi-LAT
- HESS obs. of 2021 outburst triggered by optical flare (prev. outburst ~9-26 yrs)
- >6sigma/day in first 5 nights with HESS
  (also seen by MAGIC Acciari etal 2022)
- Hadronic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











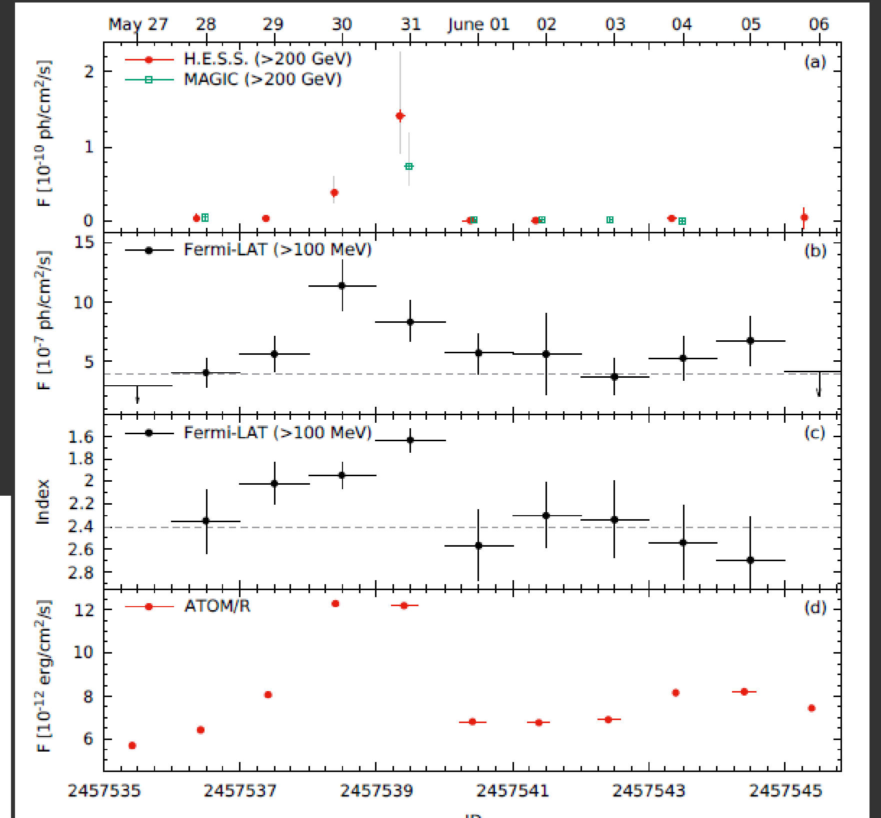
PKS1510-089 FSRQ z=0.361

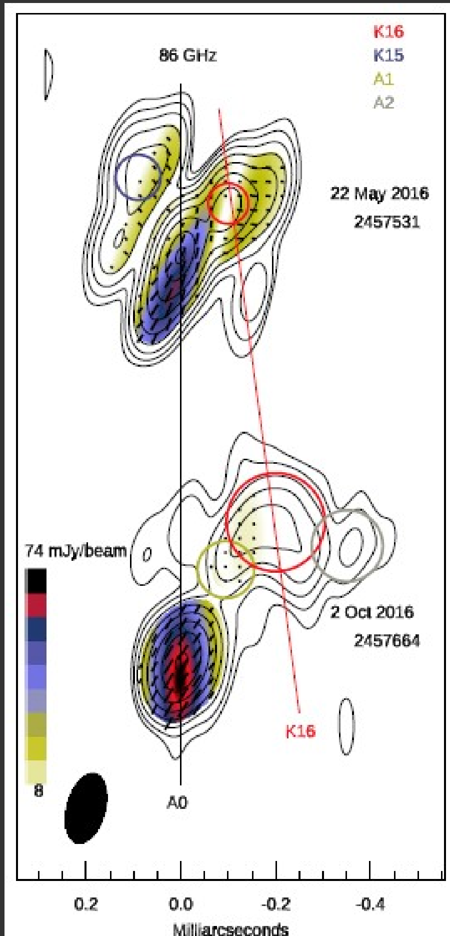
HESS, MAGIC , A&A 648, A25 (2021)

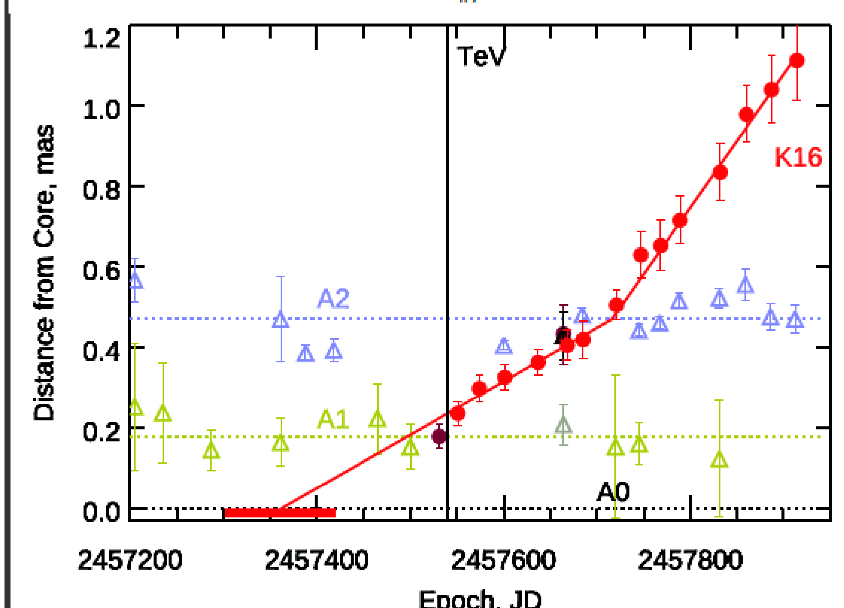
TeV & optical intra-day variation (May 2016)

HESS+MAGIC+Femri-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 → absorption from EBL, not BLR.
- Gamma emission $>2.6R_{BLR}$ from BH
- Flare associated with rapidly moving radio knot K16?

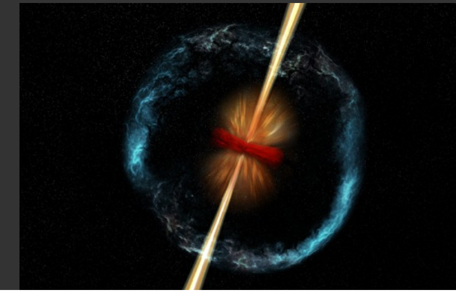


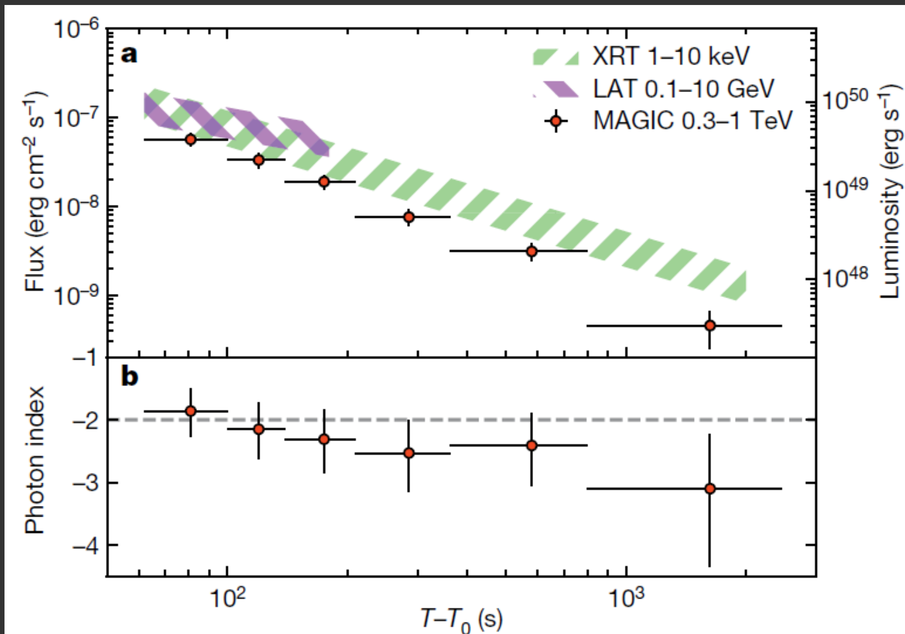


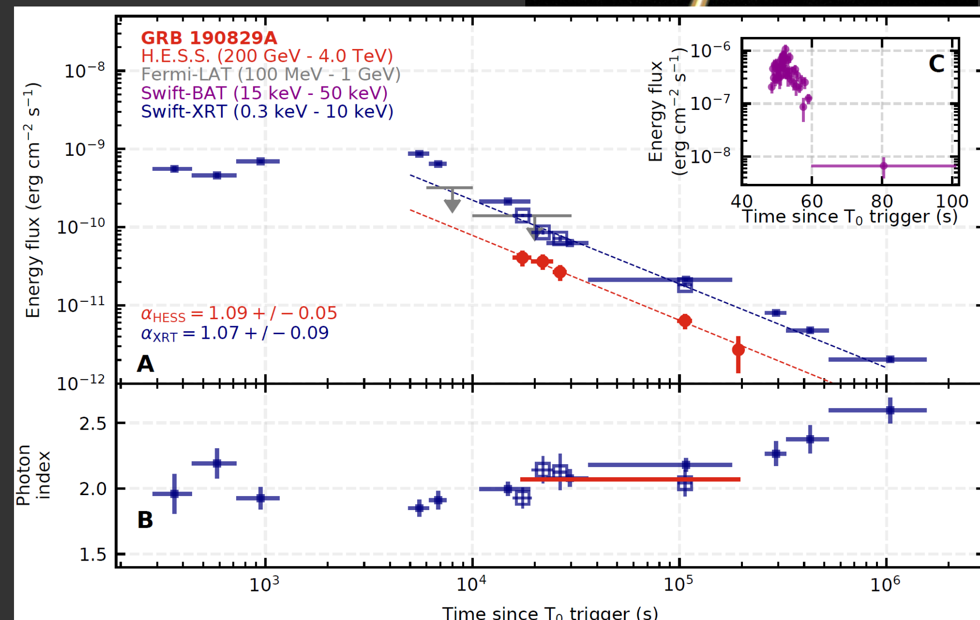


TeV Gamma Ray Bursts : A New Era Begins

(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 etal 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

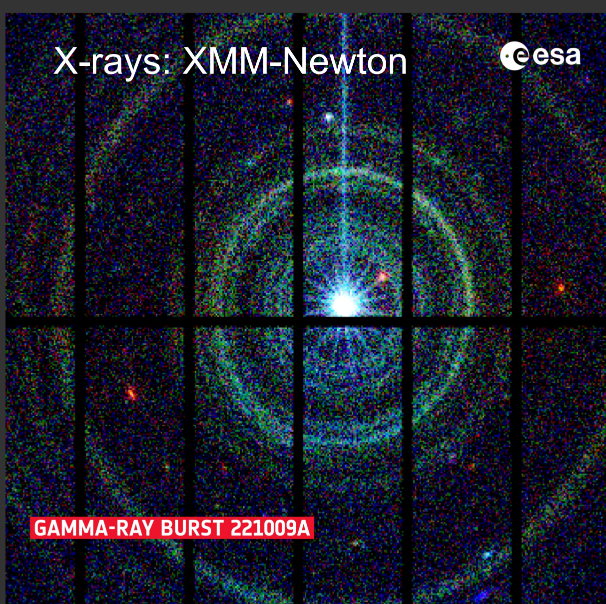
- LHASSO detection GCN32677

E>500 GeV   >100σ

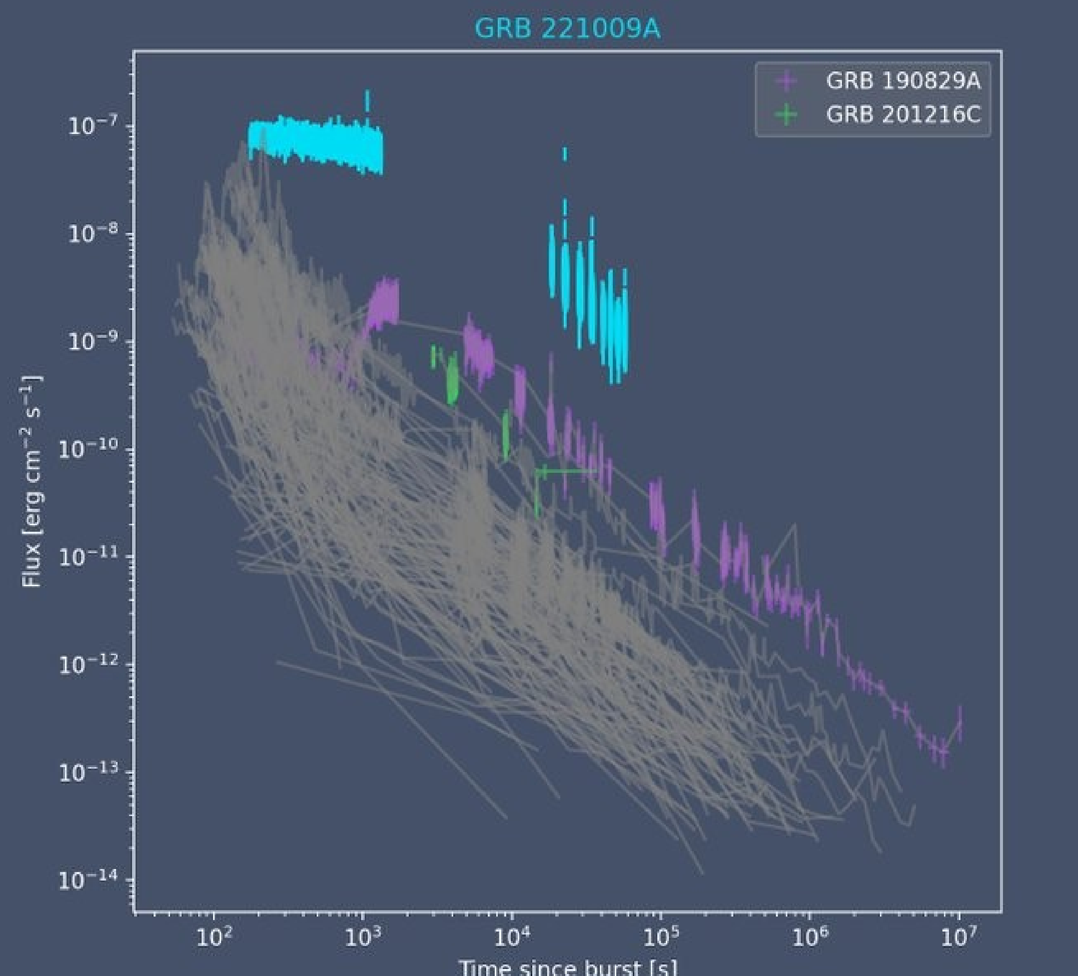
Emax = 18 TeV

→ Axions or Neutrino origin?

(7 arXiv papers)

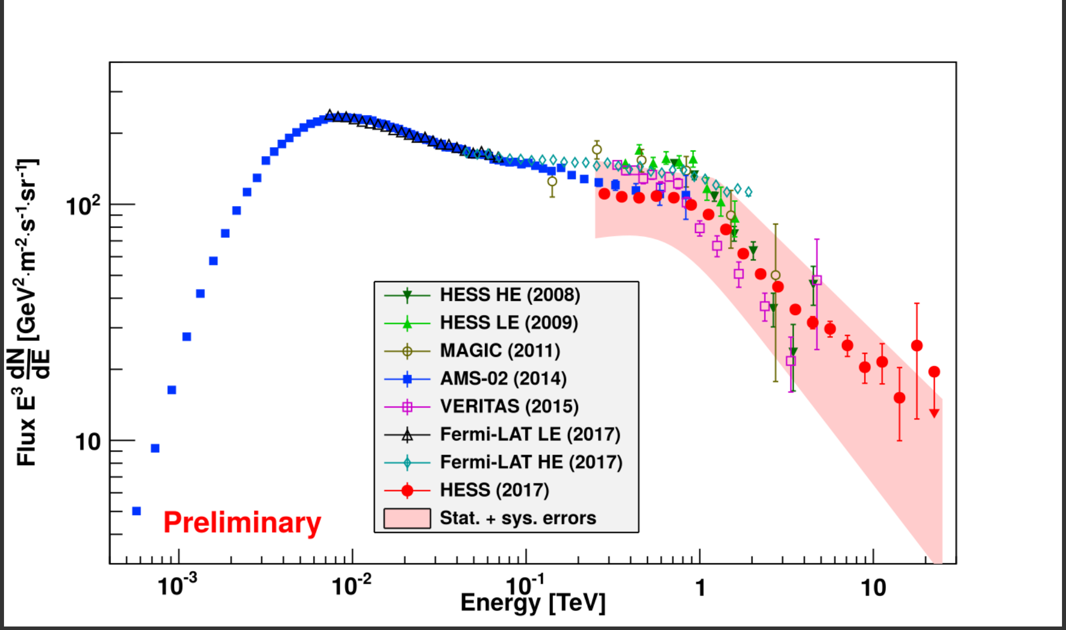


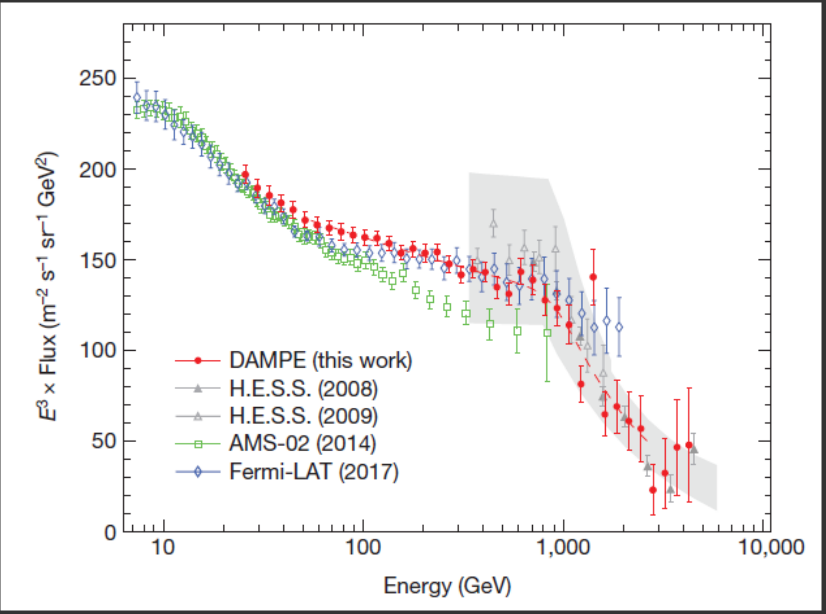
https://twitter.com/astrocolibri/status/1579478412678561792

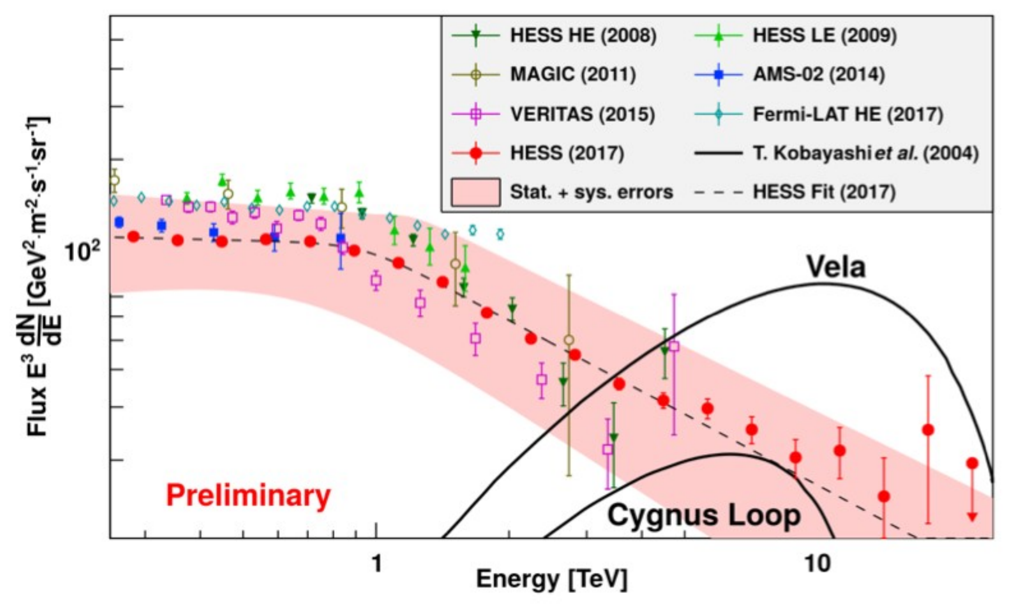


Electron Spectrum as seen by HESS

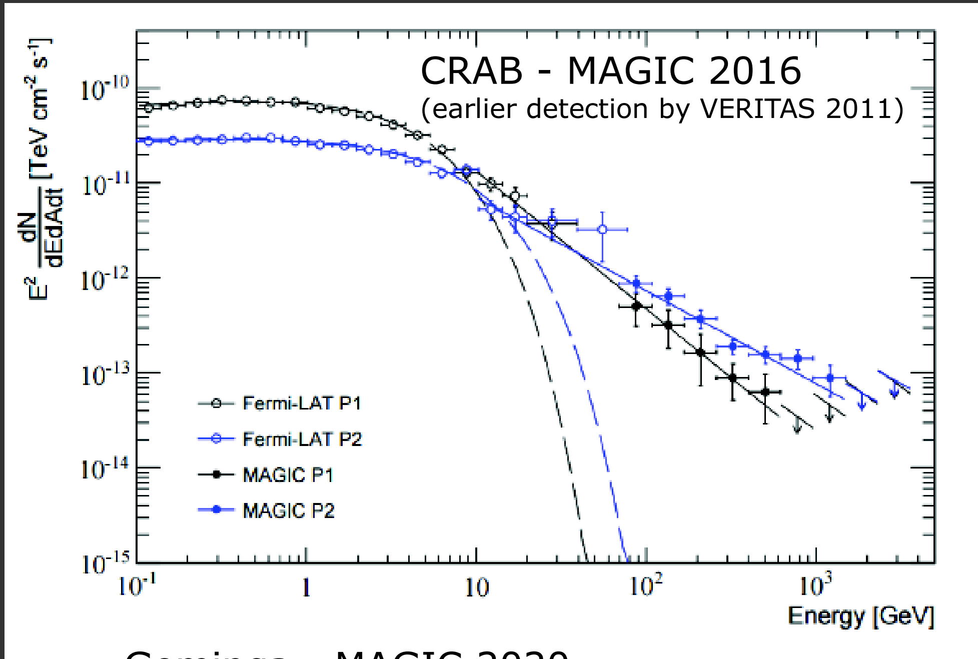
- HESS pushes electron spectrum up to ~20 TeV   HESS (2017)
- Spectral break at ~1 TeV
- Spectral break also reveal by DAMPE (2017)
- Electron spectrum >1 TeV constrains local accelerators

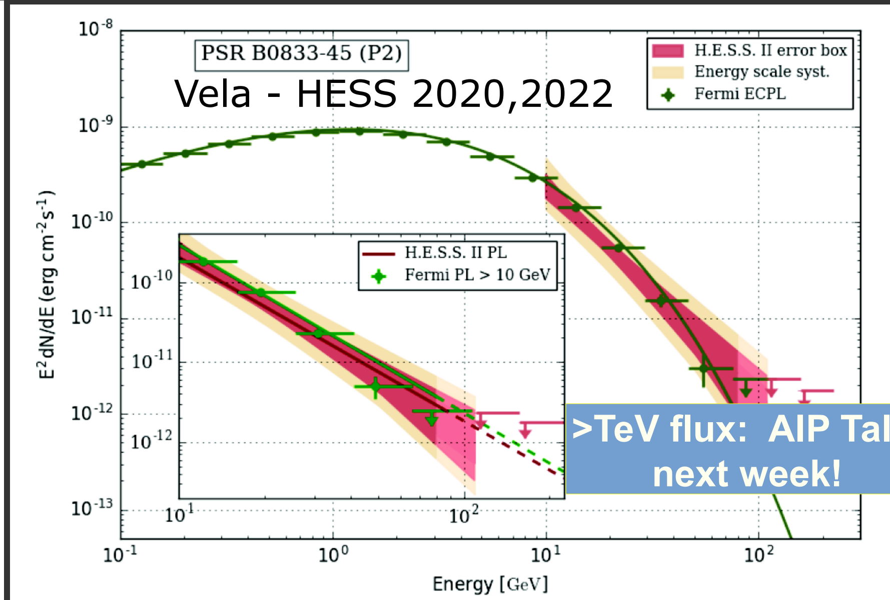




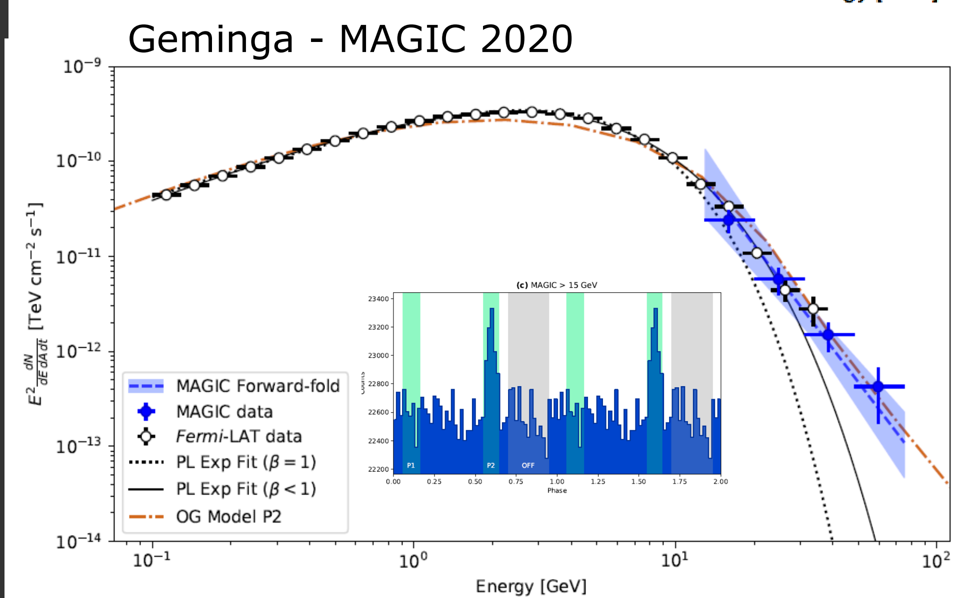


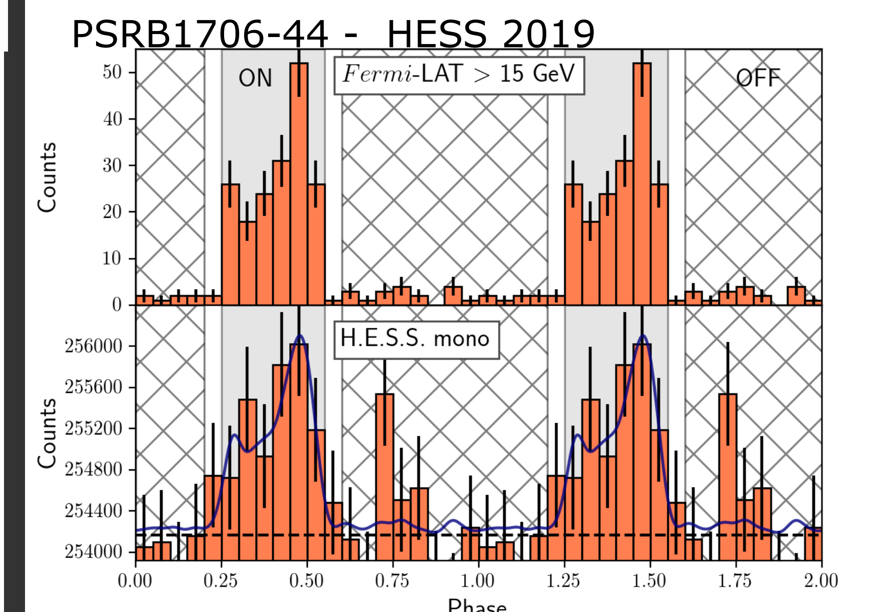
Now Four Pulsars Detected with Ground-Based Gamma-Ray Telescopes
– Crab, Vela, PSR B1706-44, Geminga (brightest pulsars in Fermi-LAT 2PC)
→ New electron components (e.g. inv-Compton) beyond curvature radiation...





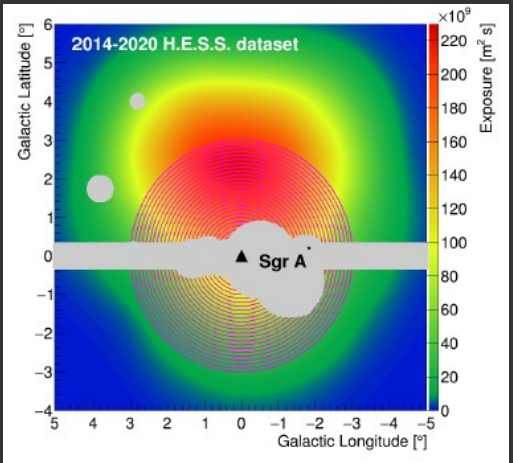
>TeV flux: AIP Talk next week!



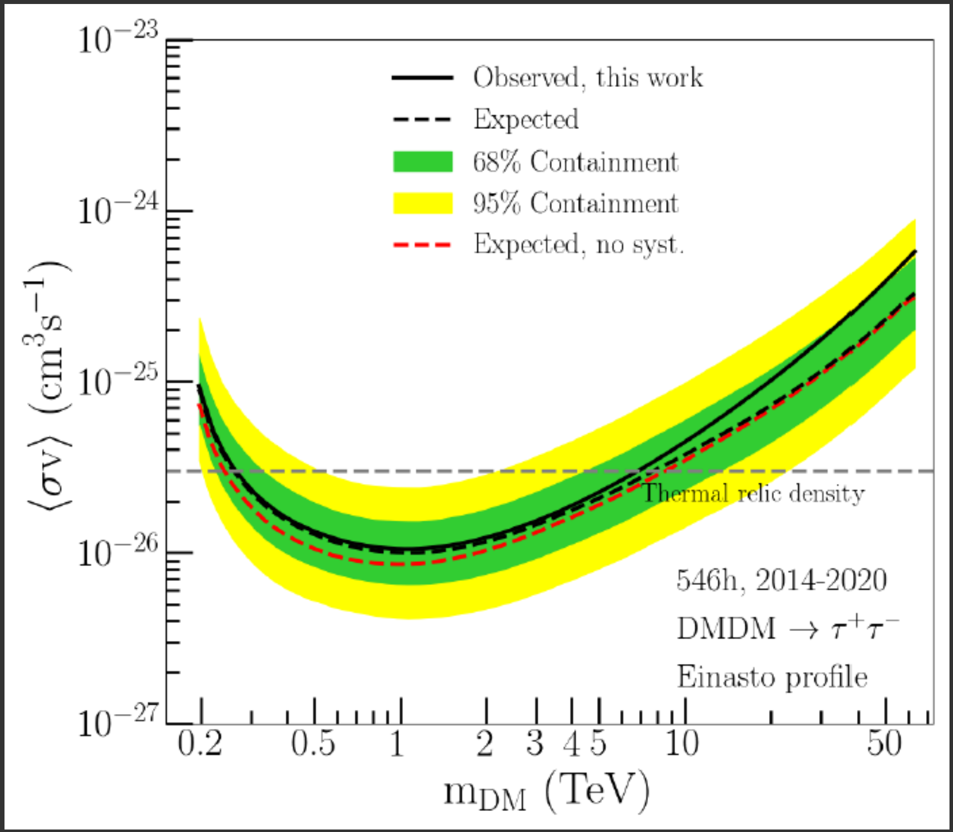


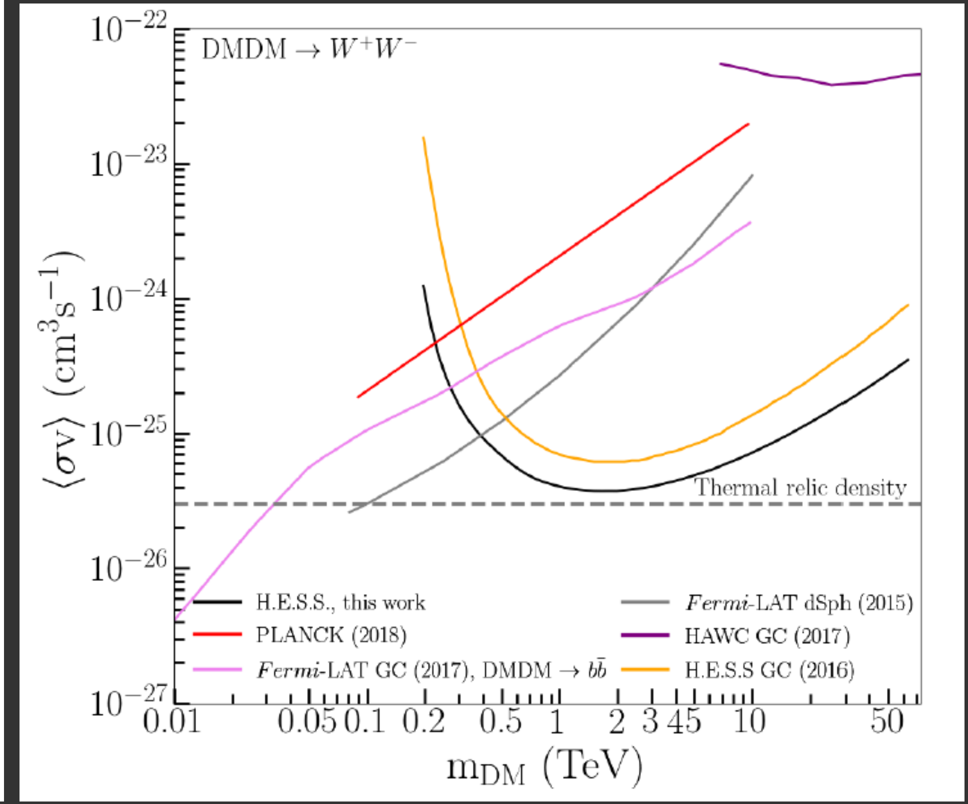
Dark Matter Search – Inner Galaxy Survey

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

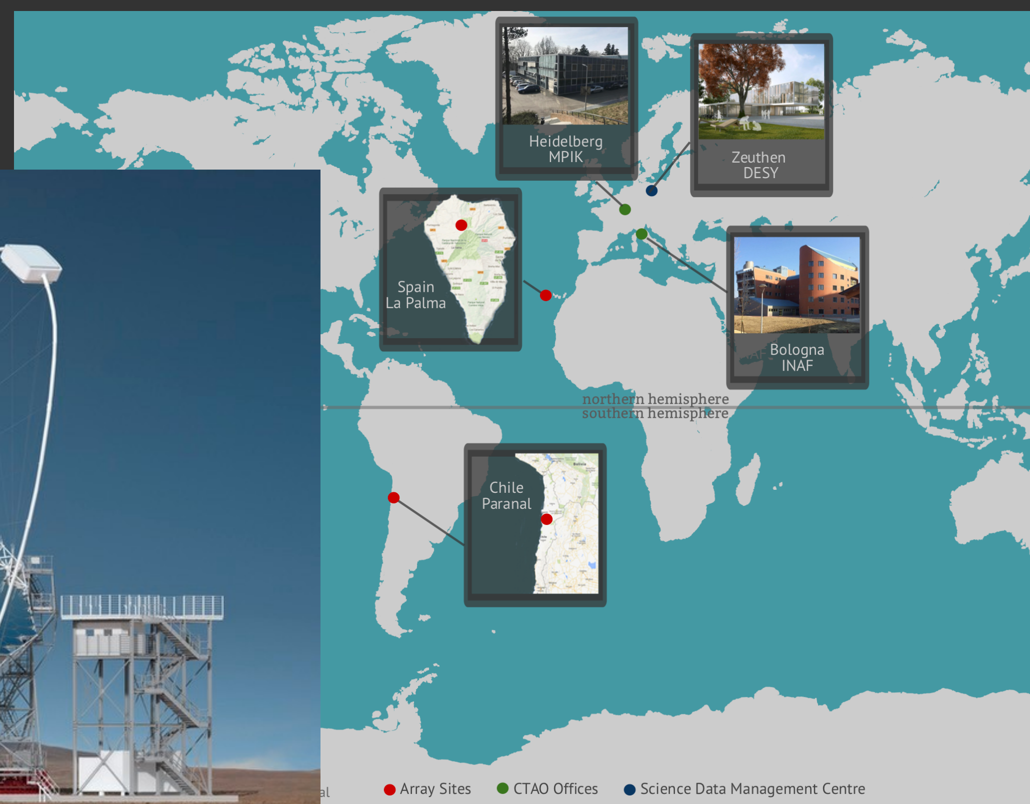
– Northern Array: 4 LSTs + 9 MSTs (La Palma, Spain)
1[st] telescope in operation!

– Southern Array: 14 MSTs + 37 SSTs (Paranal, Chile)
site prep. work underway

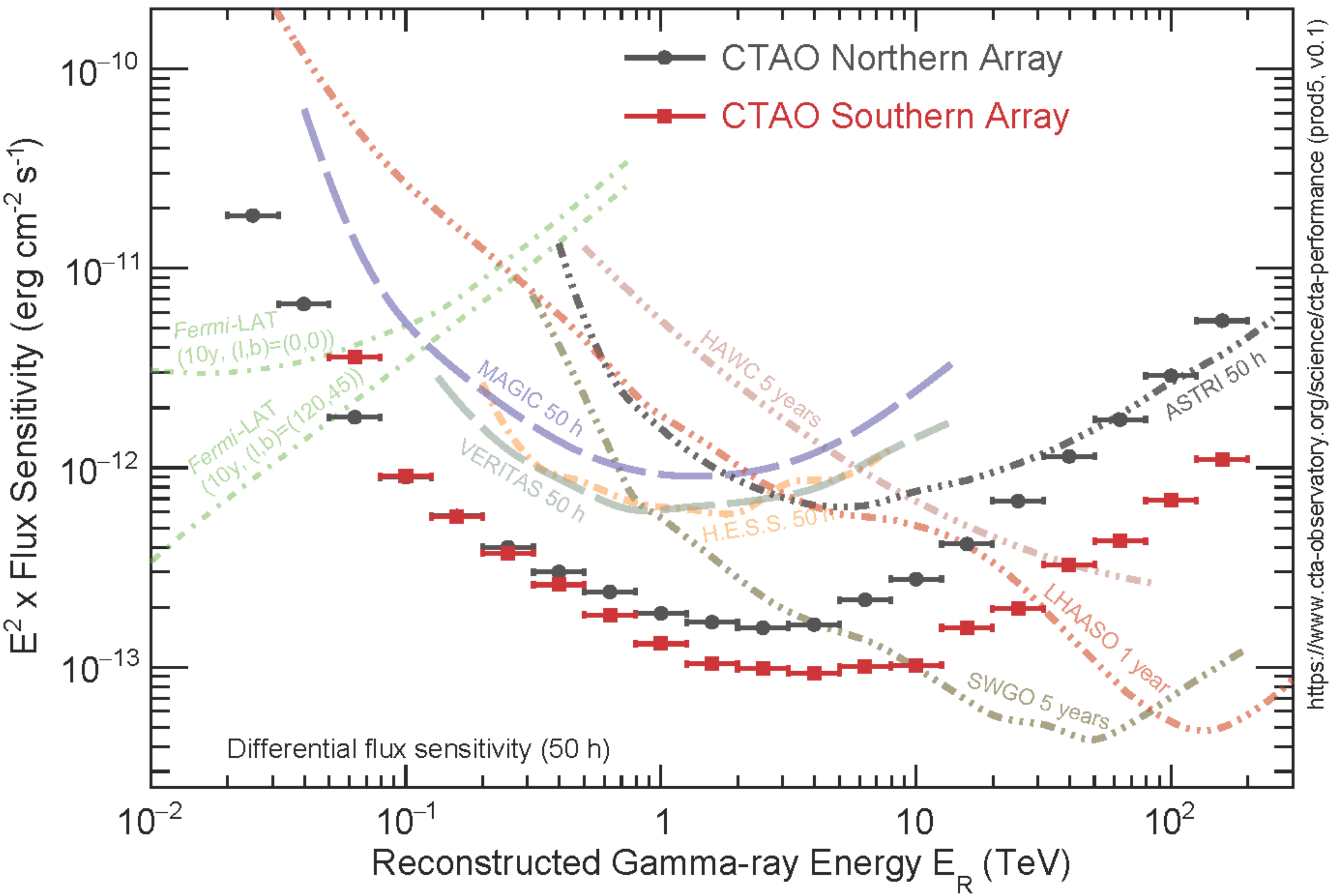
- CTA HQ, Bologna

- CTA Data Centre, Berlin

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

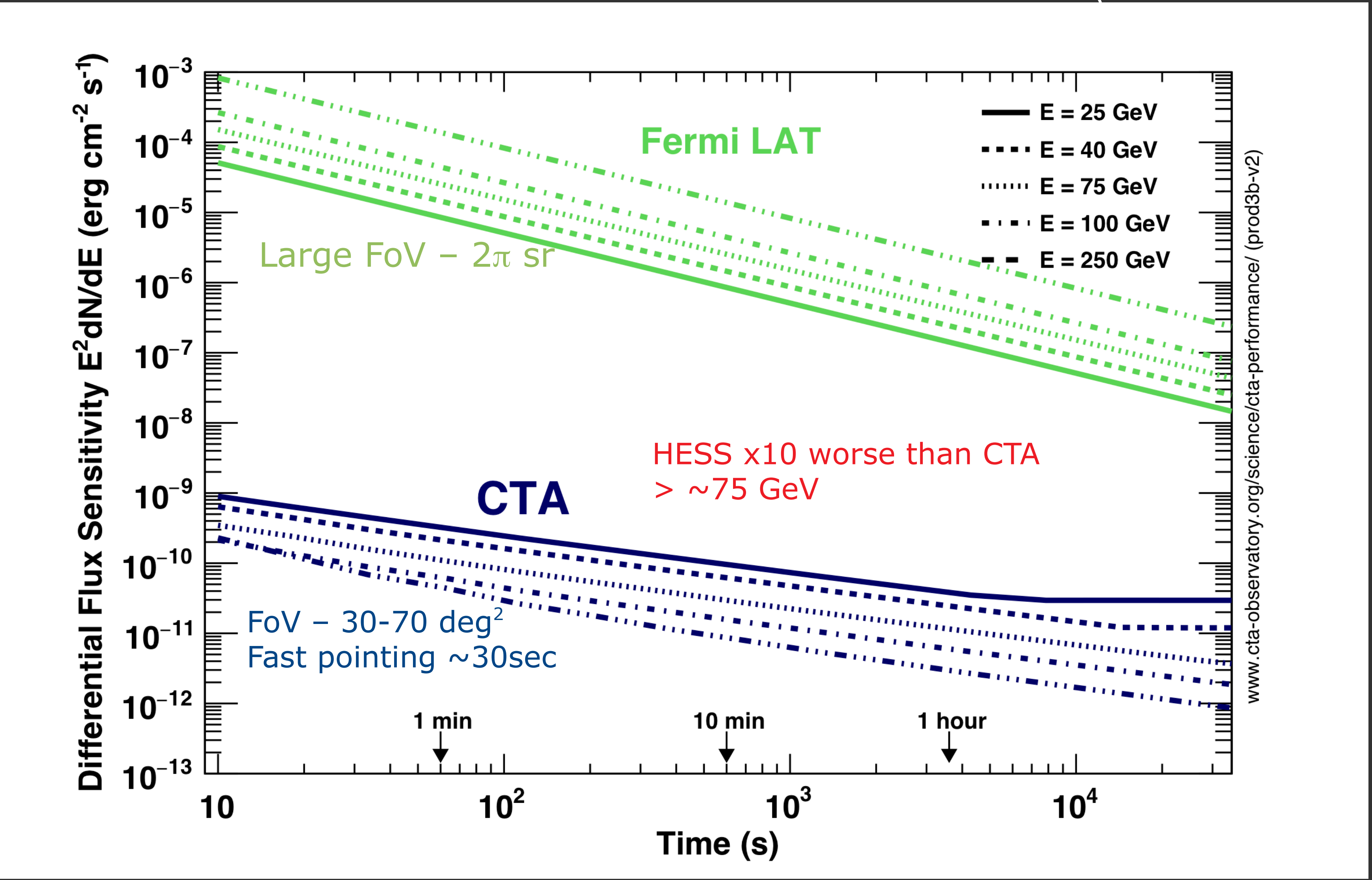


CTA Flux Sensitivity (50hr) vs. Others



Transients & Variable Sources: CTA Sensitivity vs. Time

(CTA Collab 2019)



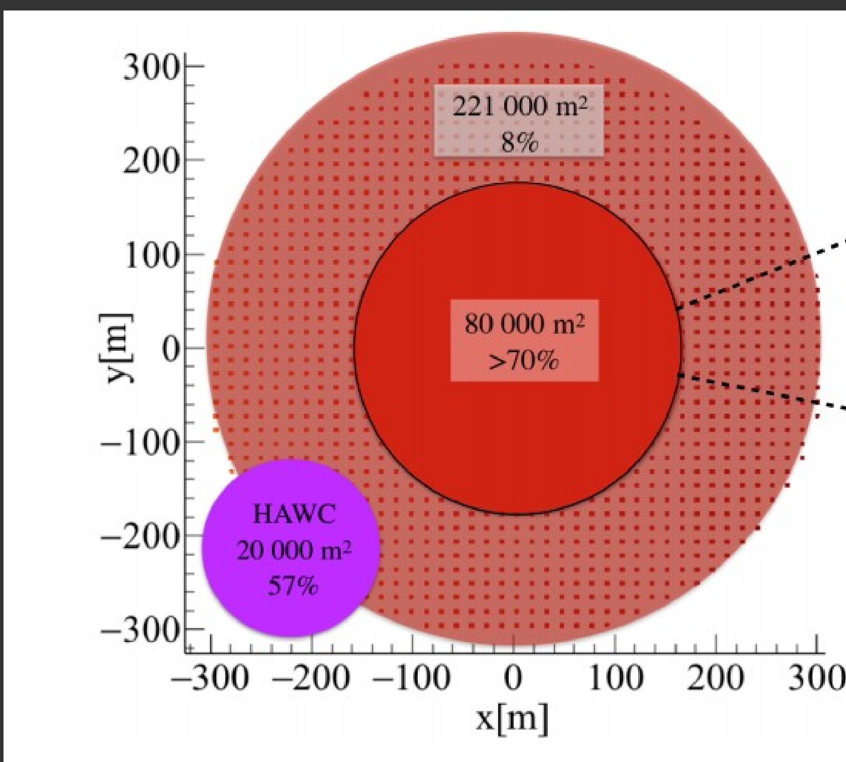
CTA >10,000 times more sensitive than Fermi-LAT in multi-GeV range

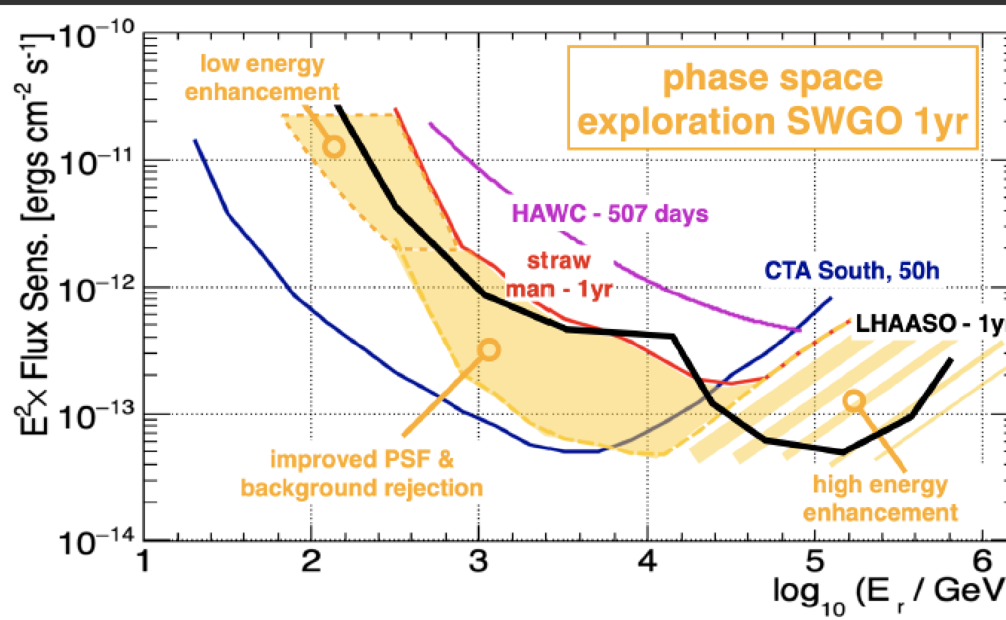
→ GRBs, AGN, giant pulses, FRBs, GW, SGR bursts......

SWGO – Southern Widefield Gamma ray Observtory

https://www.swgo.org

- 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





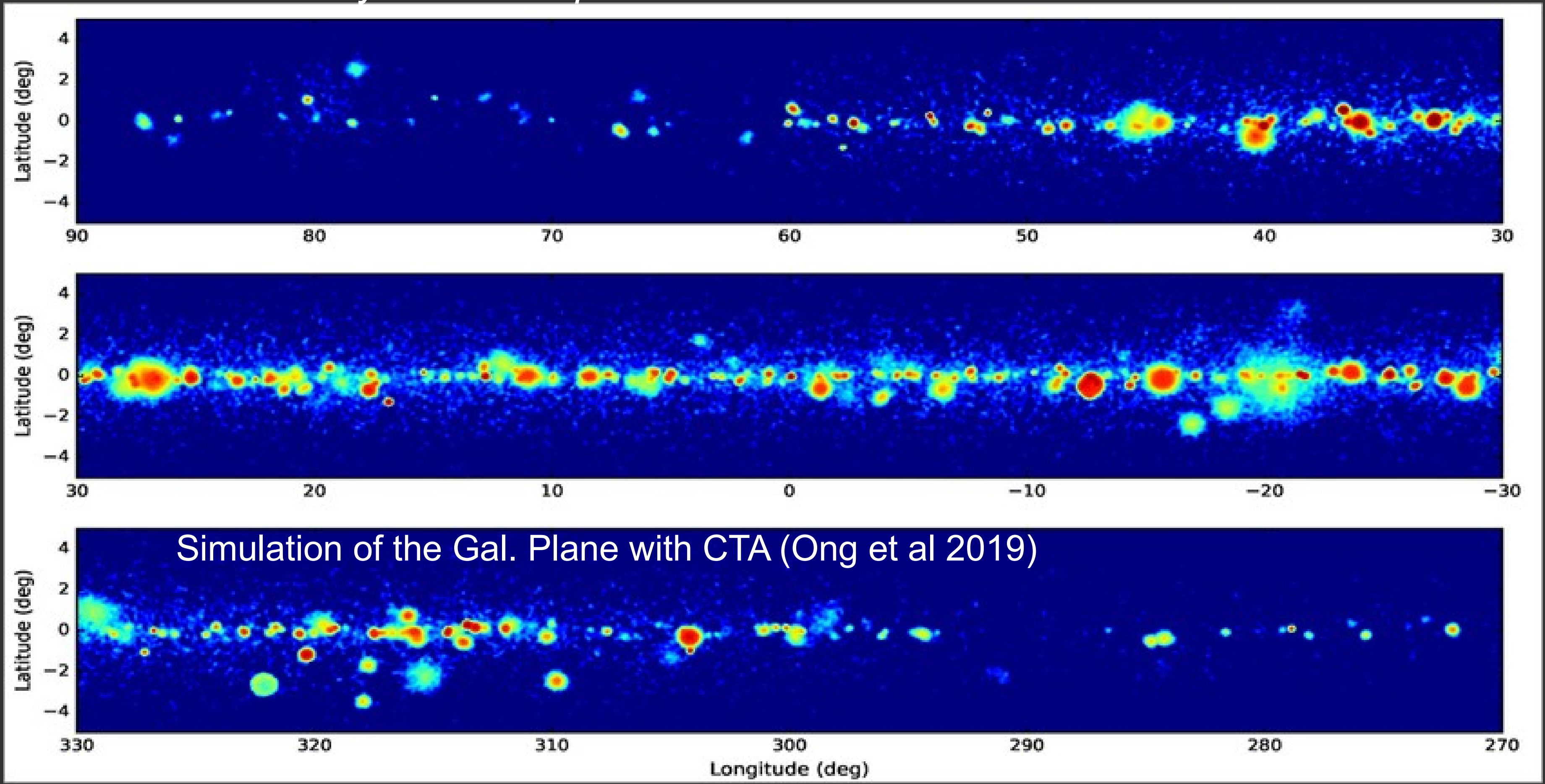
Galactic Plane: A major astrophysical challenge for CTA

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

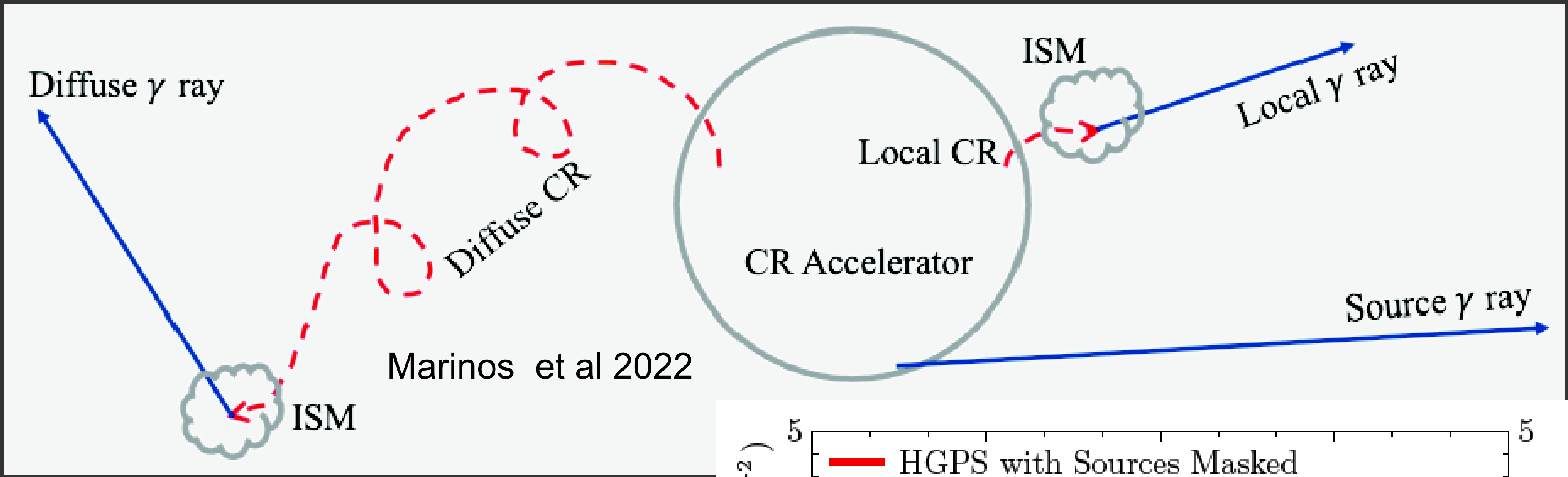
Already hints for TeV & PeV diffuse emission from HESS (2014) and Tibet ASgamma (2021), but maybe from unresolved sources Vecchiotti etal 2022

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 >100s pc from their accelerators → interacting with ISM → gamma rays



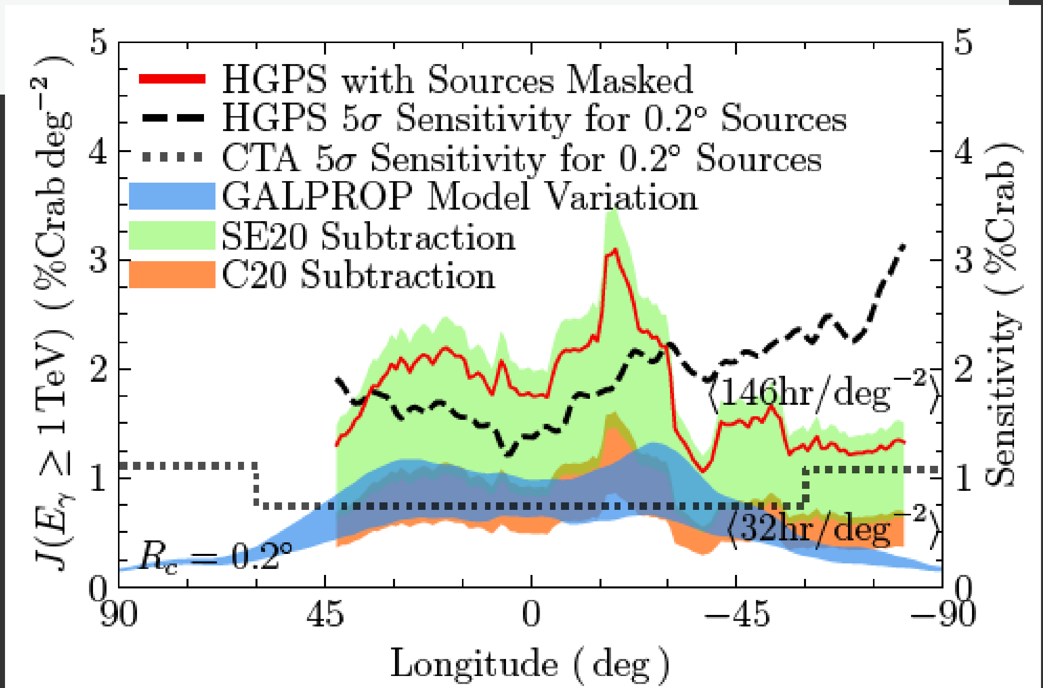
Marinos et al 2022

GALPROP predictions >1 TeV

- Subtract discrete sources from HESS Gal. Plane Survey & estimates of unresolved sources.
  → estimate of TeV diffuse emission

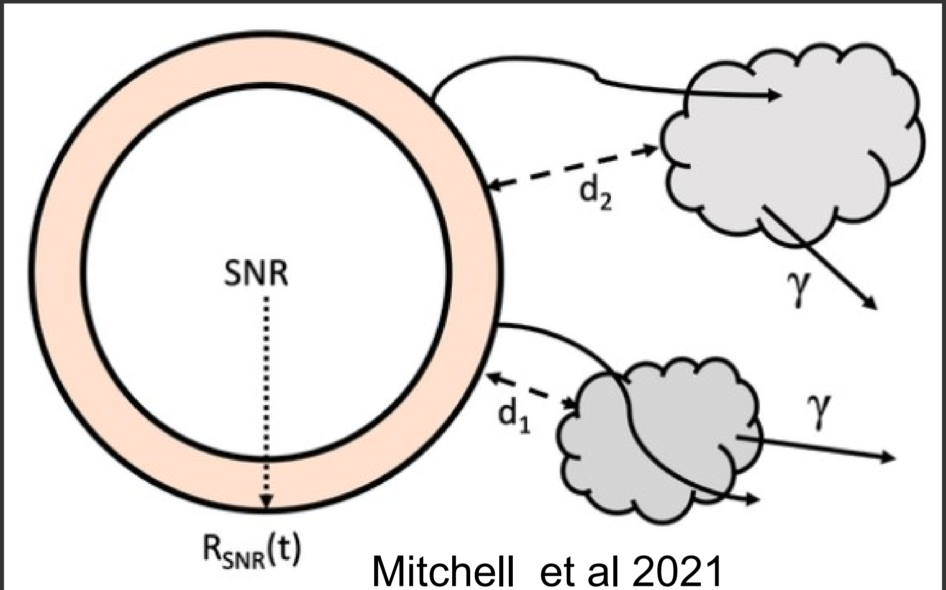
- Compare to GALPROP under variety of inputs (blue region)

→ CTA will detect this emission

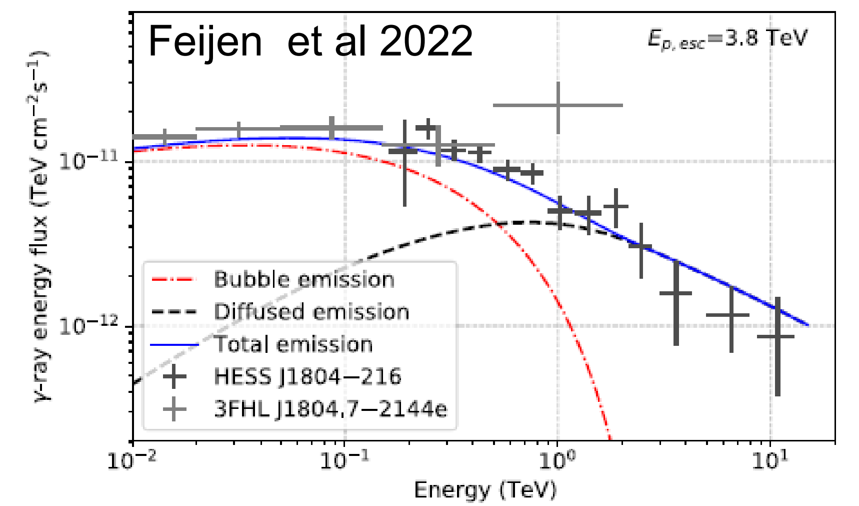


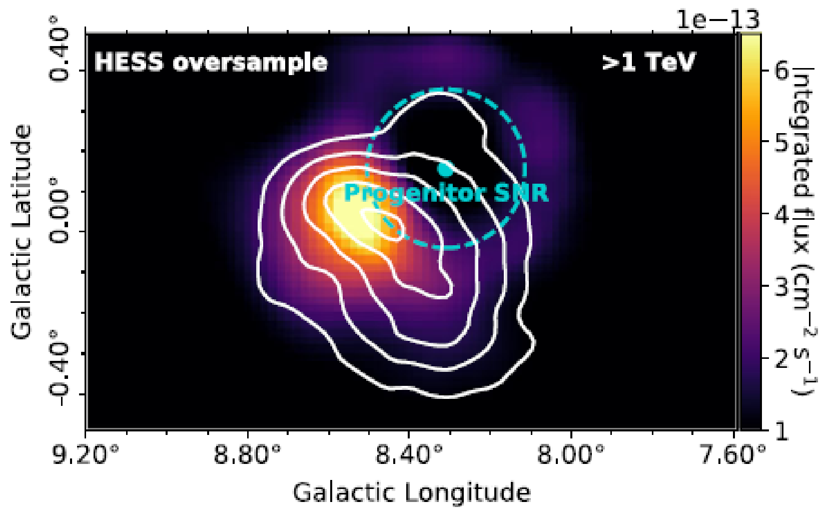
Galactic Plane: A major astrophysical challenge for CTA

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



Mitchell et al 2021





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

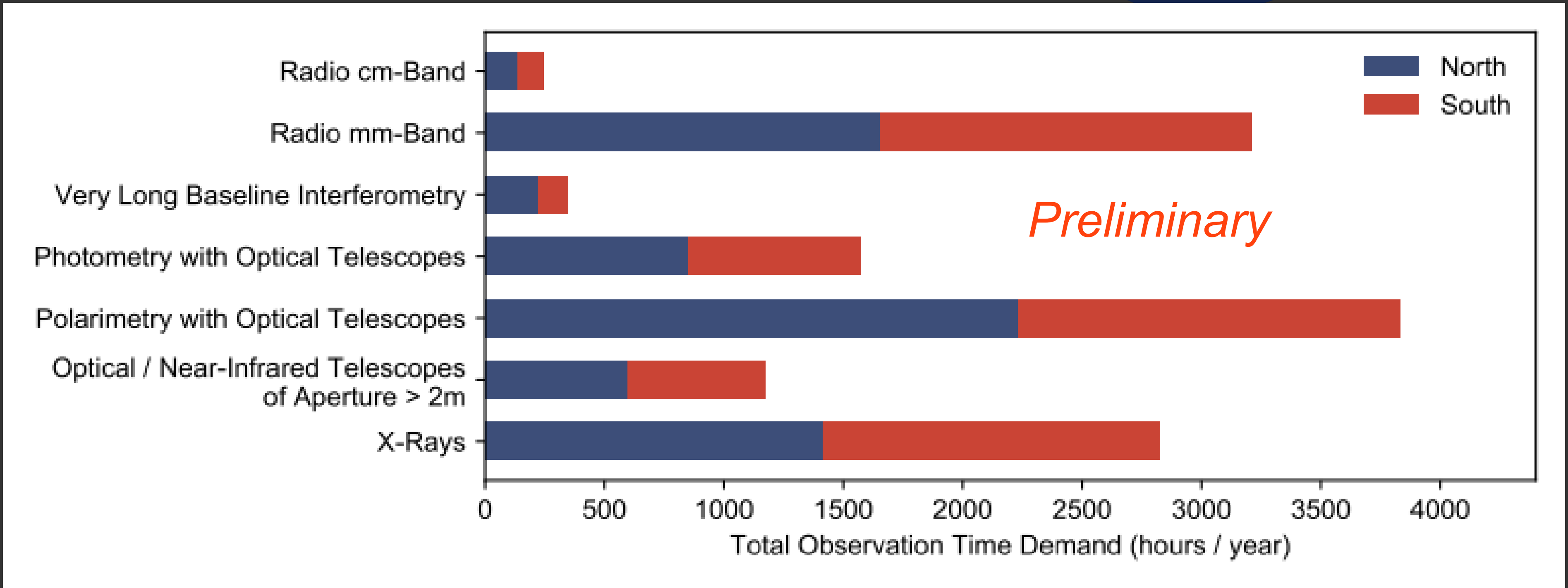
Thank you...

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 etal 2017, Ruhe etal 2019
+ Einecke, Rowell, Lee….

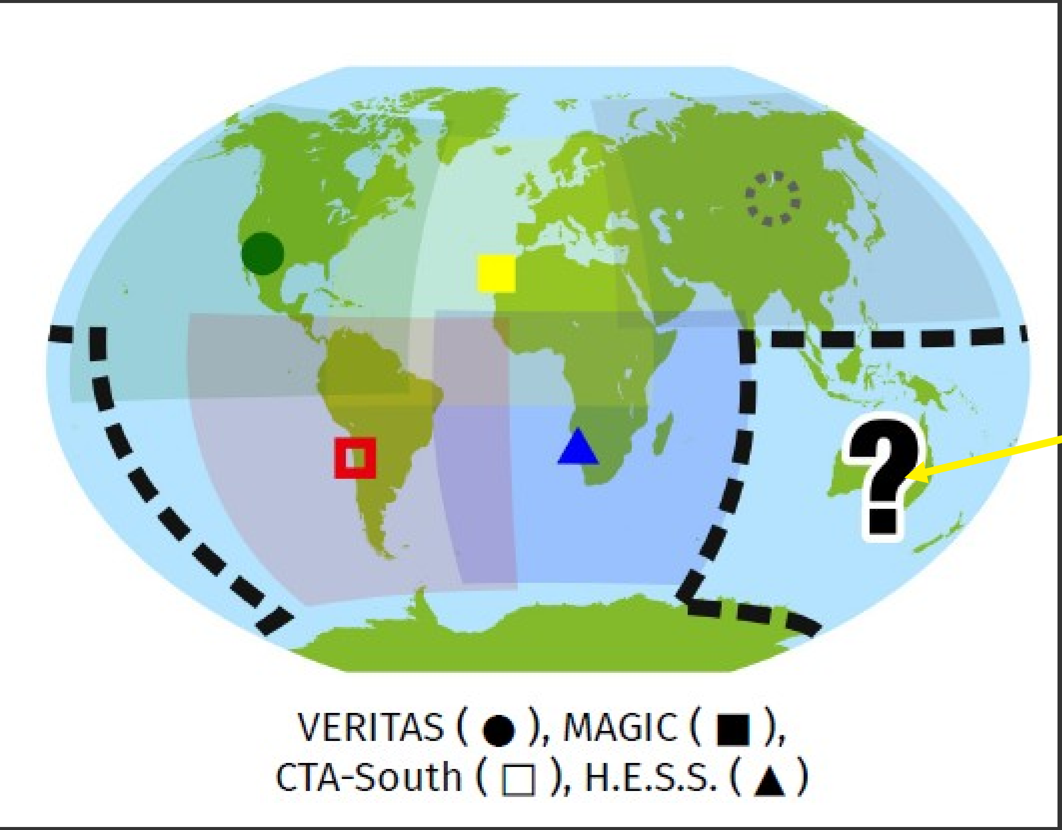
- Worldwide network of Cherenkov telescopes

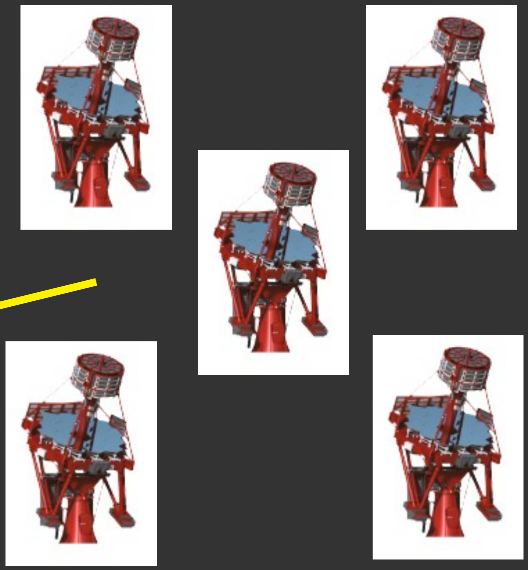
→ need to provide >=1 km^2 instantaneous collection area

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!