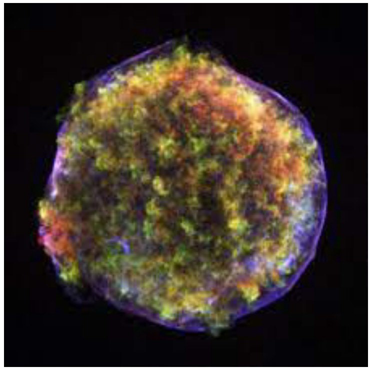
Very High Energy Gamma-Ray Astronomy and the search for PeVatrons

Heide Costantini
Aix-Marseille Université-CPPM

Why Gamma-ray astronomy ?

- Gamma-rays are produced in the most extreme enviroments of the Universe

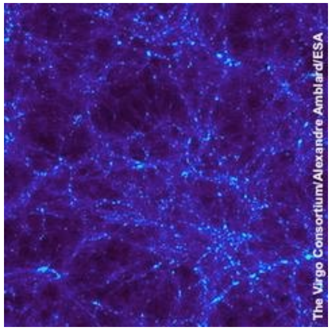
relativistic jets produced by massive and supermassive black holes ***(Micro-quasar, quasar, AGN)***



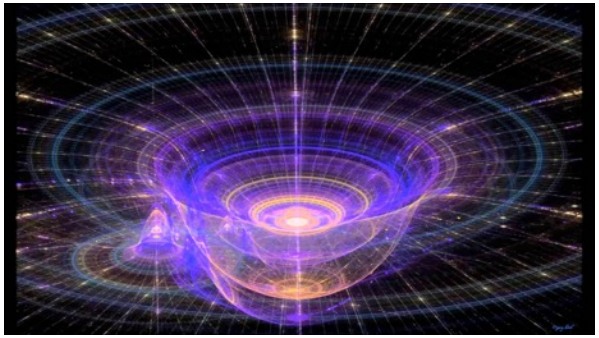
SuperNova Remnants

Gamma Ray Bursts

- Gamma-rays can be used to explore the Frontiers in Physics



dark matter annihilation signature



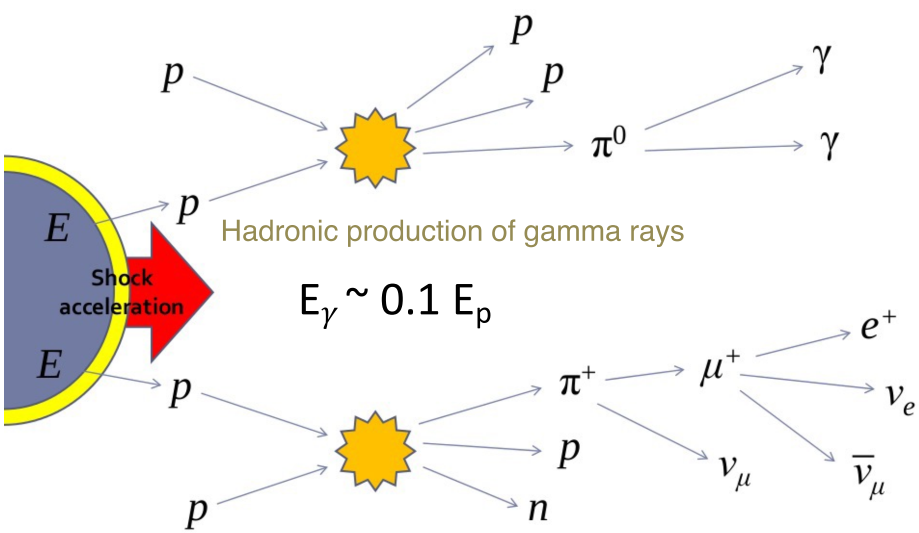
quantum gravity effects in photon propagation

The origin of Galactic Cosmic Rays

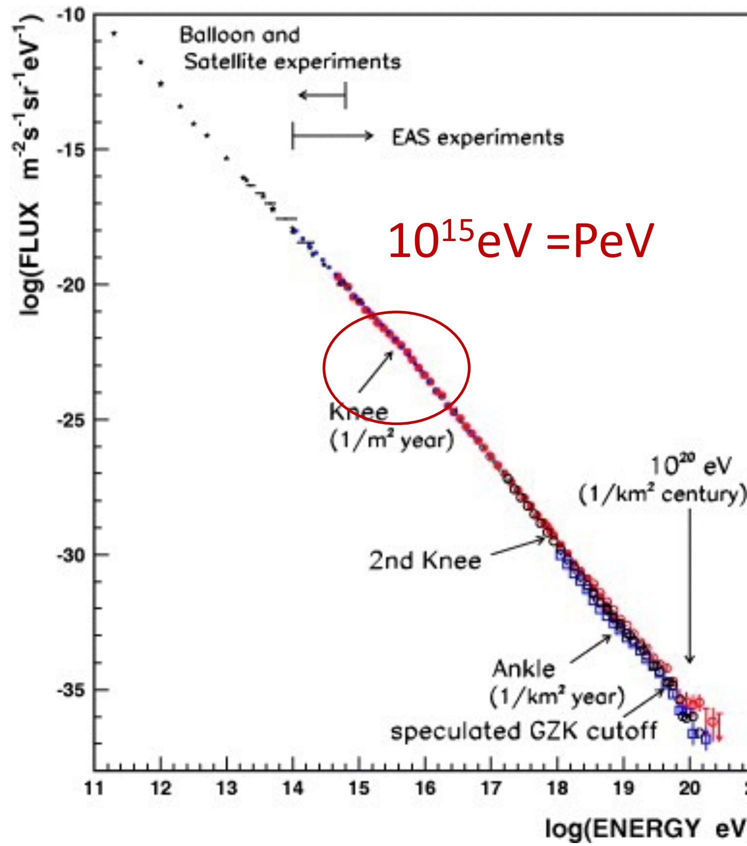
Cosmic rays with energy below the Knee ($E < 10^{15}$ eV) are thought to be of Galactic origin

PeVatrons:

Sources accelerating Charged particles up to PeV energy

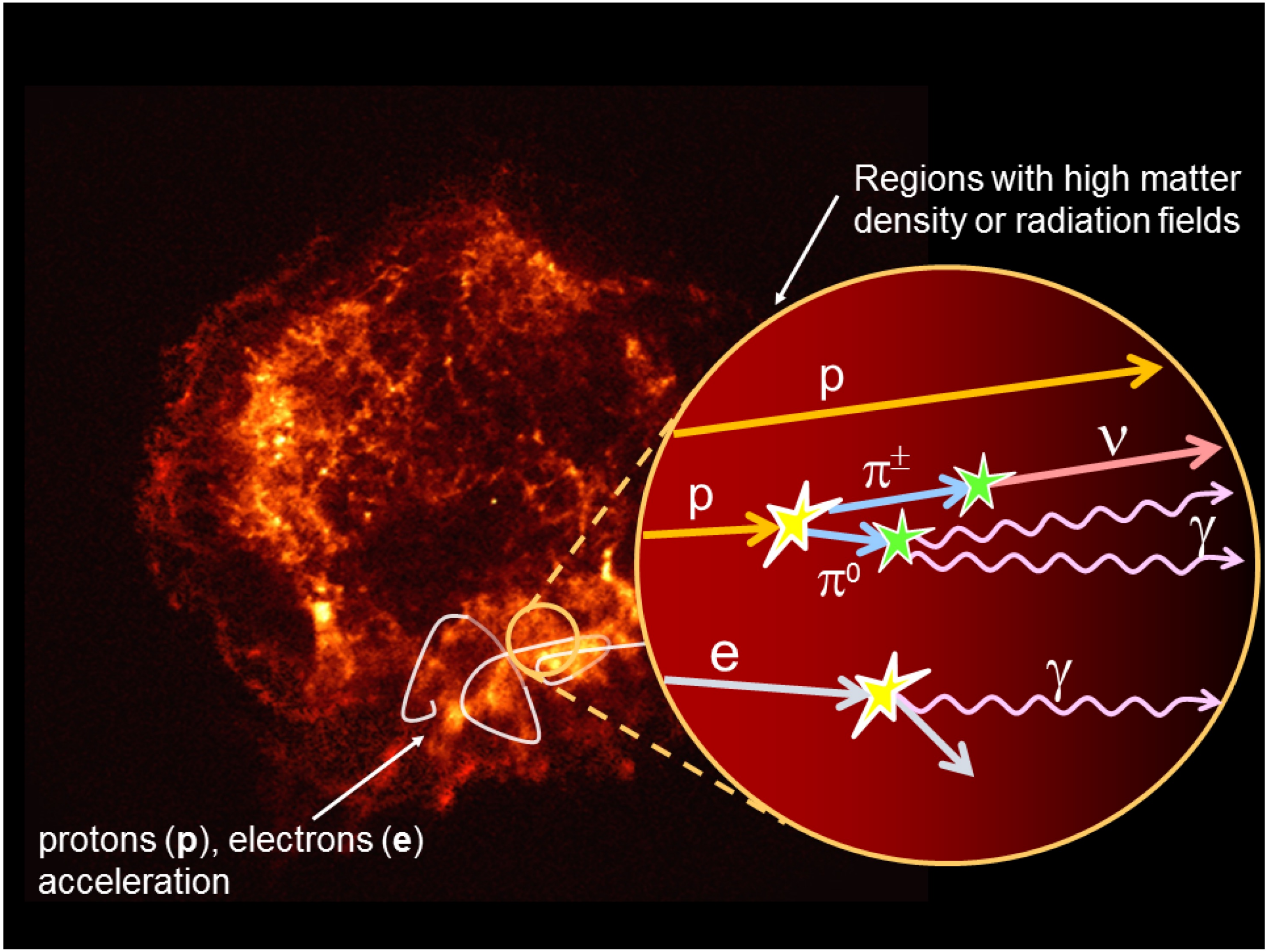


$E_\gamma \sim 0.1\, E_p$

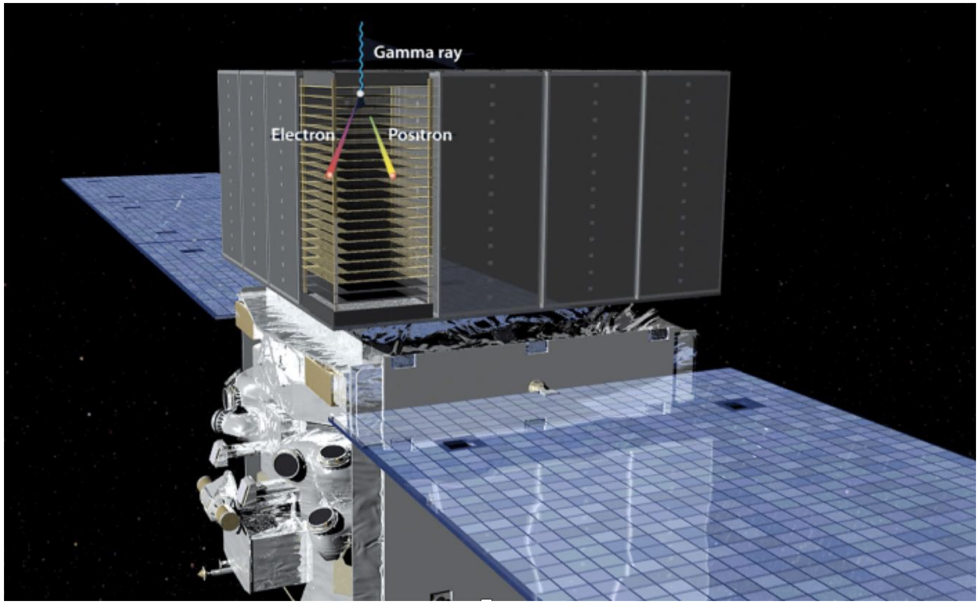


Sources of very high energy photons (>100 TeV) are good PeVatron candidates

Gamma-ray production: Hadronic and Leptonic



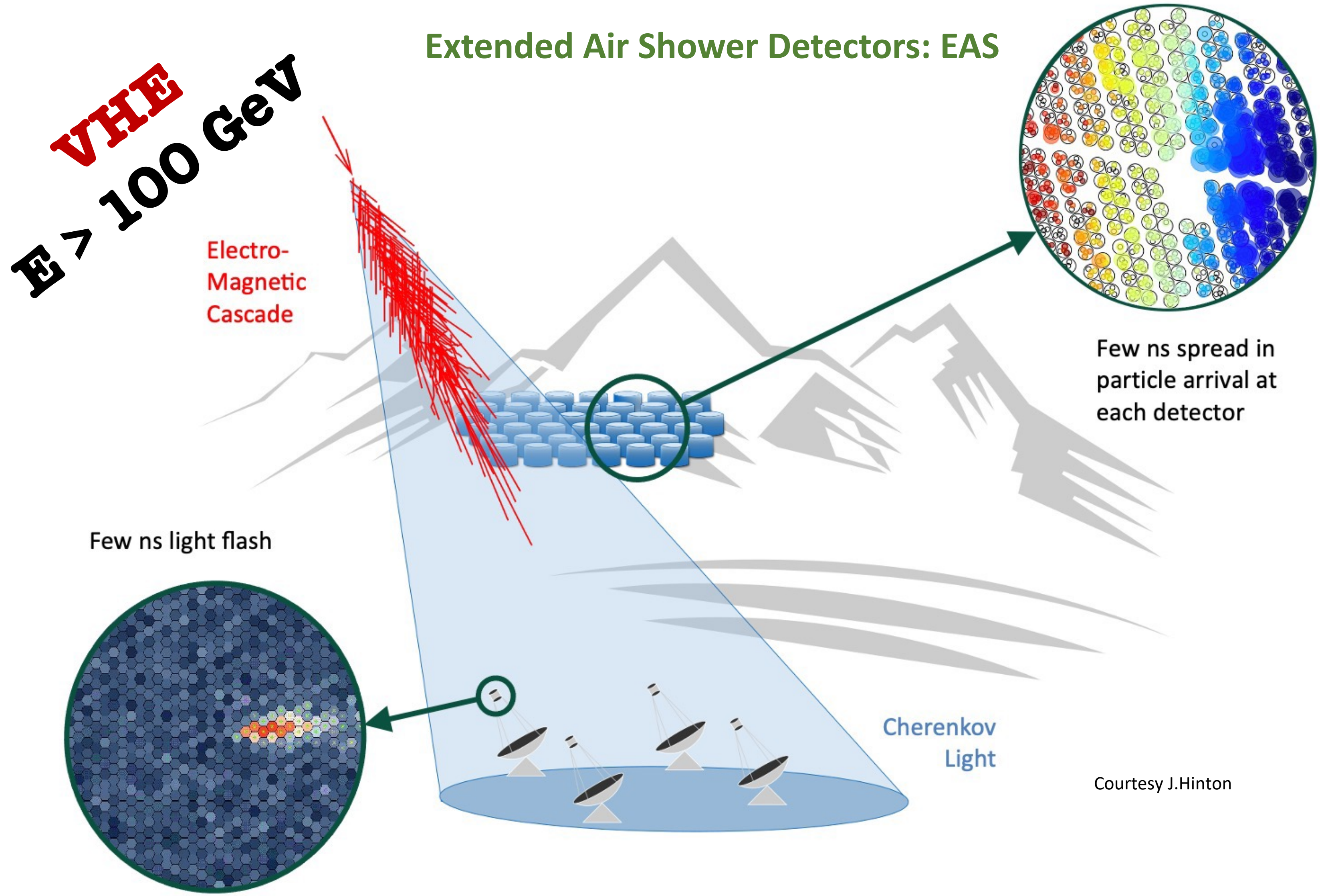
Fermi/LAT



HE
~ 10 MeV-100 GeV

- Energy range: 20 MeV - 300 GeV
- Angular resolution : 3.5° (100 MeV) – 0.15° (100 GeV)
- Large Field of view

Detection techniques on the ground

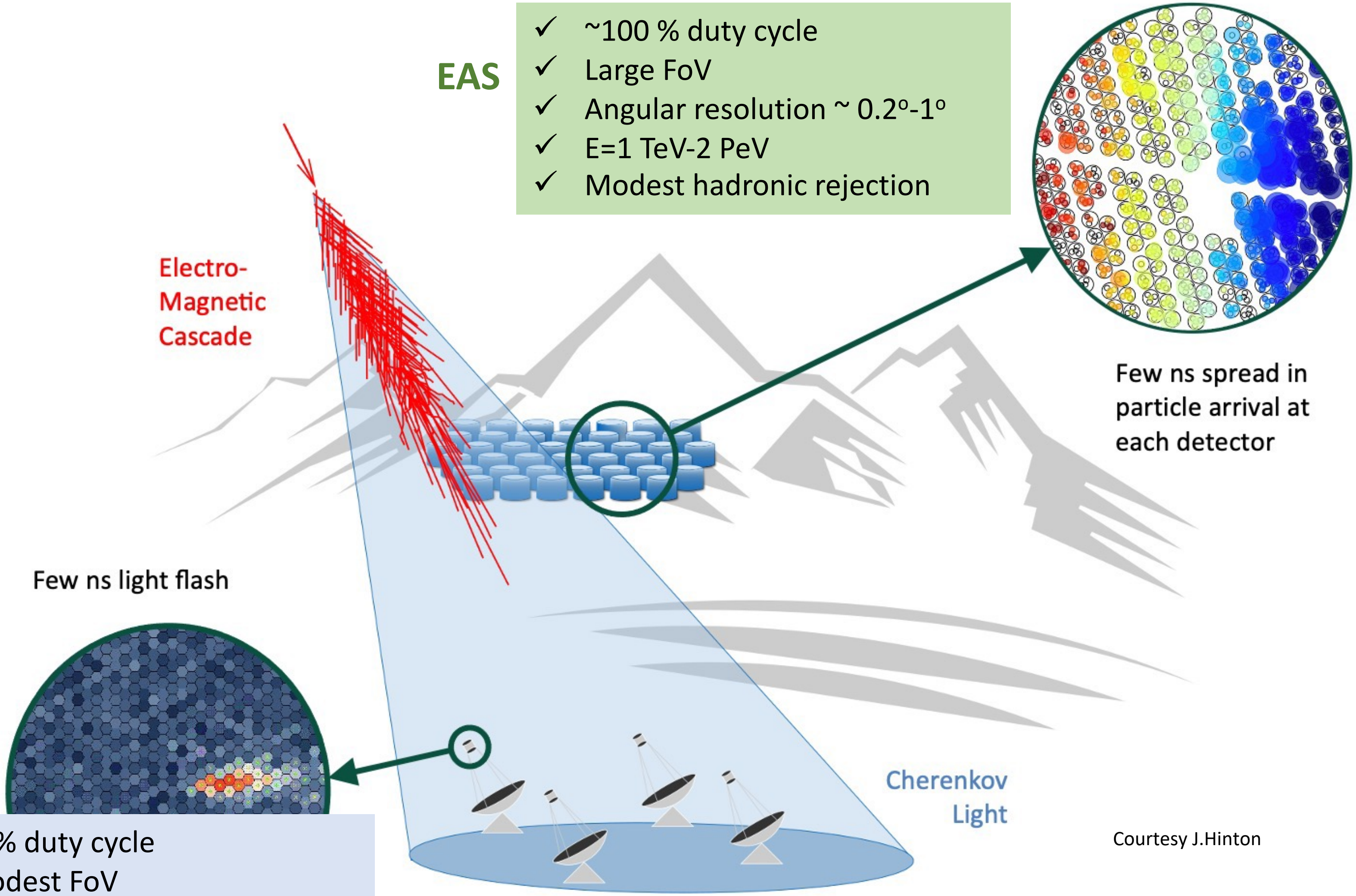


Imaging Air Cherenkov Telescopes; IACT

Detection techniques on the ground

EAS

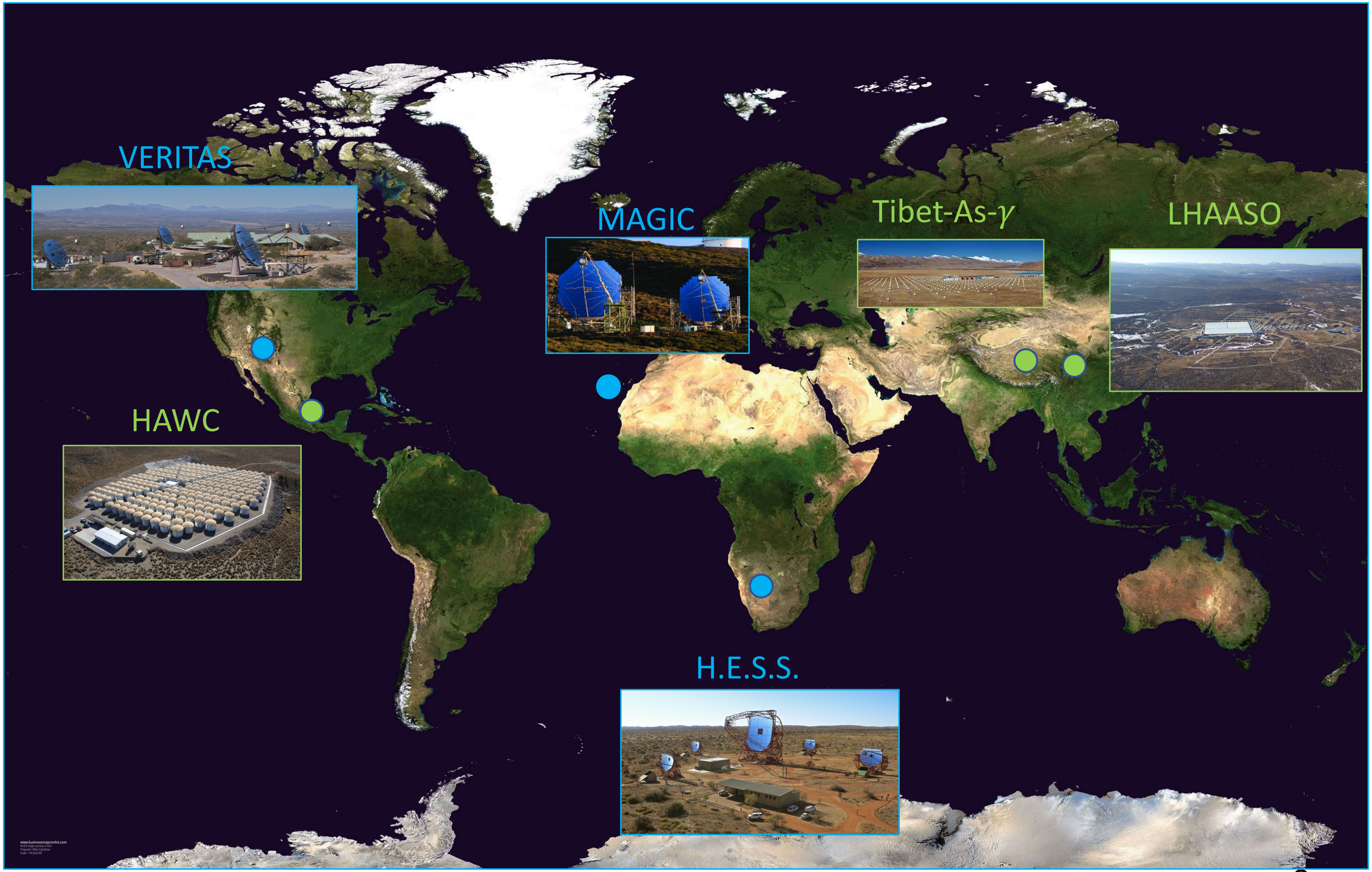
- ✓ ~100 % duty cycle
- ✓ Large FoV
- ✓ Angular resolution ~ 0.2°-1°
- ✓ E=1 TeV-2 PeV
- ✓ Modest hadronic rejection



IACT

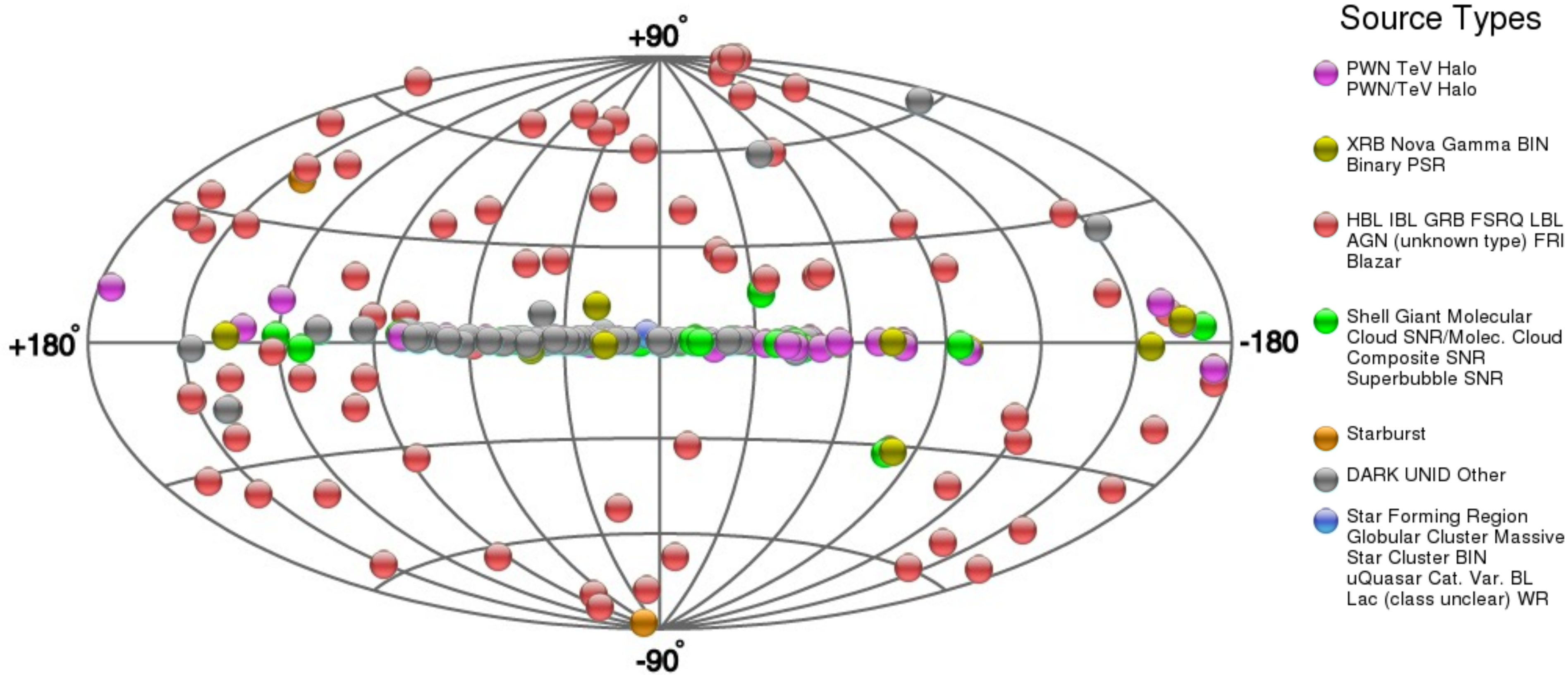
- ✓ 15% duty cycle
- ✓ Modest FoV
- ✓ Angular resolution ~ 0.1°
- ✓ E= 0.03-100 TeV
- ✓ Very good hadronic rejection

Current instruments: IACT, EAS



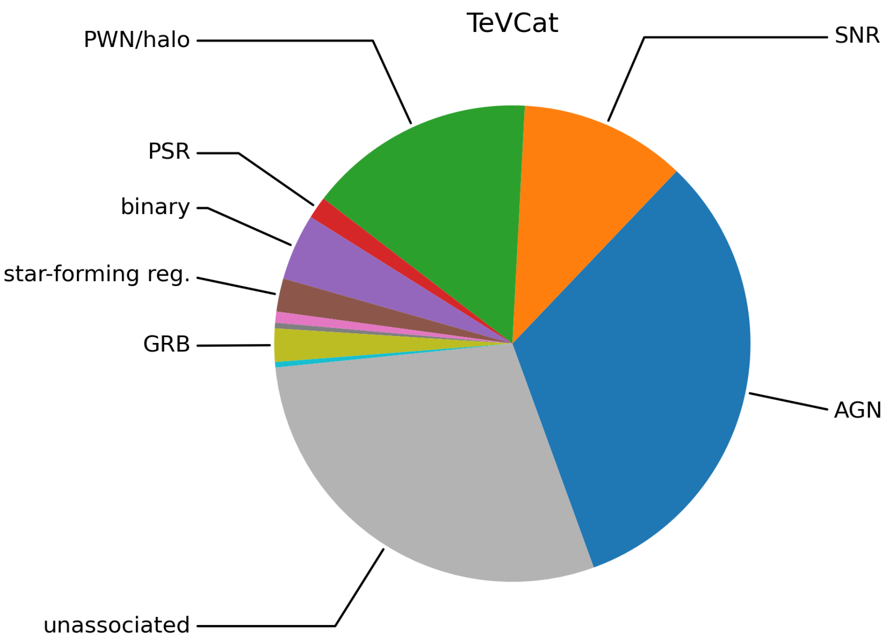
Sources at VHE

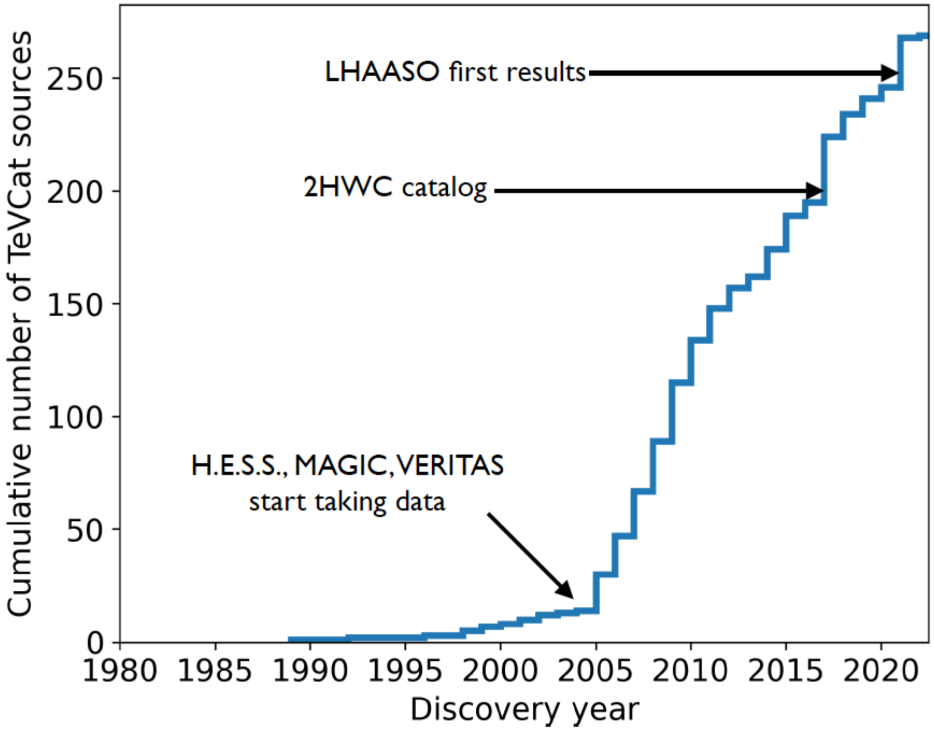
~250 sources detected in the TeV energy band



TeVCat catalog: http://tevcat.uchicago.edu/

Sources at VHE



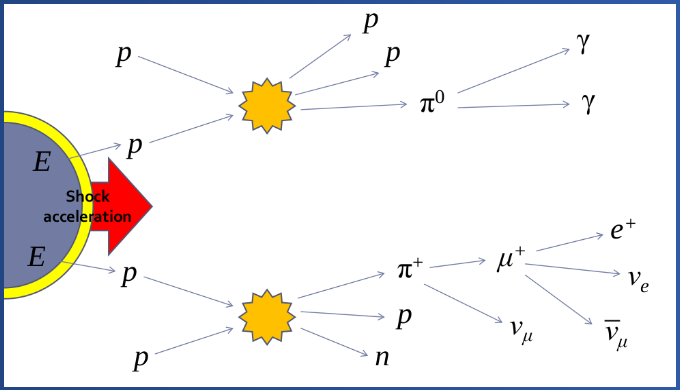


Different types of sources:
particle acceleration and transport in different astrophysical conditions and environments

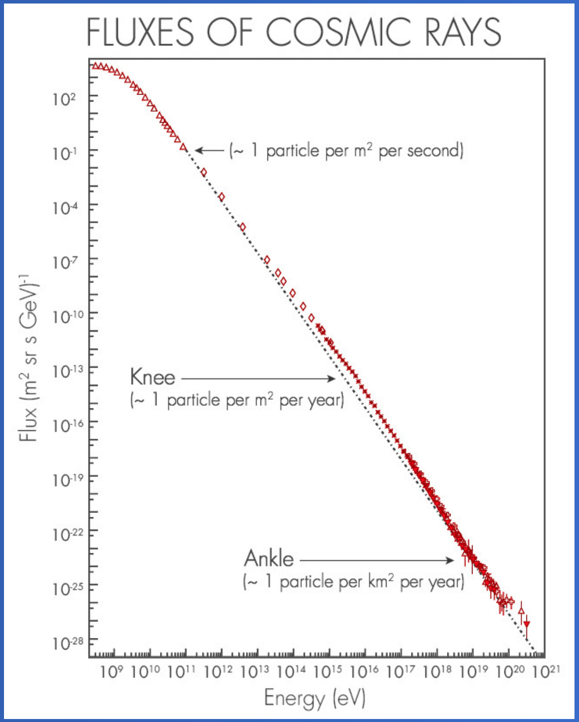
Continuous increase of detected sources:
Steep increase correlated with start of new instruments data taking

Courtesy L. Tibaldo

Cosmic ray sources in the Galaxy

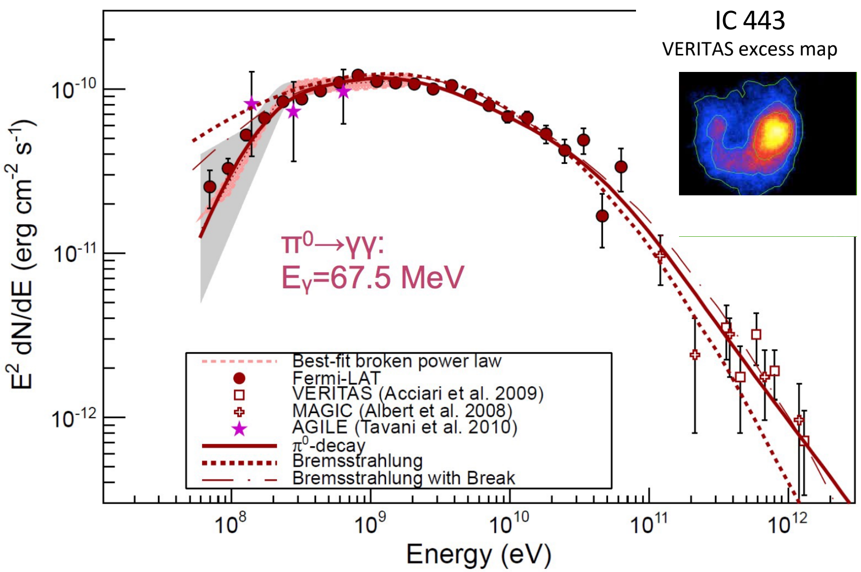


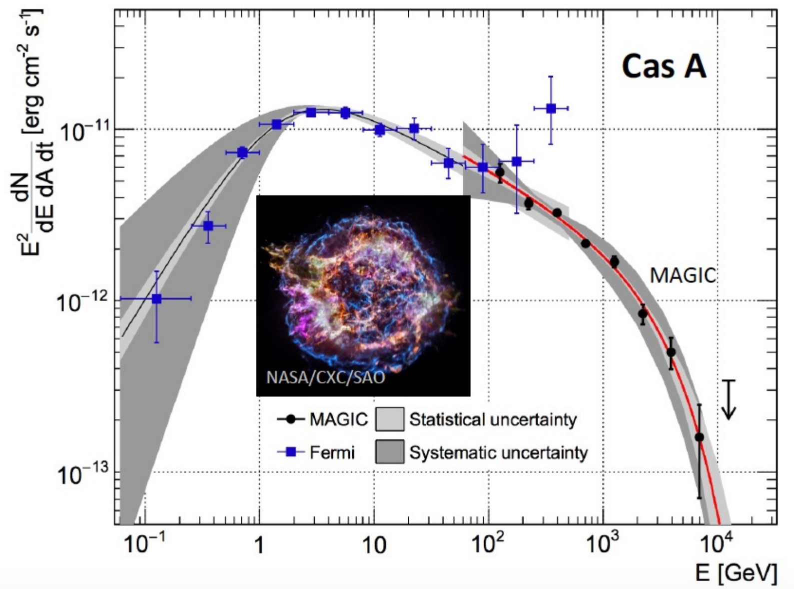
$E_\gamma \sim 0.1\ E_p$



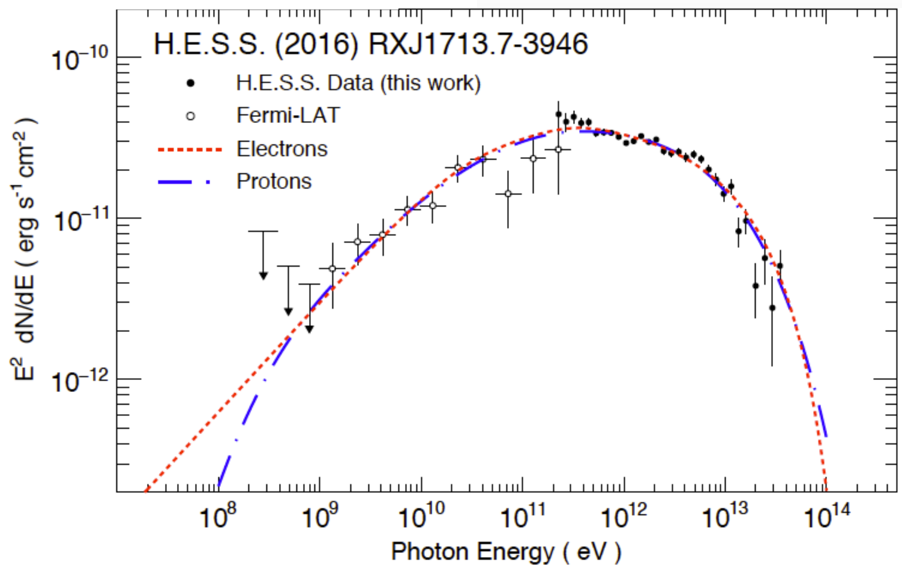
Are SuperNovaRemnants PeVatrons?

CR Energy density ~1 eV/cm3 is equal to 10% of SNR total explosion energy

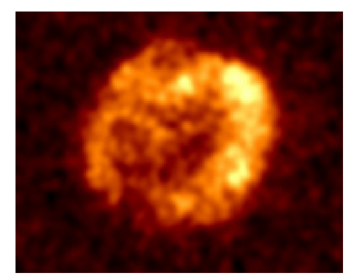




No SuperNovaRemnant detected as PeVatron up to now



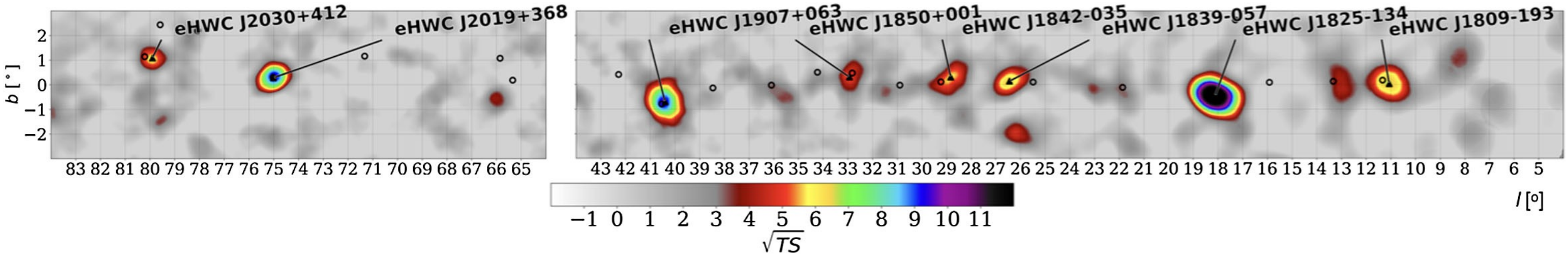
RXJ1713.7-3946
seen by H.E.S.S.



The beginning of UHE gamma-astrophysics

HAWC: emission at E_γ > 56 TeV

PRL 124 021102 (2020)

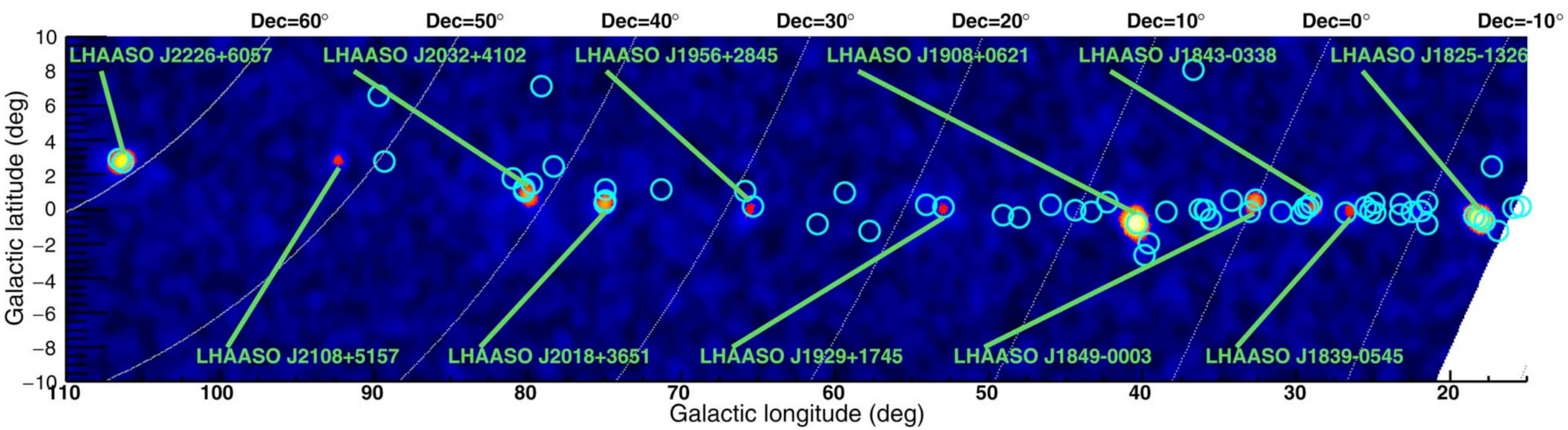


LHAASO: emission at E_γ > 100 TeV

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao, F. A. Aharonian, [...]X. Zuo

Nature **594**, 33–36 (2021) | Cite this article



UHE LHAASO sources

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030,
						2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8\,d}_{-0.7}$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\,l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

Uncertain nature of sources due to poor angular resolution:

- Only one source clearly identified: the Crab!
- Not many SNRs
- Many PSRs (large PSF of LHAASO)
- 2 young massive SC

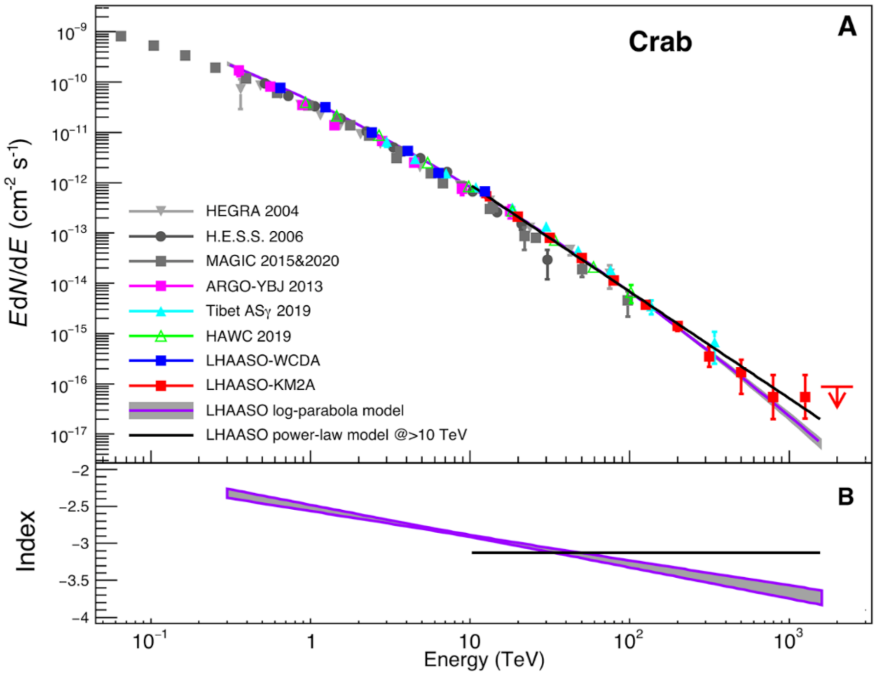
The Crab: a leptonic PeVatron?

- Leptonic origin of gamma-rays > 100 TeV is possible (energy losses dominated by IC in the case of intense radiation fields)

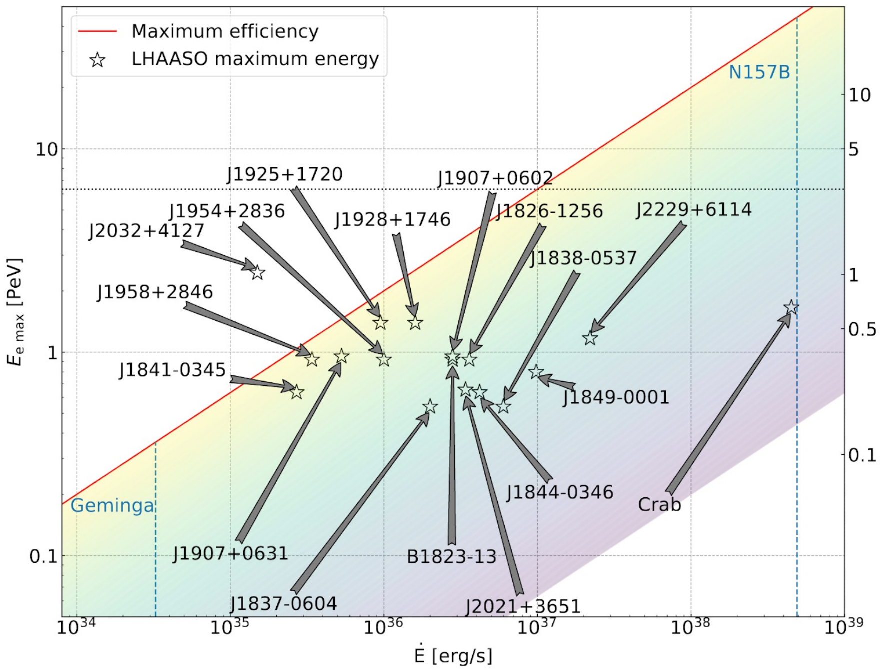
- Maximum photon energy mostly consistent with limit from pulsar potential drop

- Theoretically PWNe can be hadronic PeVatrons as well

LHAASO Coll, 2021, Science, vol. 373, pp.425-430

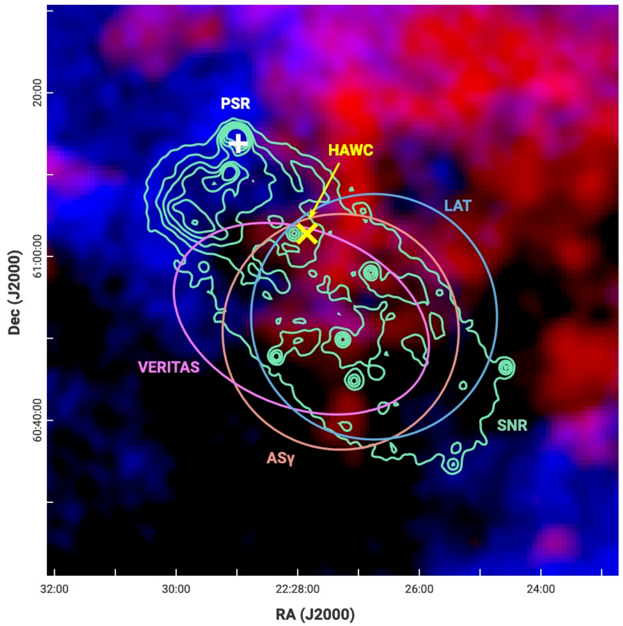


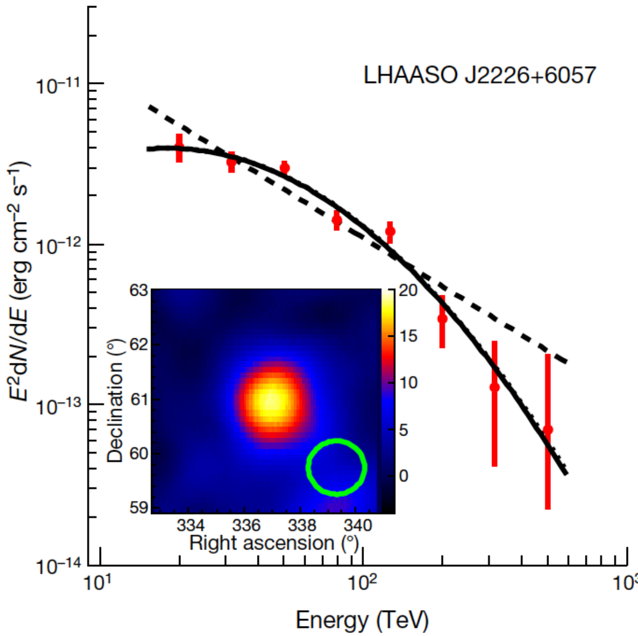
de Oña Wilhelmi+ 2022 ApJL 930 1 L2



PeVatron candidate: The Boomerang (G106.3+2.7)

Ge et al, 2020



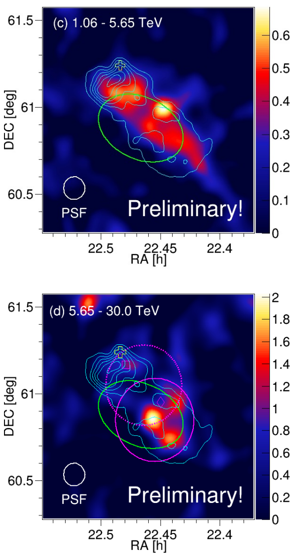


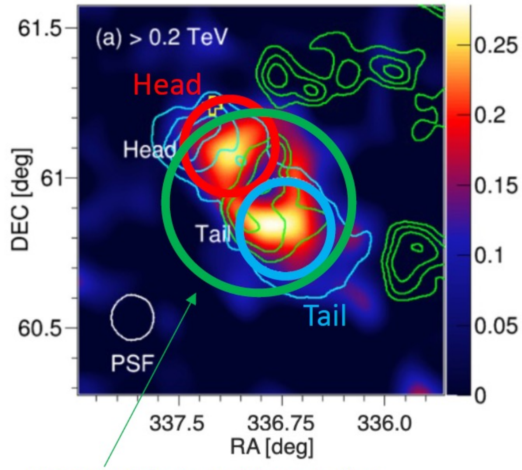
- Comet shape SNR with head and tail seen in radio continuum.
- Powerful Pulsar in the head region
- Correlation with molecular clouds
- VHE emission detected by Fermi, VERITAS [2009], HAWC [2020], Tibet As γ[2021].
- UHE emission detected by LHAASO.
- Both leptonic and hadronic emission can explain the data.

PeVatron candidate: The Boomerang (G106.3+2.7)

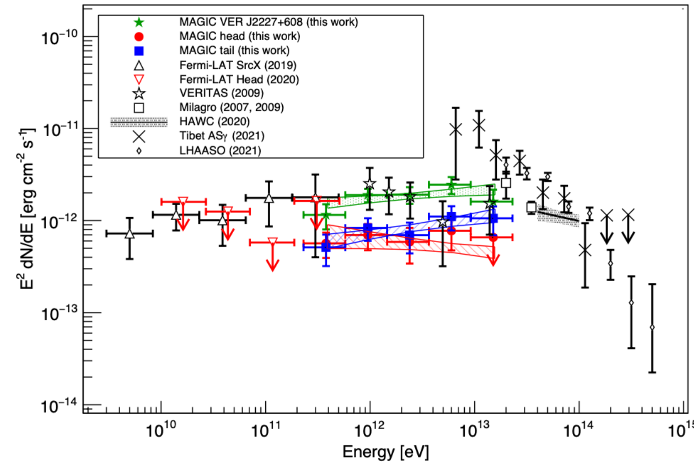
- Energy dependent morphology measured by MAGIC

MAGIC Coll. T. Saito Gamma 2022



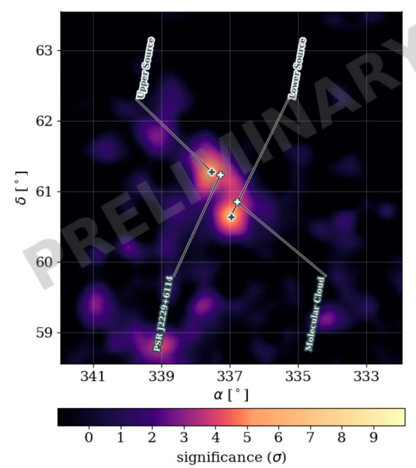


VERITAS integration region



- HAWC starts to see 2 components as well

P. Huentemeyer, ECRS 2022

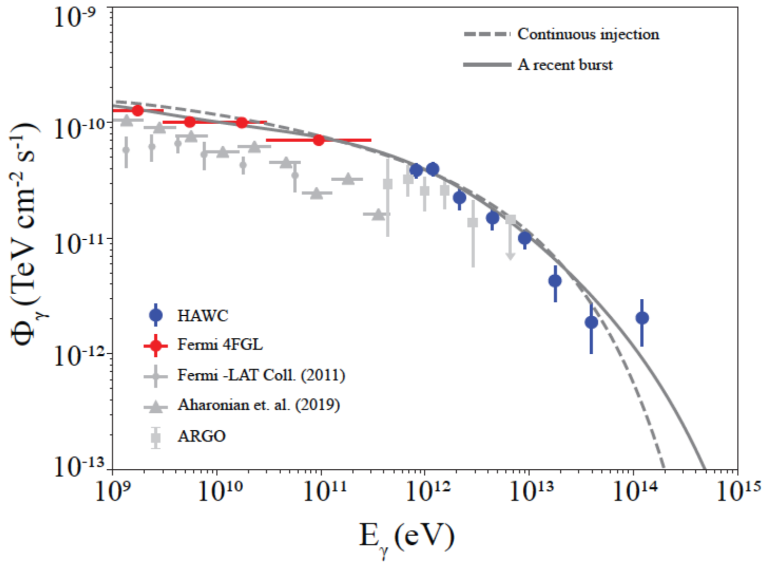


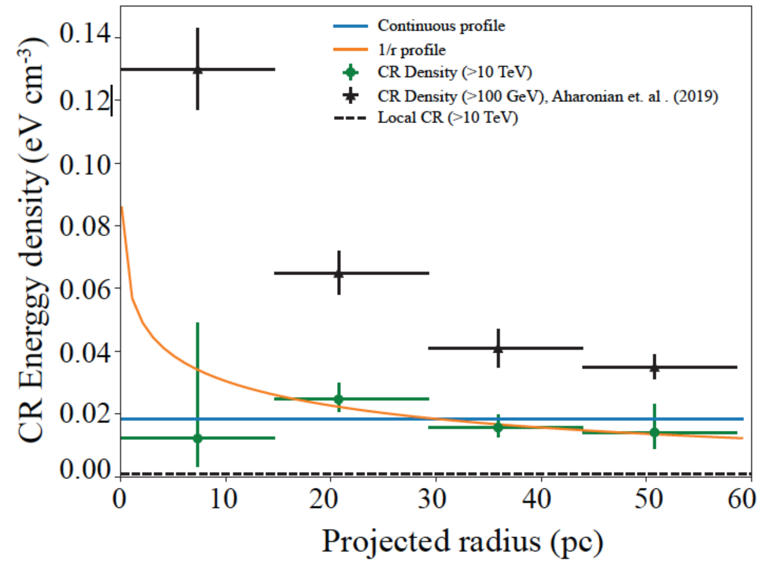
Precise VHE observations in a large energy range are required to resolve the head and tail emissions

PeVatron candidates: The Cygnus Cocoon

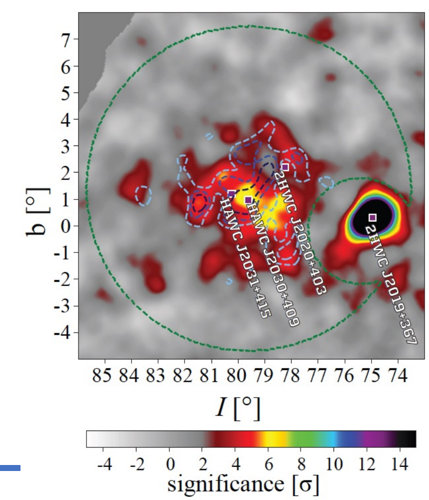
- superbubble surrounding a region of OB2 massive star formation.

HAWC Coll. Nat. Astro., 5, 465 (2021)

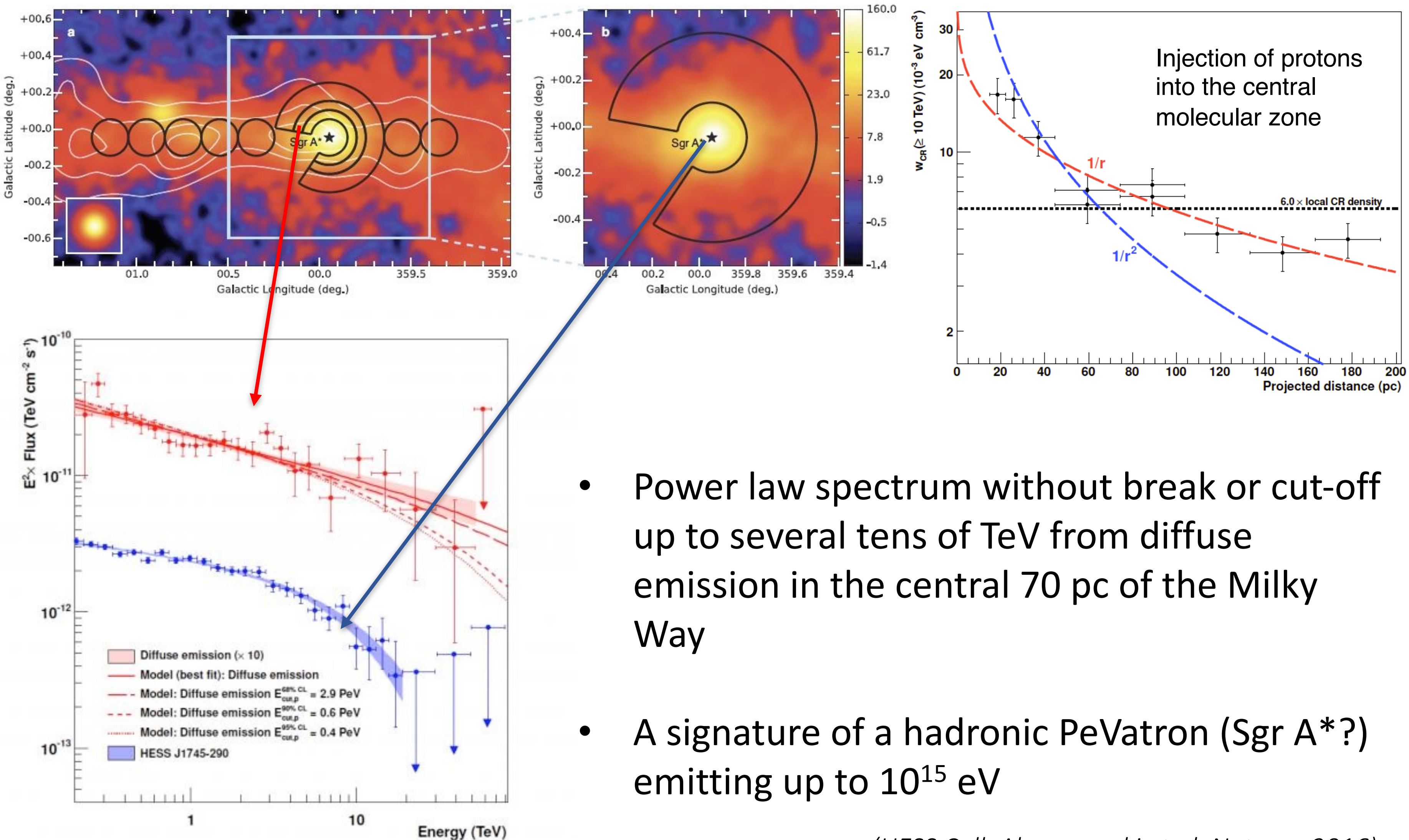




- 1.4 PeV gamma measured by LHAASO
- Spectral shape and emission profile changes from GeV to TeV energies
- Likely of hadronic nature



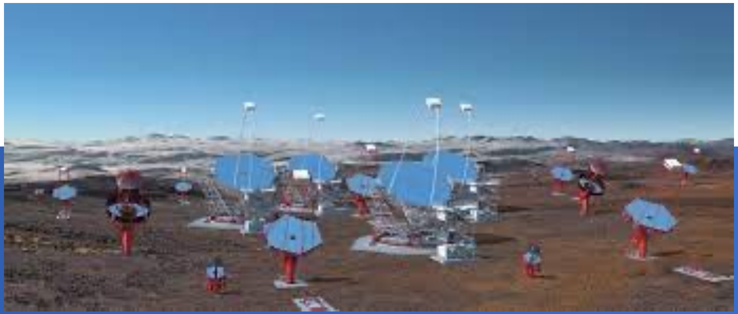
PeVatron candidate : the Galactic center



- Power law spectrum without break or cut-off up to several tens of TeV from diffuse emission in the central 70 pc of the Milky Way
- A signature of a hadronic PeVatron (Sgr A*?) emitting up to 10^{15} eV

(HESS Coll, Abramowski et al, Nature, 2016)

Future instruments:



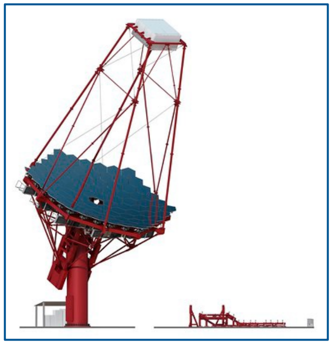
- **Better sensitivity**
- **Larger energy range**
- **Better precision**
- **Full sky coverage**
- **Both Cherenkov and EAS telescopes needed**

The Cherenkov Telescope Array: CTA

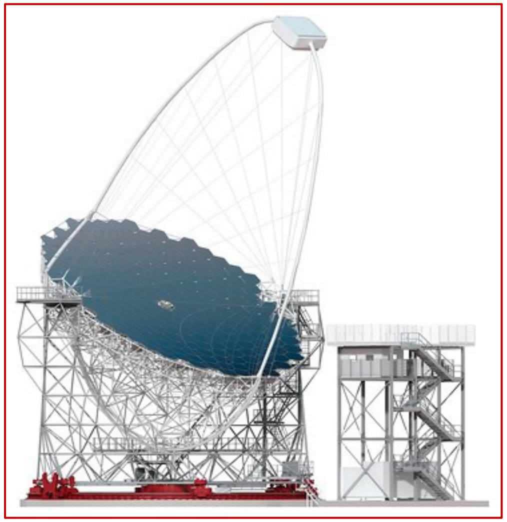
- two sites for full sky coverage
- funded initial (alpha) configuration
- three telescope types optimized for different energy ranges

SST

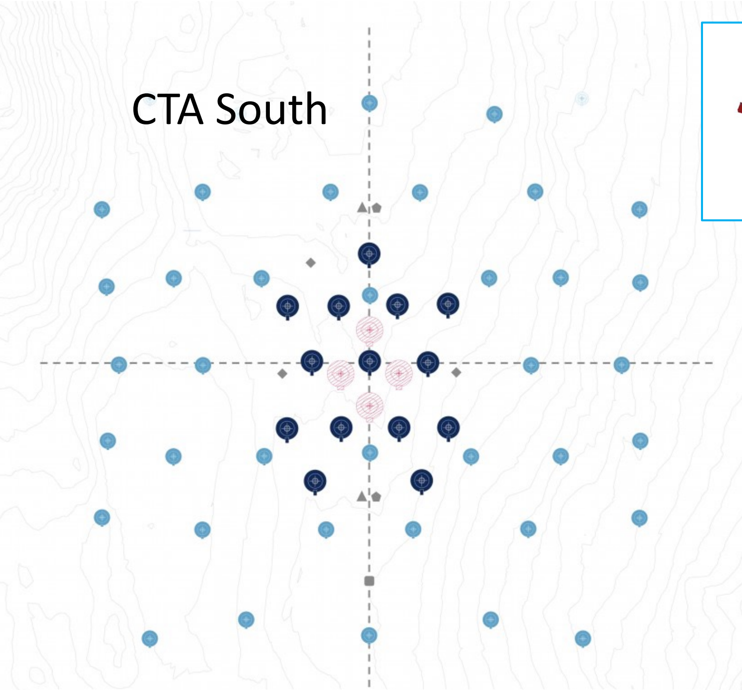
MST



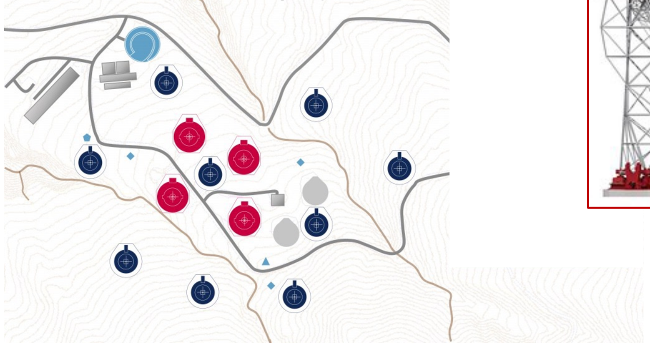
LST



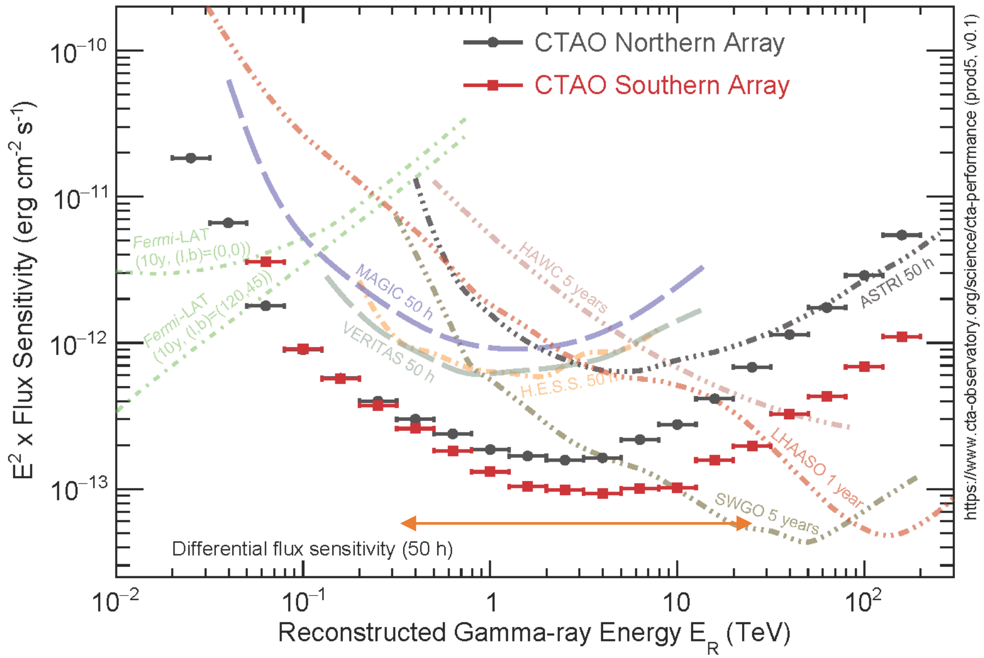
CTA South



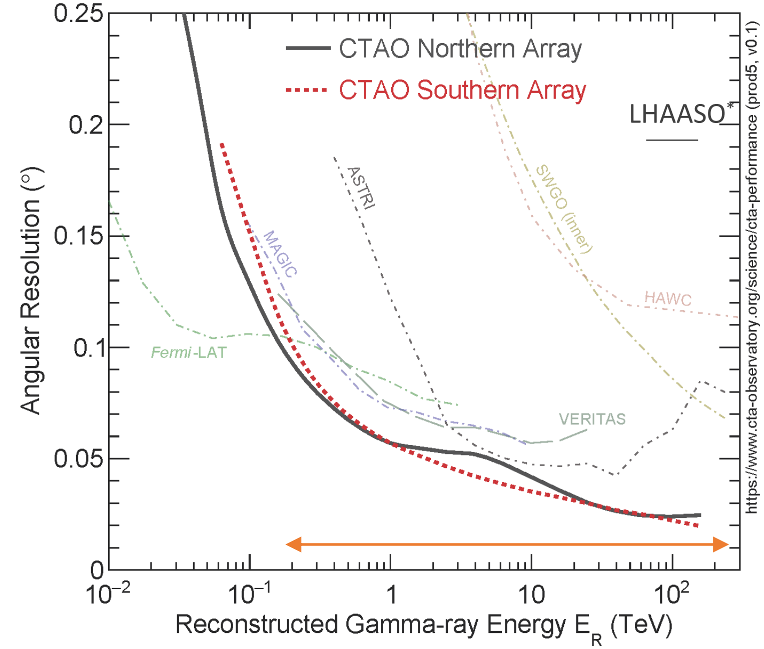
CTA North



CTA Performance



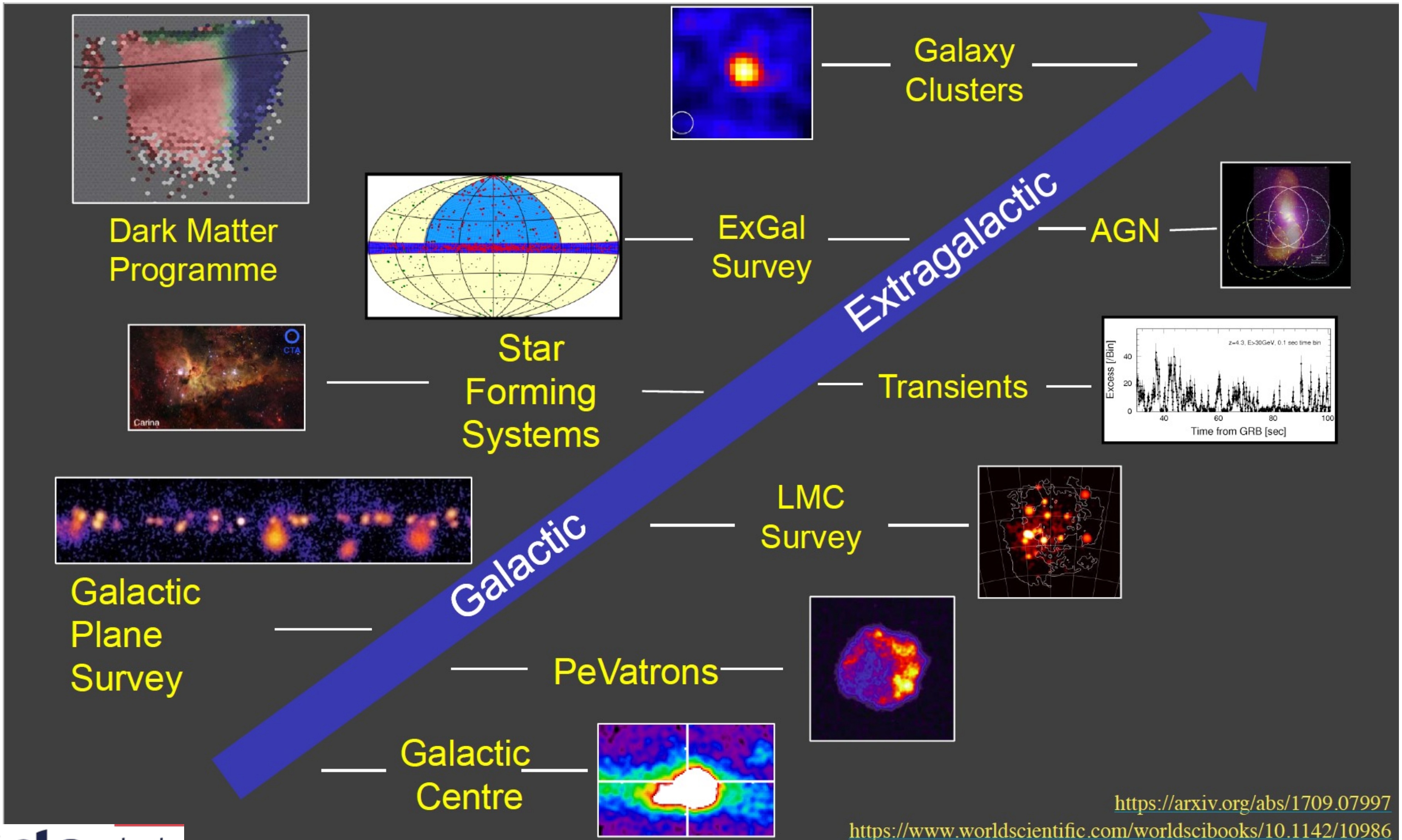
*R. Yang , CDY seminar (Nov. '21)



Best sensitivity in **50 GeV – 10 TeV** Energy region

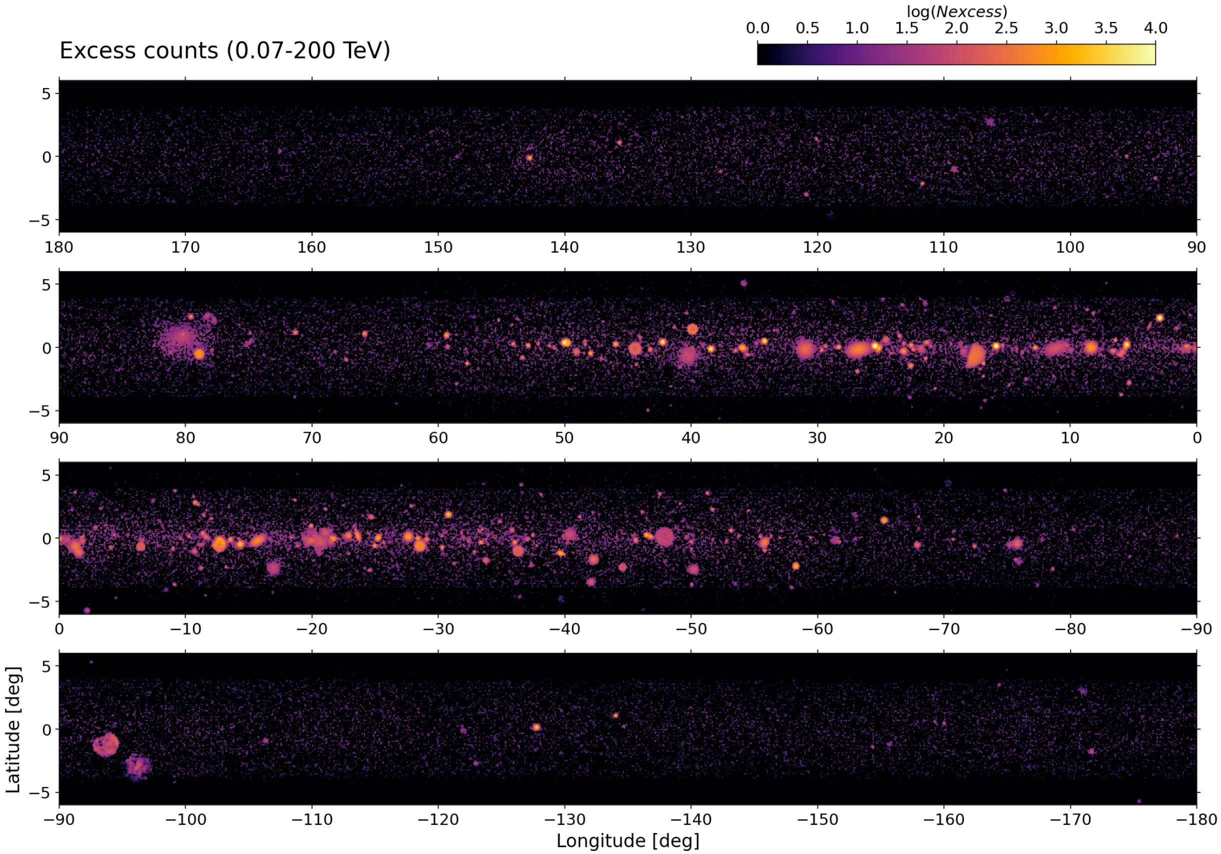
Best angular resolution **for E > 100 GeV**

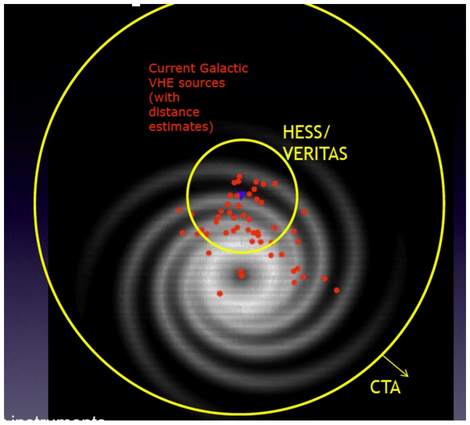
CTA : The Key Science Projects

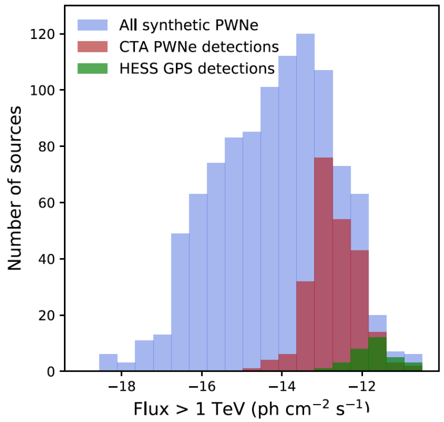


https://arxiv.org/abs/1709.07997
https://www.worldscientific.com/worldscibooks/10.1142/10986

CTA Galactic Plane Survey





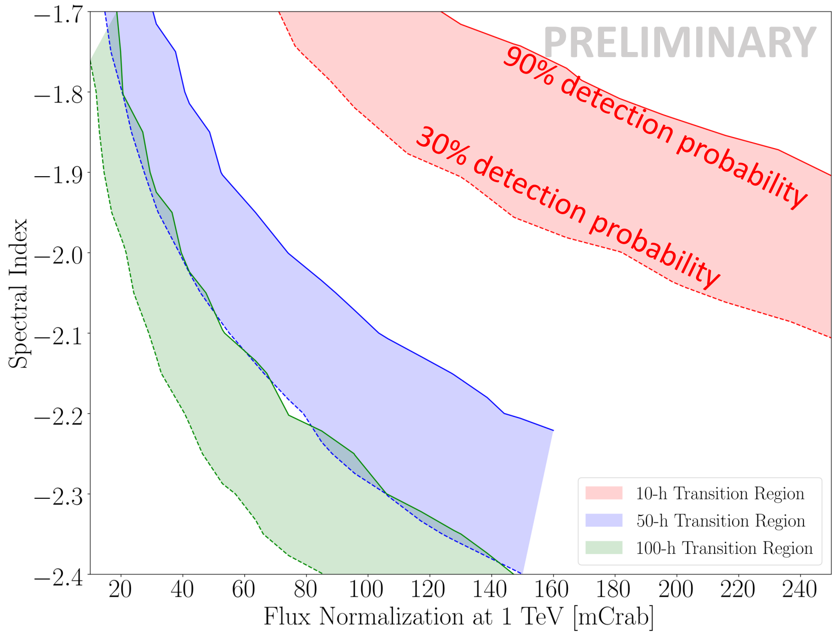


- Increase in source counts by ~5 with respect to HESS GPS or 3HAWC catalogue
- Detect sources across the entire Galaxy

Remy et al. PoS(ICRC2021)886

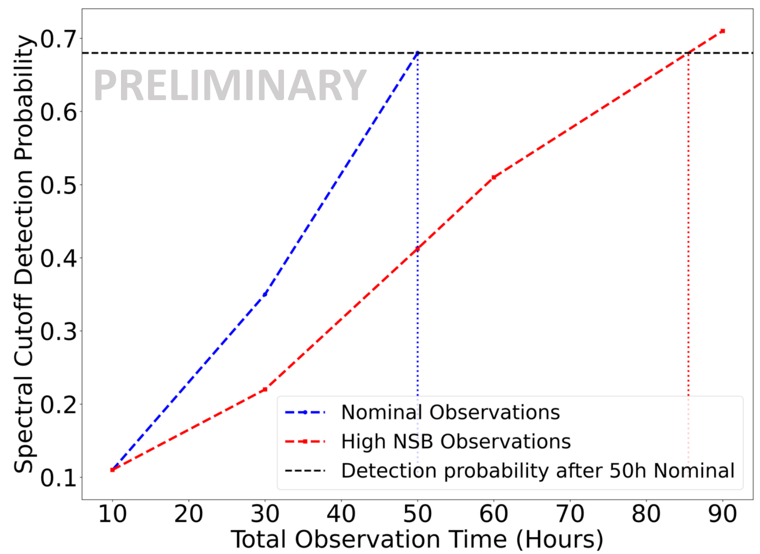
PeVatron search with CTA: spectral capabilities

$E_{c,\gamma}$= 200 TeV cutoff detection probability with Full CTA South array



Observation with SST array only (moonlight)

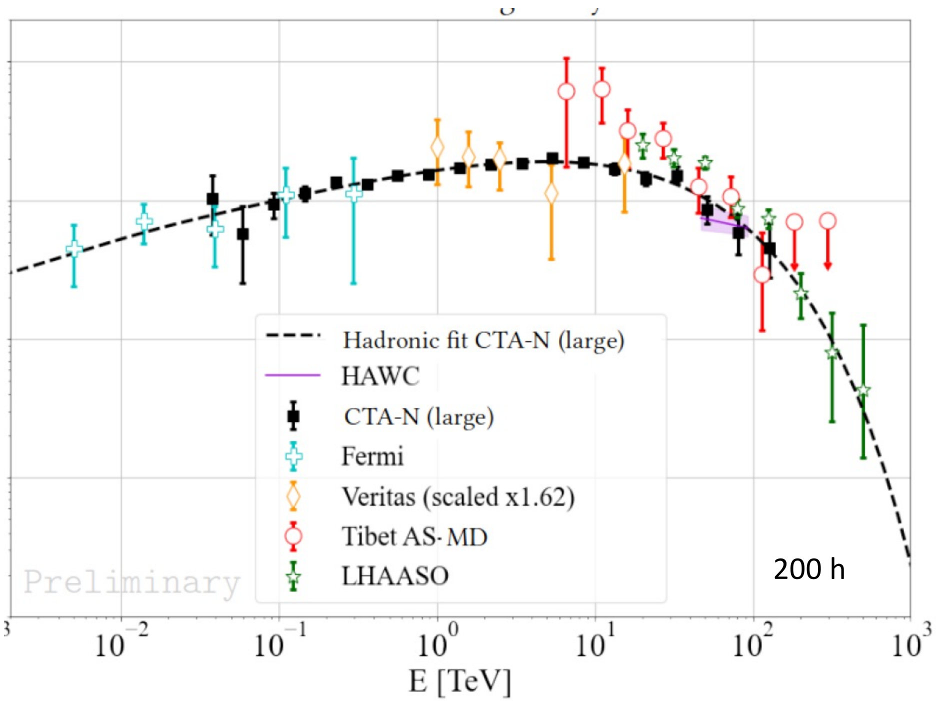
HESS J1641-463 with $E_{c,\gamma}$= 100 TeV

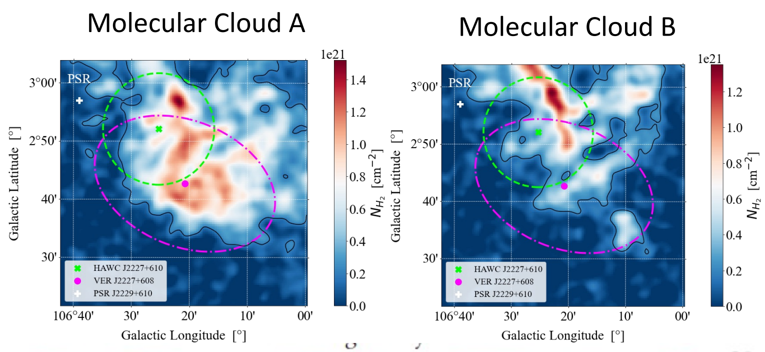


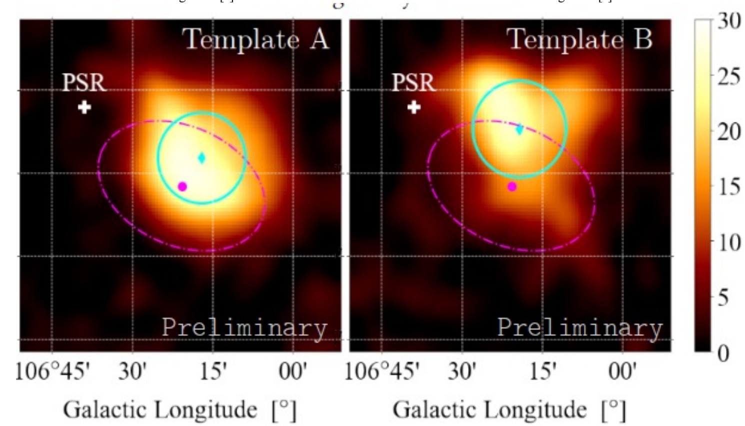
CTA Consortium: In preparation

- Limited Capability with CTA GPS data
- Deep observations can be done during moonlight to increase statistics at VHE
- Excellent prospects to find PeVatrons (UHE cutoffs) with deep observations

The Boomerang (G106.3+2.7)







- Large energy coverage to constrain spectral models

G. Verna et al PoS(ICRC2021)904

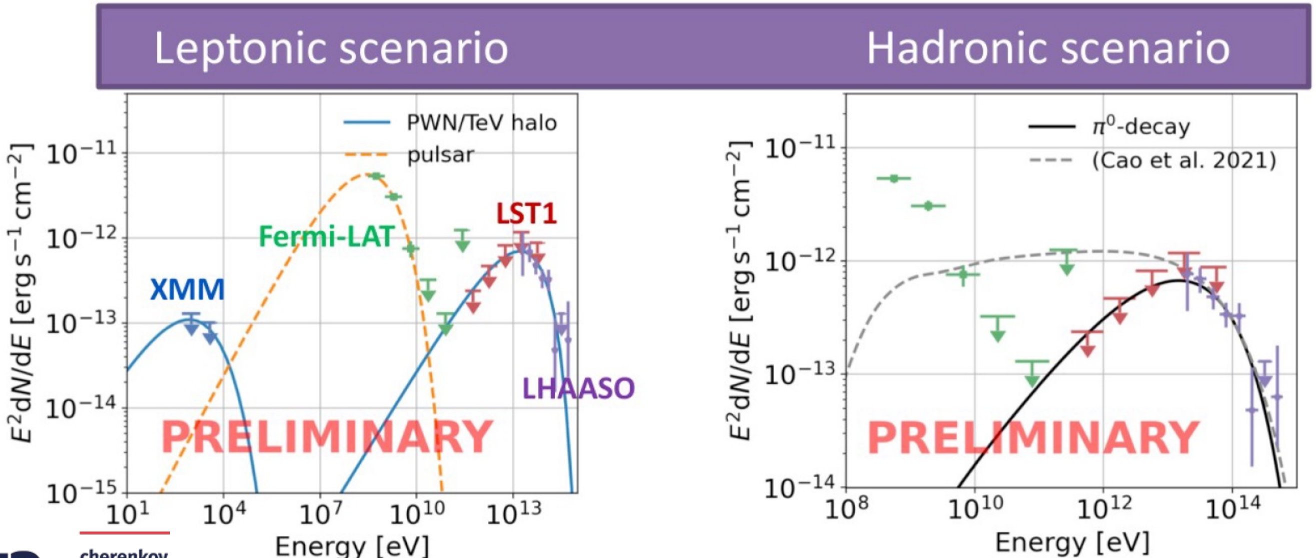
- Precise morphological studies of emission sites

First telescopes and first results

- Construction ahead of CTAO ERIC constitution

- LST-1 first telescope at CTA-North site
  - LST-1 is in commissioning
  - Performance paper to be published soon
  - First scientific results (including Novae, AGNs etc.)

- LHAASO J2108+5157 is the first gamma-ray source directly discovered in the UHE band
- 91 h observation: no detection, but relevant upper limits

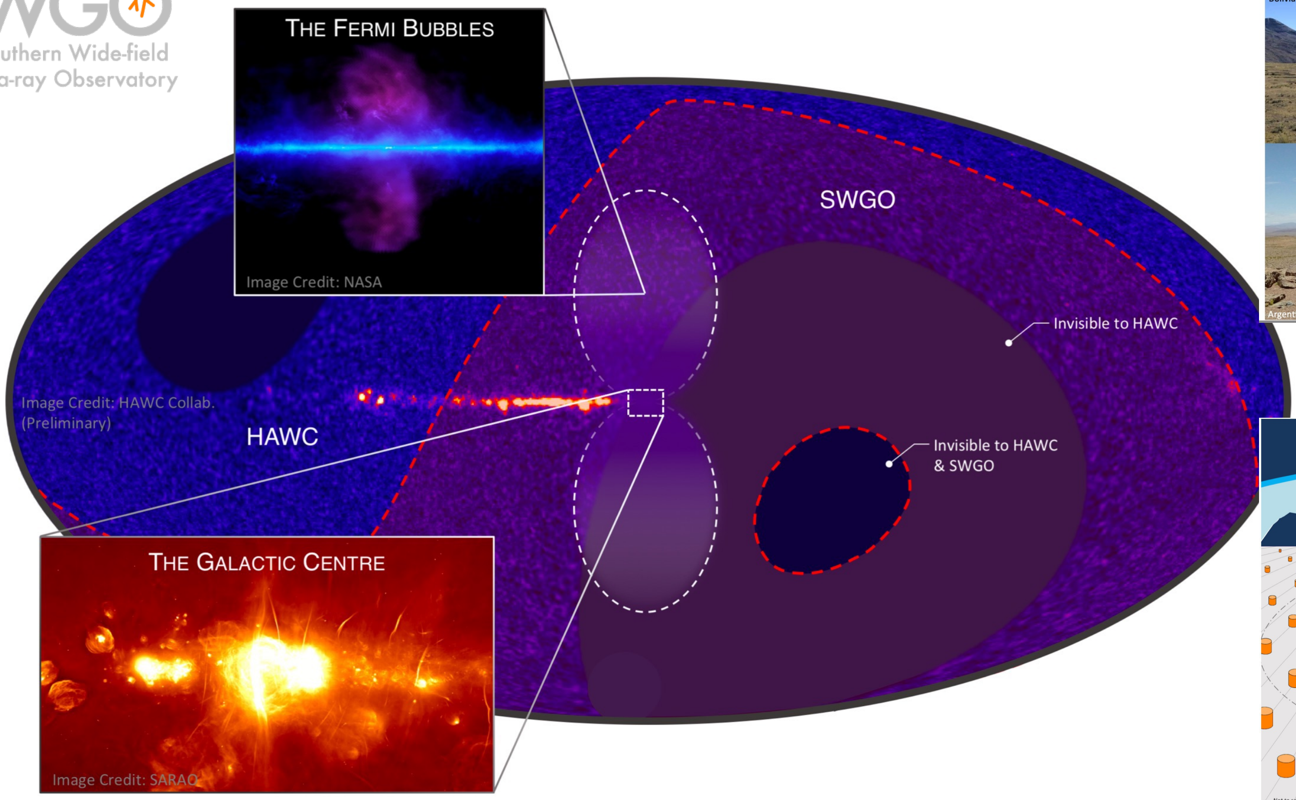


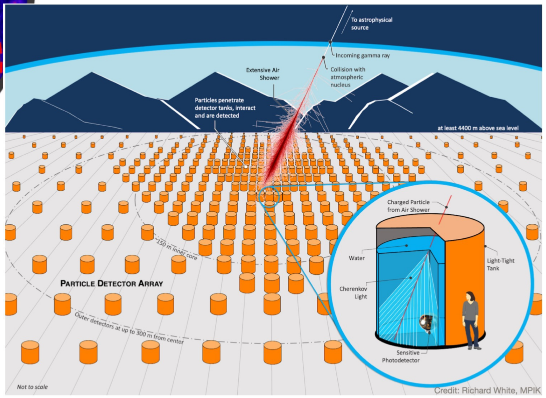
Juryšek Gamma 2022
aper in preparation

Future instruments:

- **Better sensitivity**
- **Larger energy range**
- **Better precision**
- **Full sky coverage**
- **Both Cherenkov and EAS telescopes needed**

The Southern Wide Field Gamma-ray Observatory : SWGO





- Extended Air Shower Detector in the Southern Hemisphere
- PeVatron Hunter in the South!
- Complementary to CTA-South
- R&D phase: construction starts 2026+

Conclusions

- VHE gamma-ray astronomy has become a major exciting field of research which addresses a wide, and expanding, range of astrophysical topics

- Gamma rays can shed light on the origin of cosmic rays

- UHE gamma-ray astronomy has begun !

- Present results demonstrate the importance of complementary instrumental approaches in gamma-ray astronomy

- Future observatories will improve significantly our understanding of the high energy Universe with a large potential for new discoveries