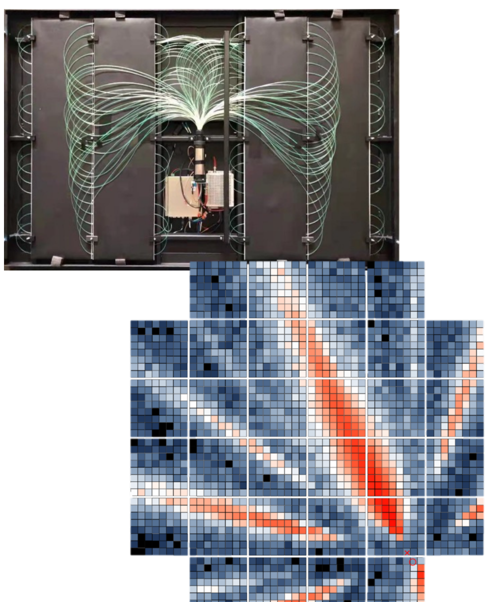
The Extreme Non-Thermal Universe: CDY Initiative

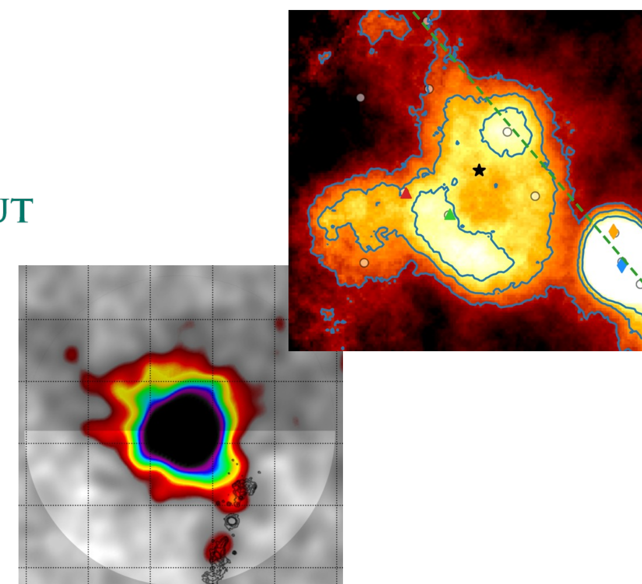
WORKING TOGETHER TO UNDERSTAND THE SITES OF EXTREME ACCELERATION…

PeVatrons – Detection Techniques and Observations



Jim Hinton

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG



MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Content?

Title: Discovery of Ultra High Energy Gamma-ray Sources by LHAASO
Speaker: *Ruizhi Yang (University of Science and Technology of China)*

Title: Extreme Particle Accelerators (Introductory)
Aim: Highlight and discuss several key topics and identify potential talks.
Speaker: *Felix Aharonian (DIAS/MPIK)*

Title: The VERITAS View of the Galactic Gamma-ray Sky
Speaker: *Jamie Holder (University of Delaware)*

Title: PeVatrons – Detection Techniques and Observations
Speaker: *Jim Hinton (Max-Planck-Institut für Kernphysik)*

?

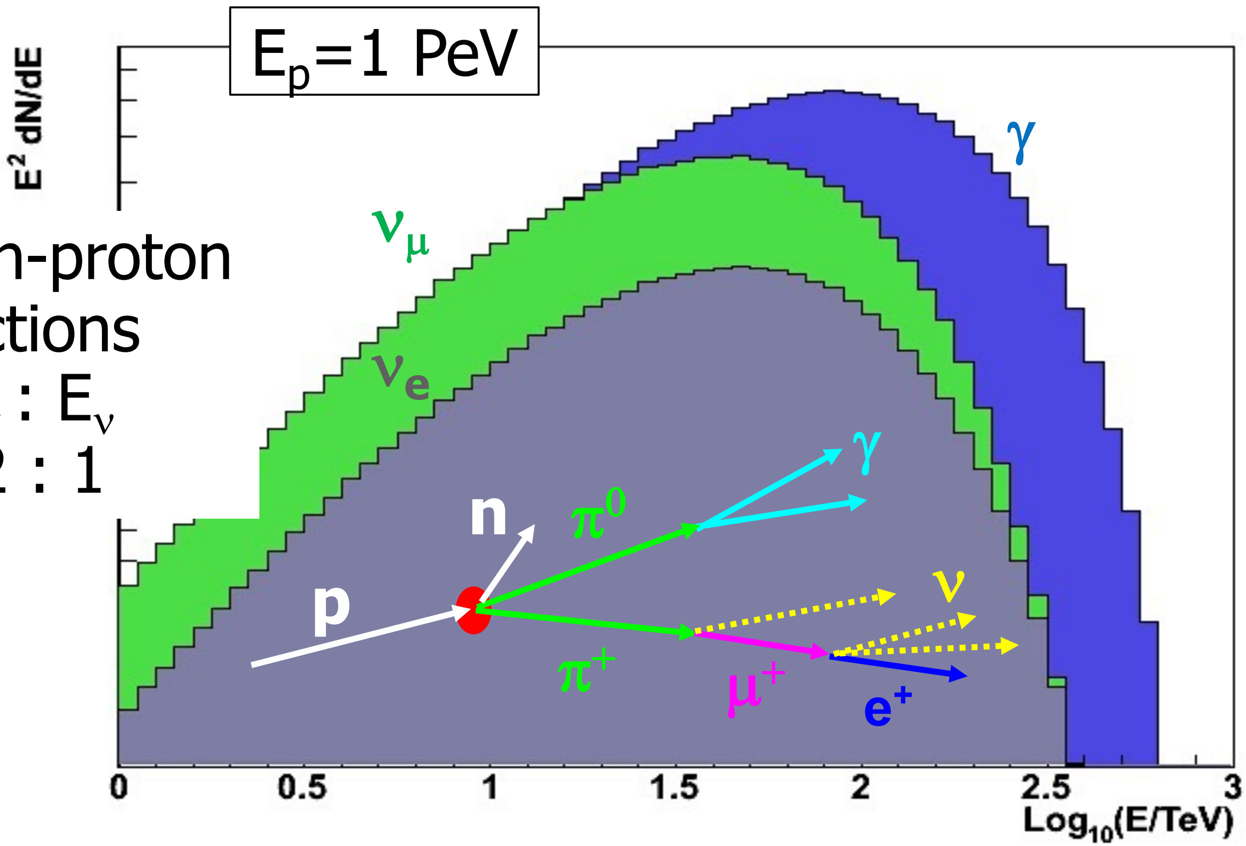
Title: The Crab Pulsar Wind Nebula
Speaker: *Elena Amato (INAF)*

Title: Gamma-ray binaries hosting a pulsar: prospects at the highest energies
Speaker: *Valenti Bosch-Ramon (Universitat de Barcelona)*

Title: Recent results from H.E.S.S. observations of the Galactic Plane
Speaker: *Emma de Oña (DESY, Zeuthen)*

Title: Surveying the TeV Gamma-Ray Sky with the HAWC Wide-Field Observatory
Speaker: *Petra Huentemeyer (Michigan Technological University)*

Pevatrons: emission signatures?



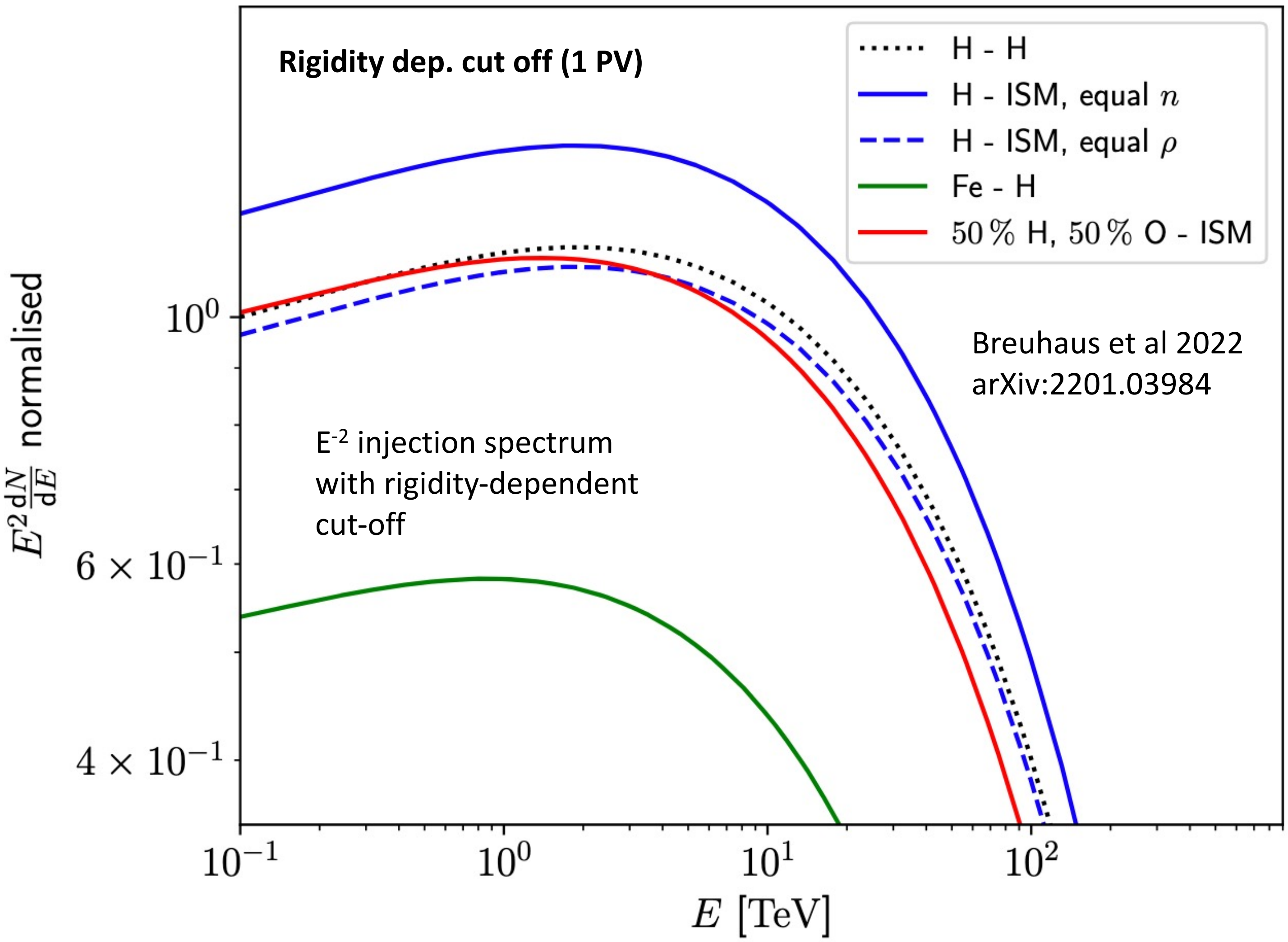
e.g. proton-proton Interactions

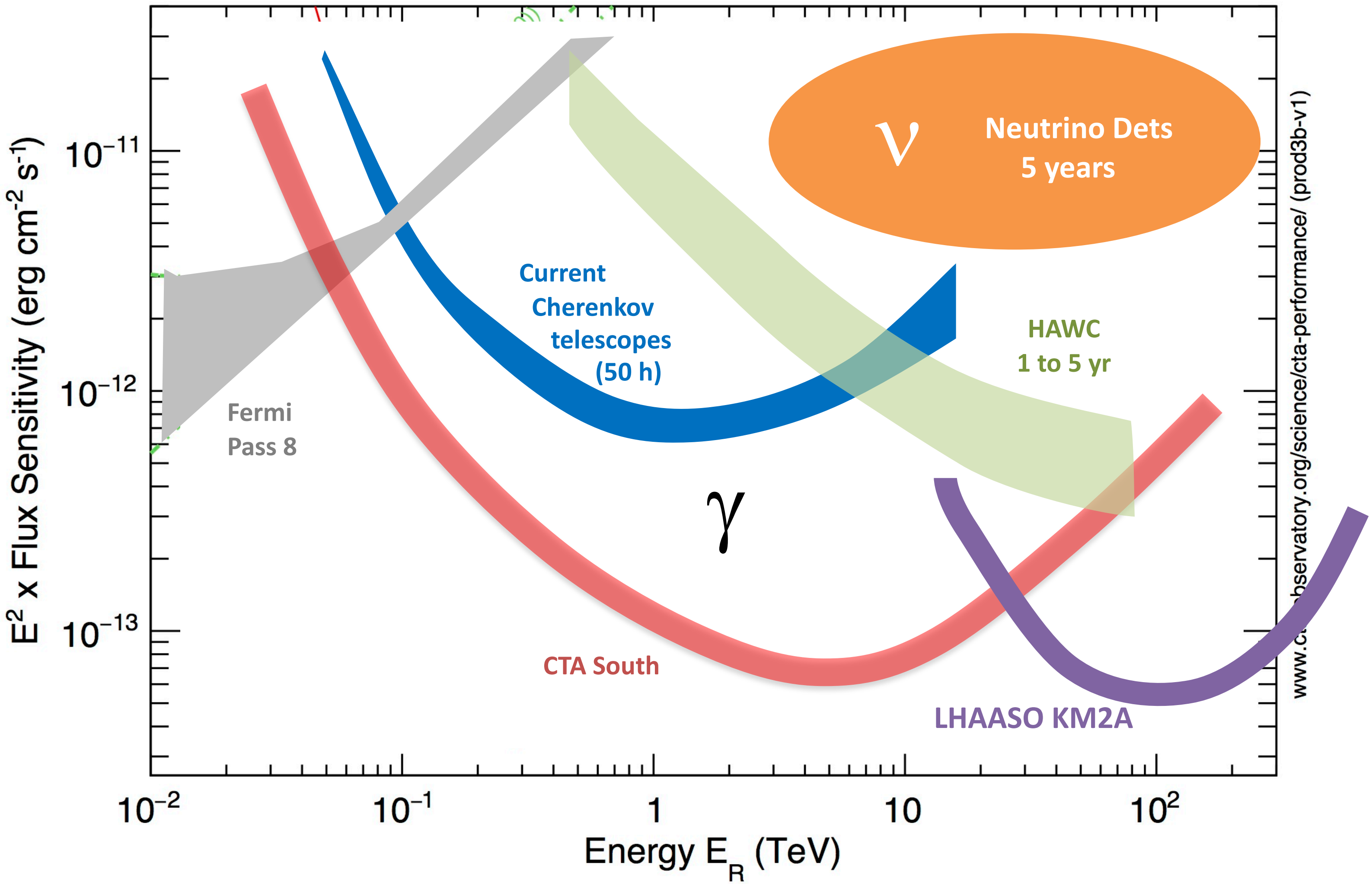
$E_p : E_\gamma : E_\nu$

20 : 2 : 1

- Most important – pion production in nuclear or photo-nuclear reactions
  - p-p (above), p-gamma (primarily excitation of the Delta++ resonance)

Pevatrons: emission signatures?

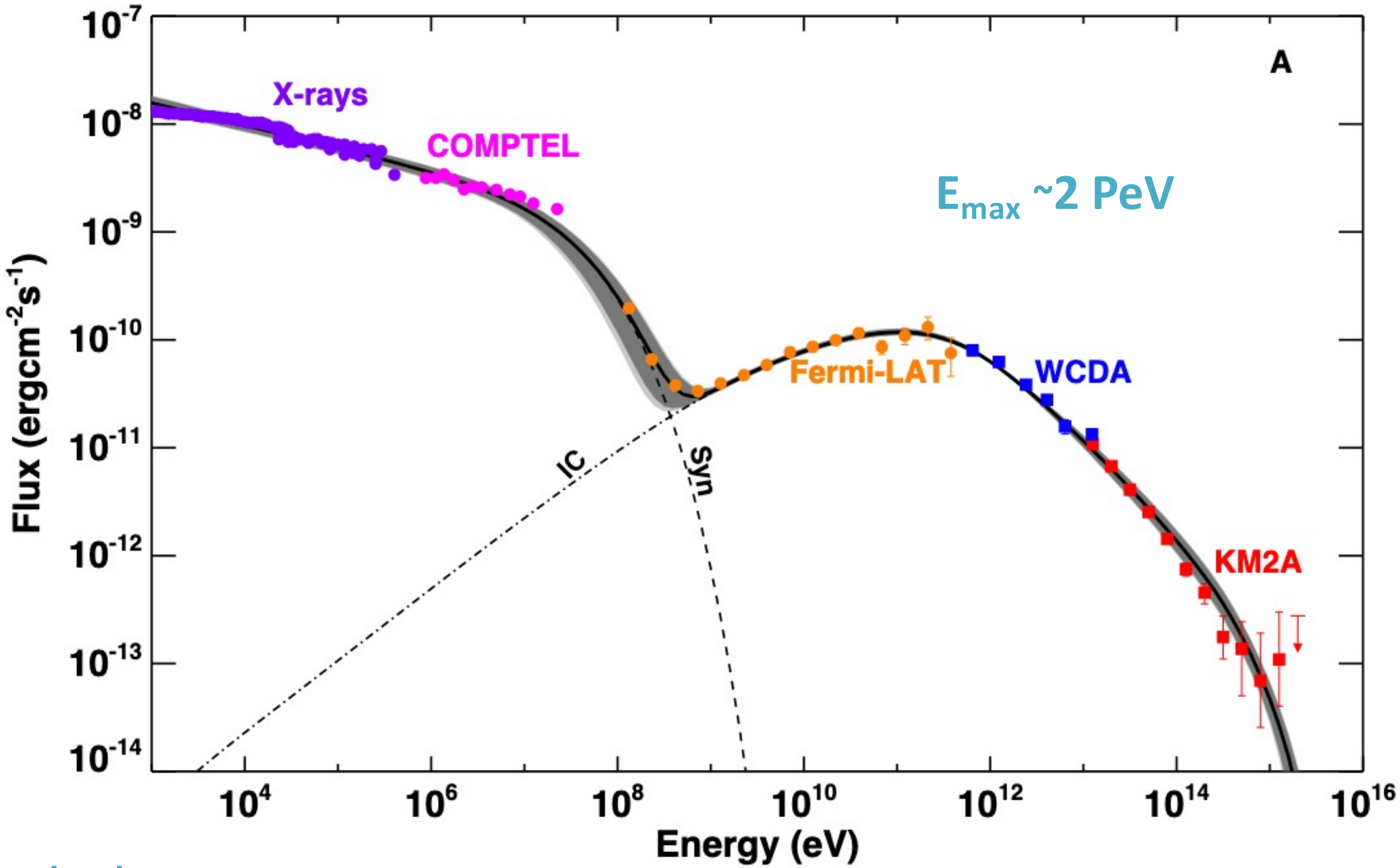




E^2 x Flux Sensitivity (erg cm^{-2} s^{-1})
10^{-11}
10^{-12}
10^{-13}
10^{-2}
10^{-1}
1
10
10^2
Energy E_R (TeV)
ν
Neutrino Dets
5 years
Current
Cherenkov
telescopes
(50 h)
HAWC
1 to 5 yr
Fermi
Pass 8
γ
CTA South
LHAASO KM2A
/science/cta-performance/ (prod3b-v1)

Pevatrons: emission signatures?

- Electrons…



E_{max} ~2 PeV

Crab Nebula

Cao et al 2022 – Science - arXiv 111.06545

Pevatron Shopping List

- Detected VHE-UHE Emission
- Spectral curvature
  - Signature of Emax, KN, spectral breaks, +++
- Spatially-resolved emission
- Correlation with target material
  - Not perfect: i.e. emission is convolution of CR distrib. with gas
- Energy-dependent morphology
  - Expected in general due to energy dependence of transport and/or cooling, exceptions:
    - **Bohm** diffusion of electrons ($r \sim \mathrm{sqrt}(D\ t_{cool})$, $D \sim E$, $t_{cool} \sim 1/E$)
    - Advection of protons (t_{cool} = const, $r \sim v\ t_{cool}$)
- A multi-wavelength counterpart!

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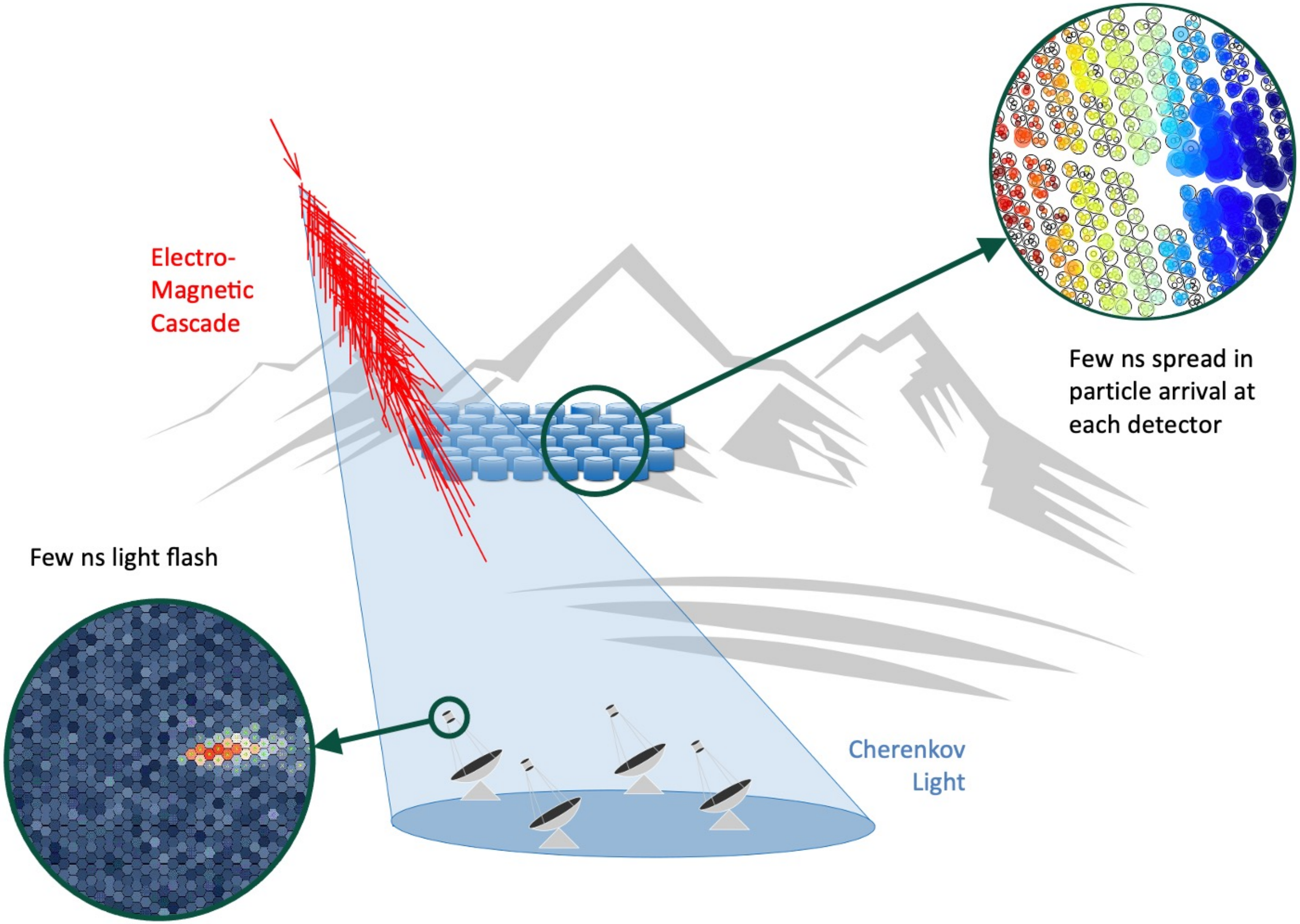
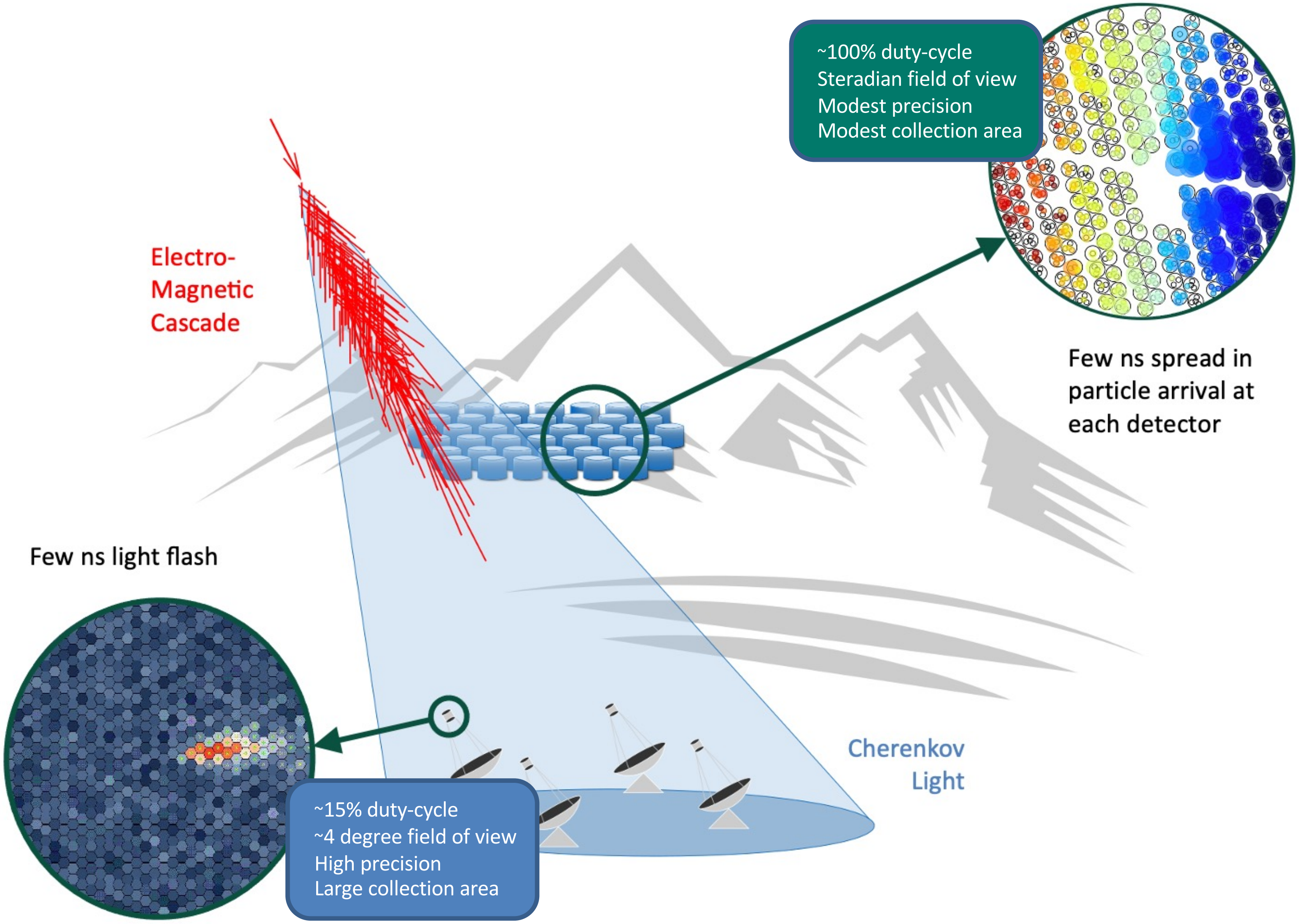
Highest Energy Sensitivity

Wide band Sensitivity

Angular Resolution

Part 1: Detection Techniques




~100% duty-cycle
Steradian field of view
Modest precision
Modest collection area
Electro-
Magnetic
Cascade
Few ns spread in
particle arrival at
each detector
Few ns light flash
Cherenkov
Light
~15% duty-cycle
~4 degree field of view
High precision
Large collection area


HAWC


MAGIC
© Daniel Lopez, IAC


Tibet ASγ


VERITAS

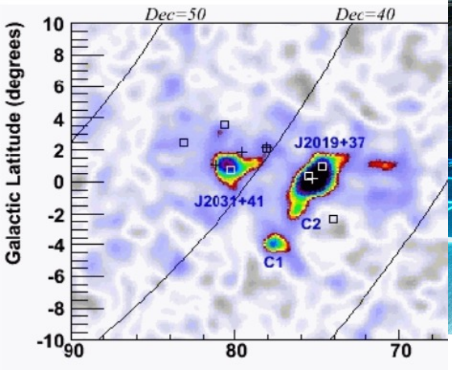

LHAASO

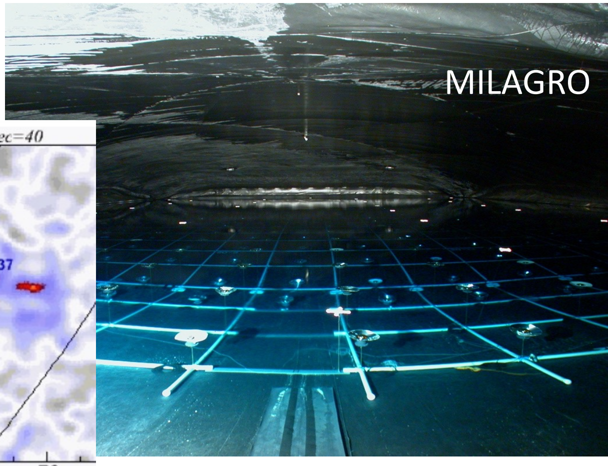

HESS
© Vikas Chander

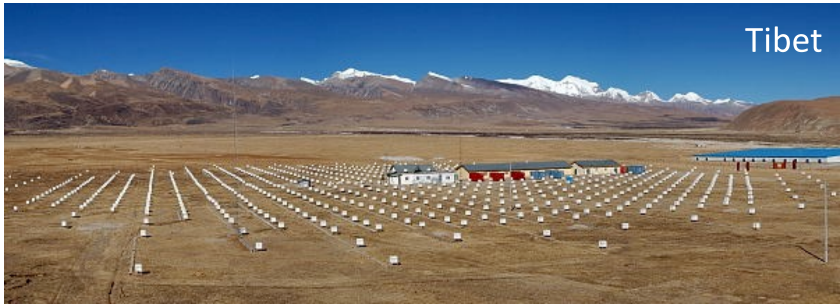
Ground-particle Detectors

- 2.5 km ⊙ MILAGRO – 2001-2008
- 4.1 km ⊙ HAWC – 2015 -
- 4.3 km ⊙ Tibet AS γ +ARGO – 1990s -
- 4.4 km ⊙ LHAASO – 2021 -
- 4.4-5.0 km ⊙ SWGO – 202X -

MILAGRO:
Cygnus Region







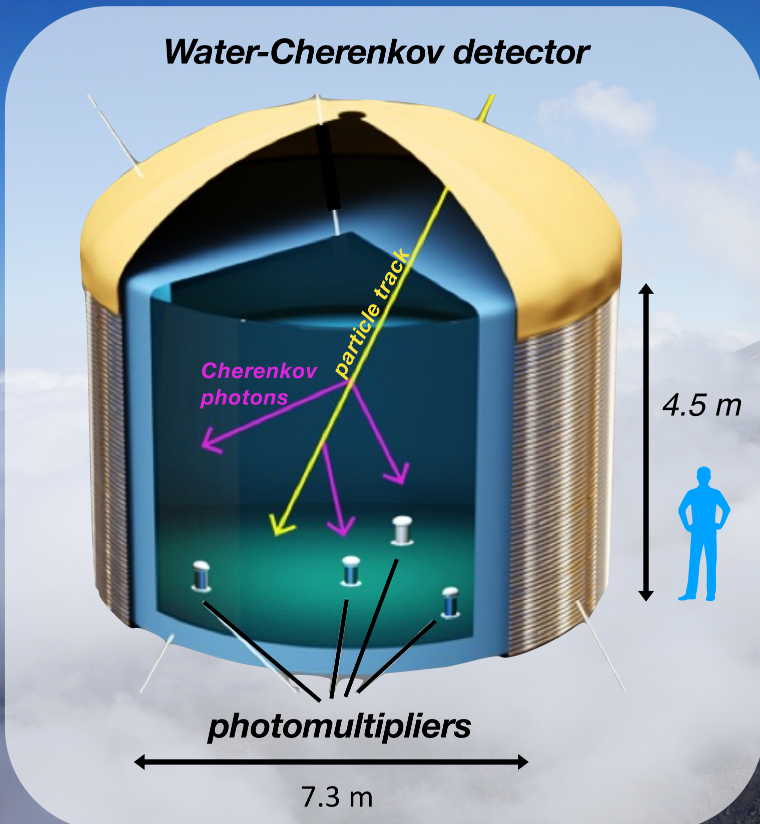
Drivers of performance:

size, **fill factor** and **altitude** (move detector up to shower max)

Increase altitude: MILAGRO → HAWC → SWGO
Increase also fill-factor and size: Tibet → LHAASO & SWGO

+ muon detection

e.g. HAWC



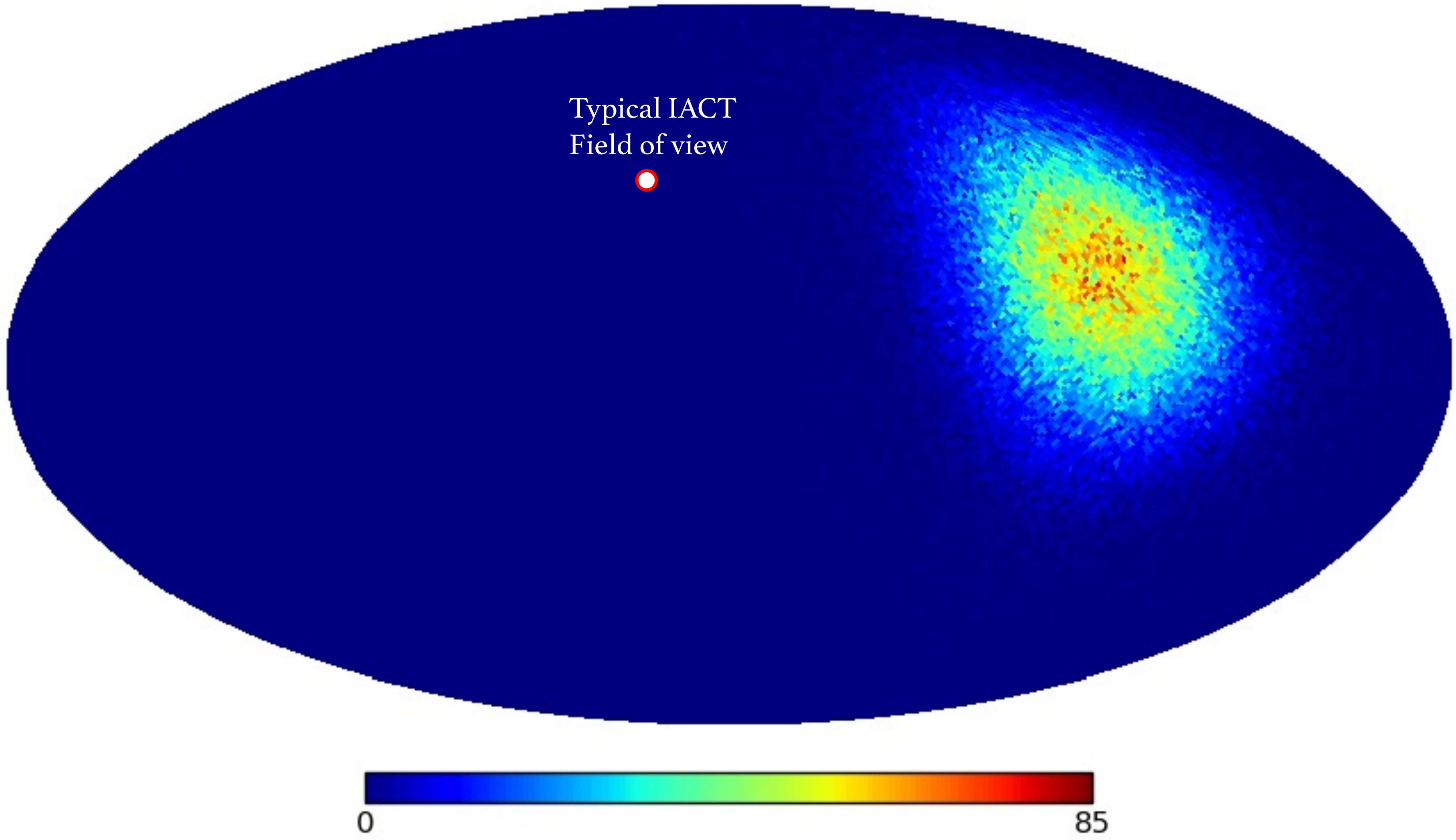
Pico de Orizaba (5636 m)

- 300 Water Cherenkov Particle detectors
- 1200 Photo-Multiplier-Tubes
- Completed March 2015
- ~95% uptime
- Area 22000m^2

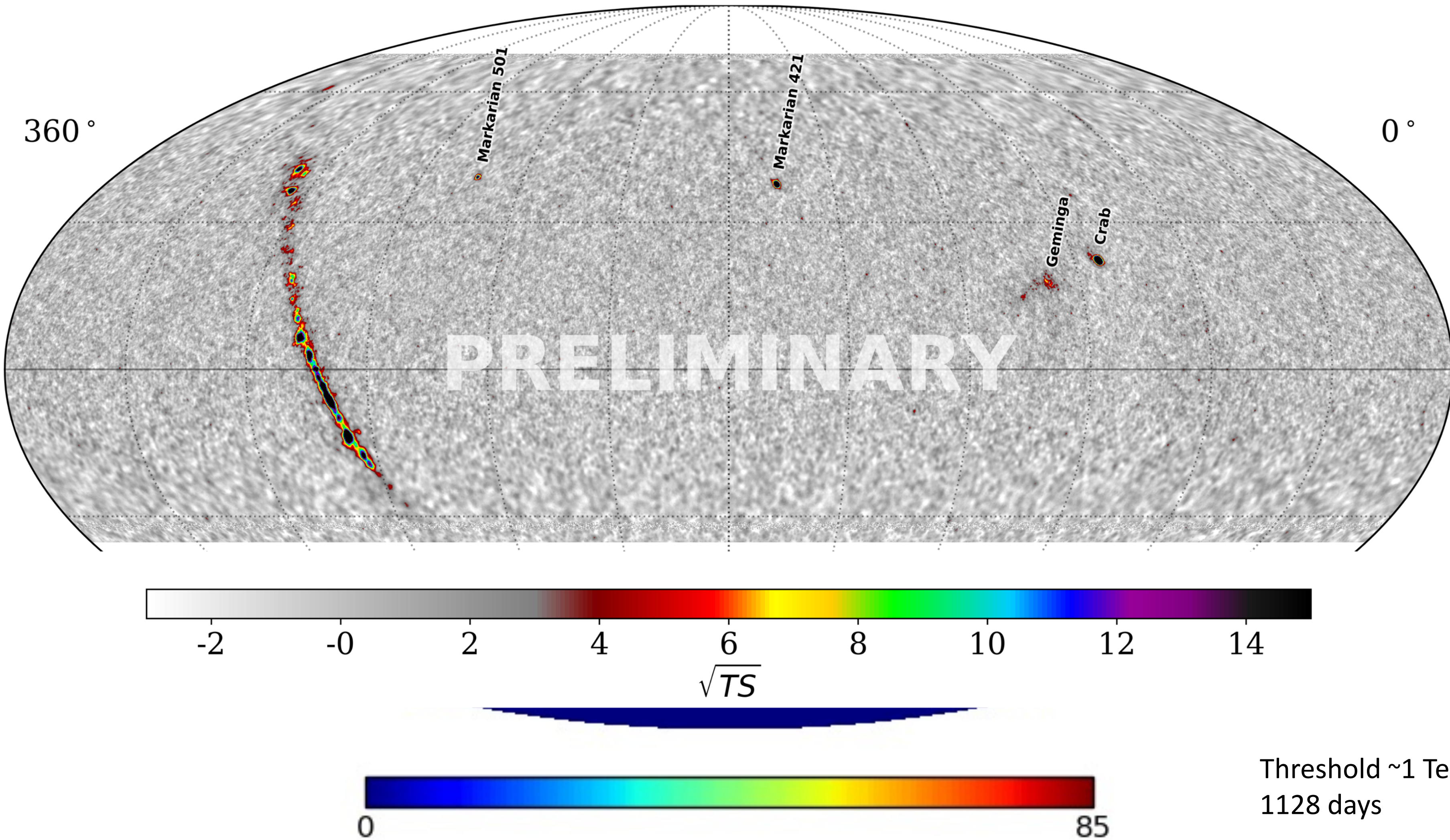
HAWC (4100 m)

+outrigger upgrade 2018

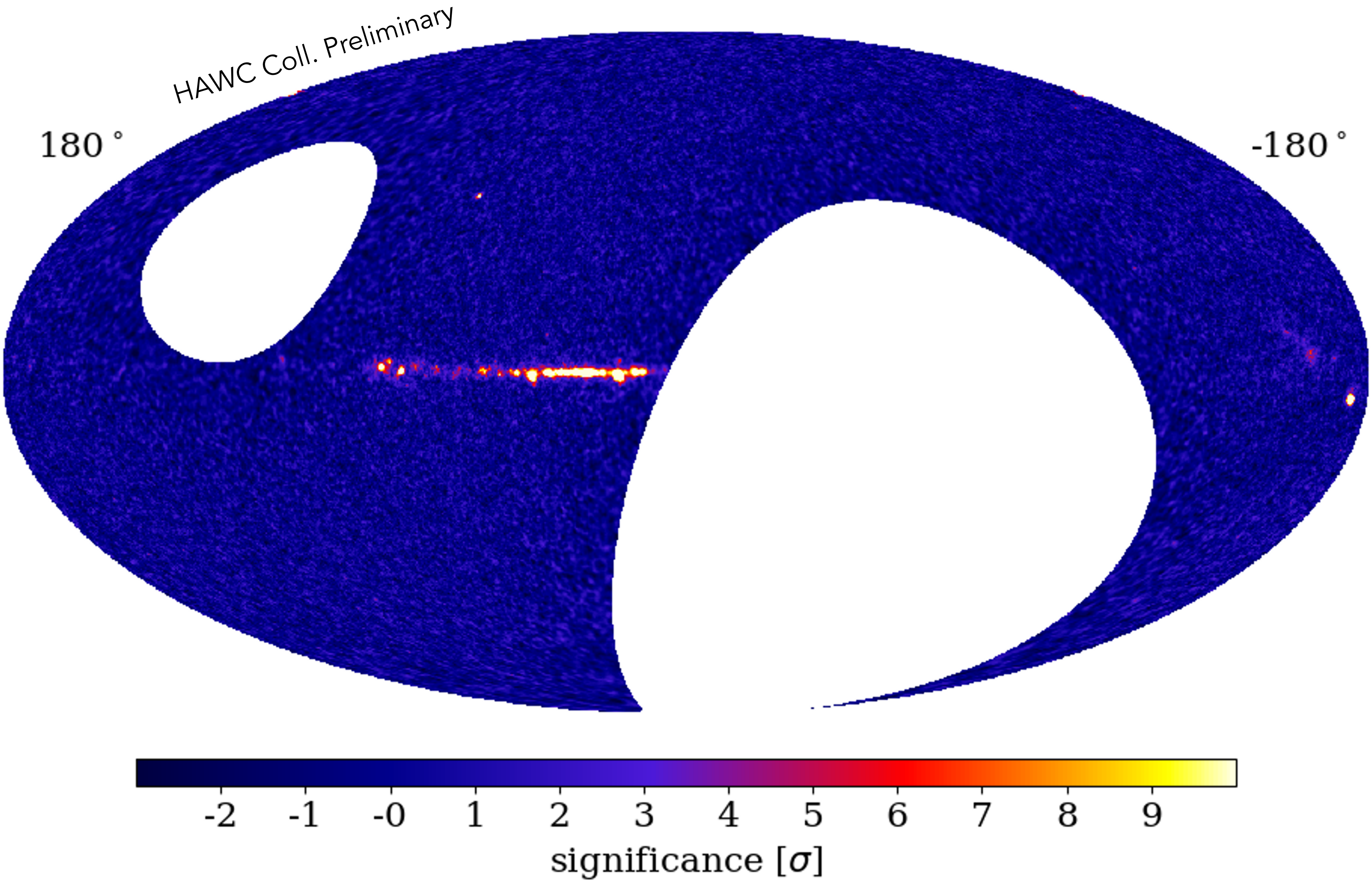
e.g. HAWC

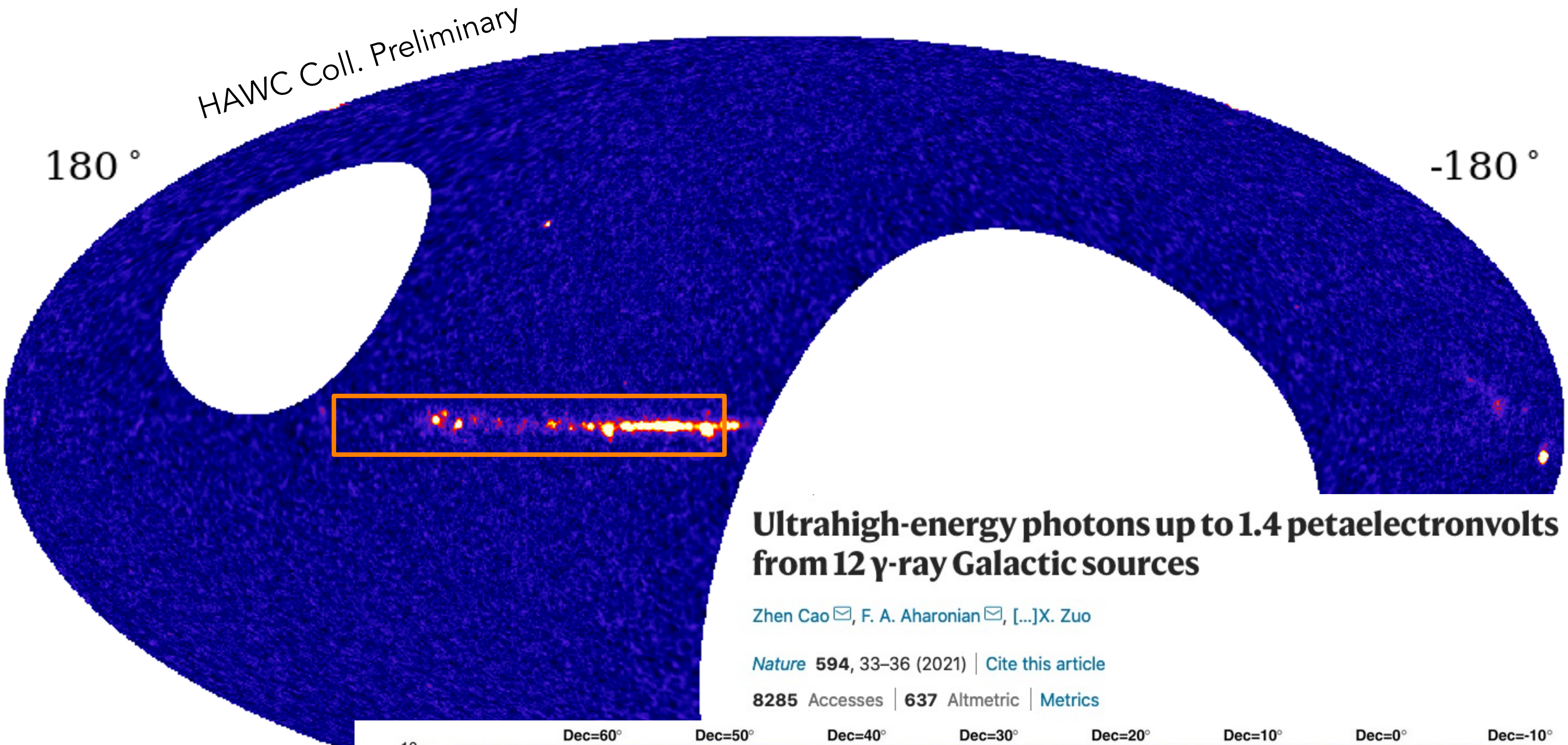


HAWC



Threshold ~1 TeV
1128 days


HAWC Coll. Preliminary
180 °
-180 °
-2
-1
-0
1
2
3
4
5
6
7
8
9
significance [σ]

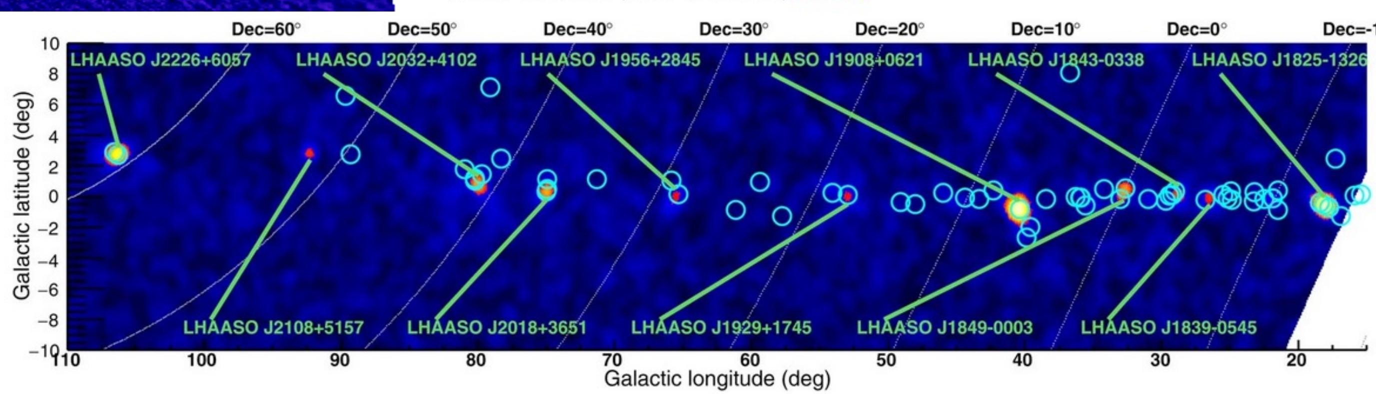


Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao, F. A. Aharonian, […]X. Zuo

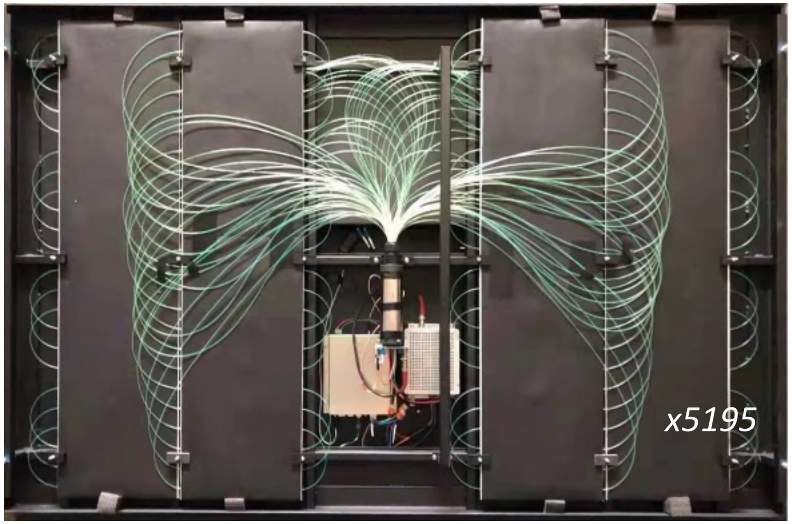
Nature **594**, 33–36 (2021) | Cite this article

8285 Accesses | **637** Altmetric | Metrics

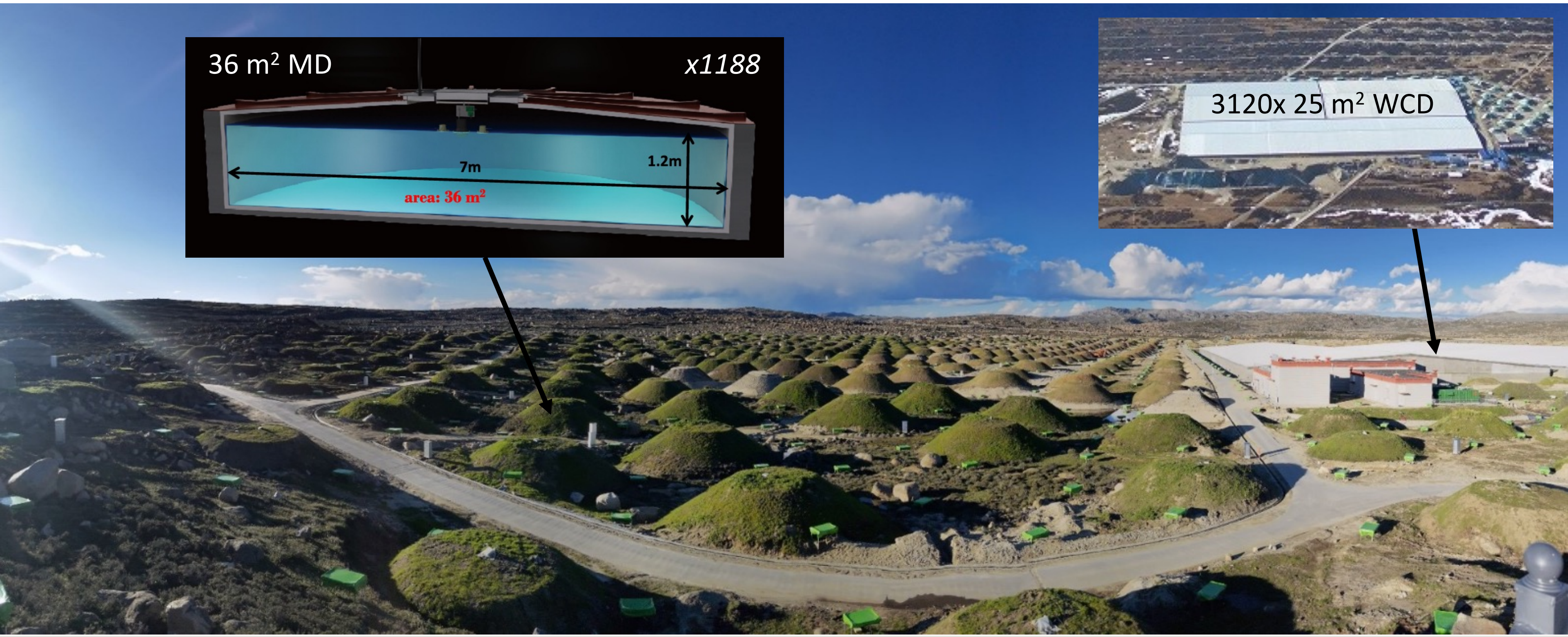


LHAASO

1 m^2 ED
Green Boxes
Below



- Completed 2021
  - KM2A:
    - ED scintillators, MD buried muon dets



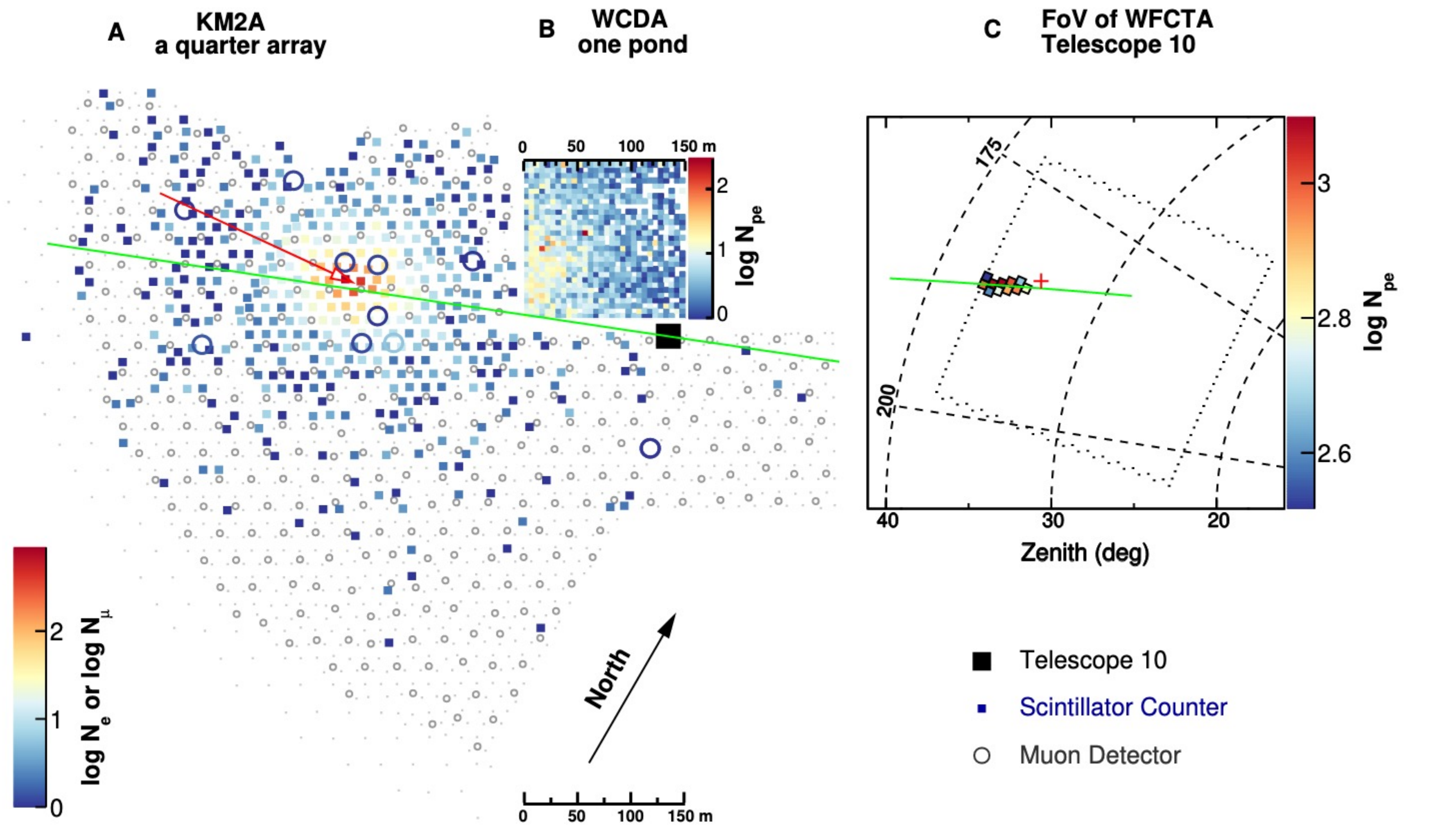
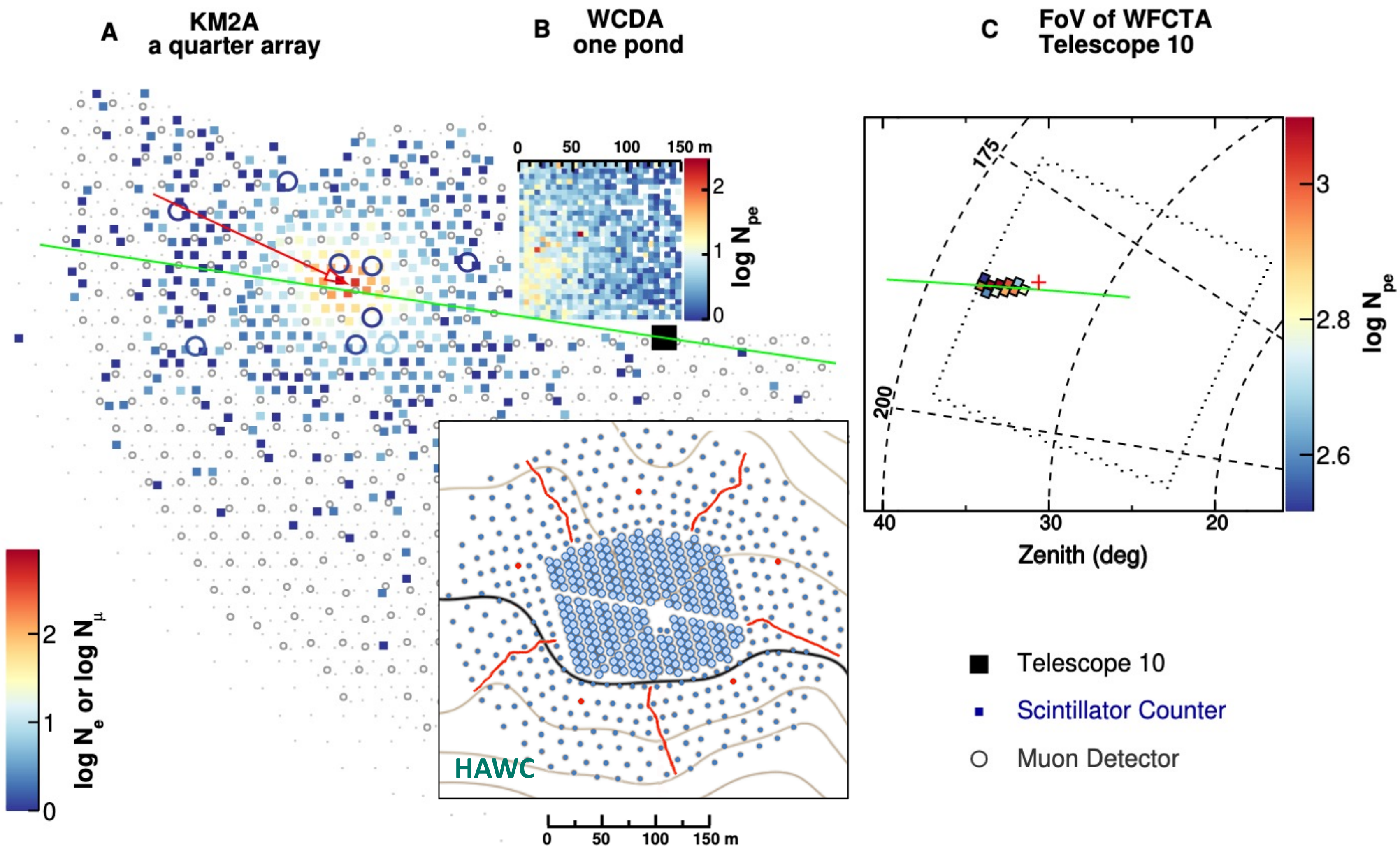


Figure 1: **The 0.88 PeV γ-ray event from the Crab recorded by the LHAASO detectors.** In panel A, squares indicate the scintillator counters of KM2A, colored according to the logarithm of number of detected particles N_e (color bar). The open circles indicate the 11 Muon Detectors of KM2A triggered by the shower. The position of the core is indicated by the red arrow, which is orientated in the arrival direction of the primary photon. The panel



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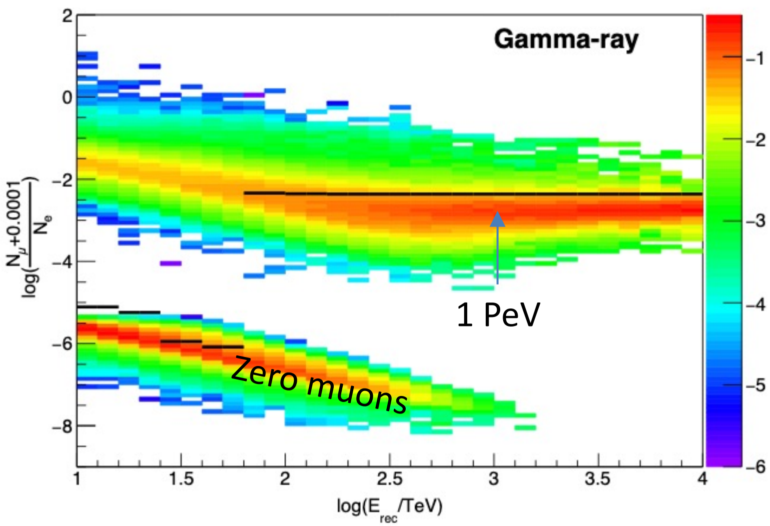
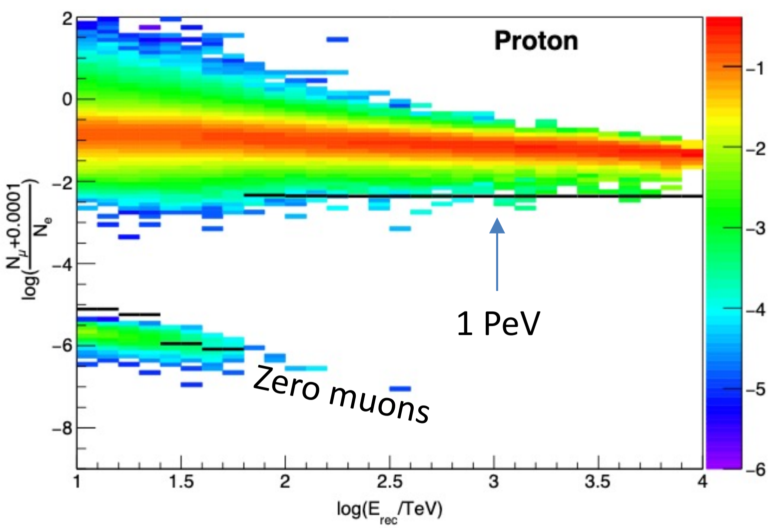
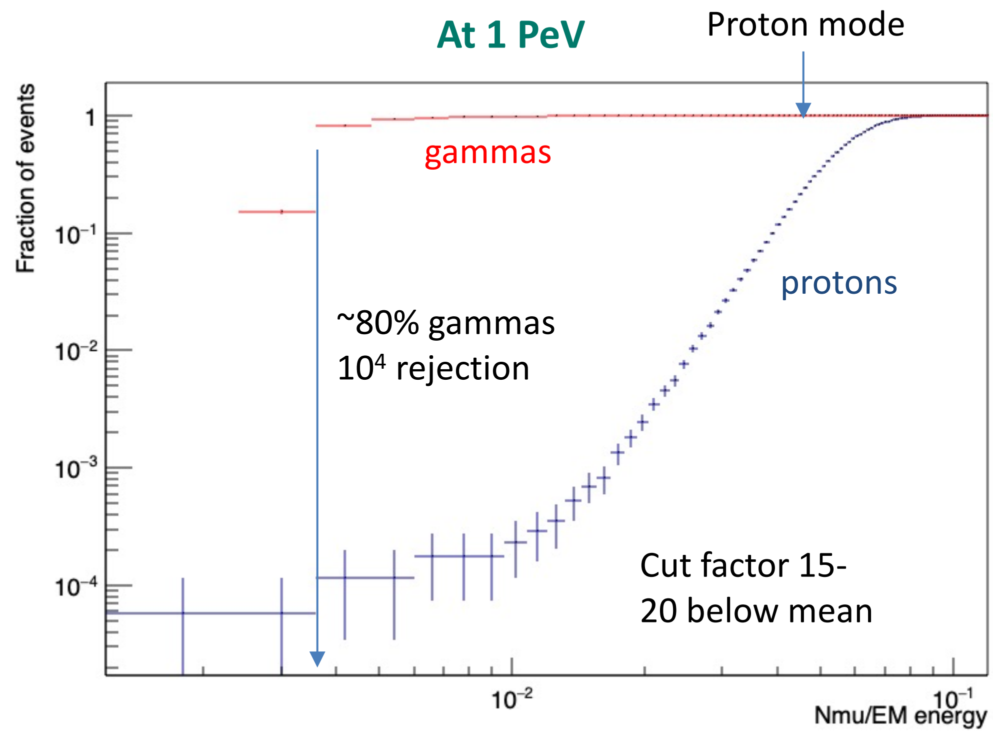
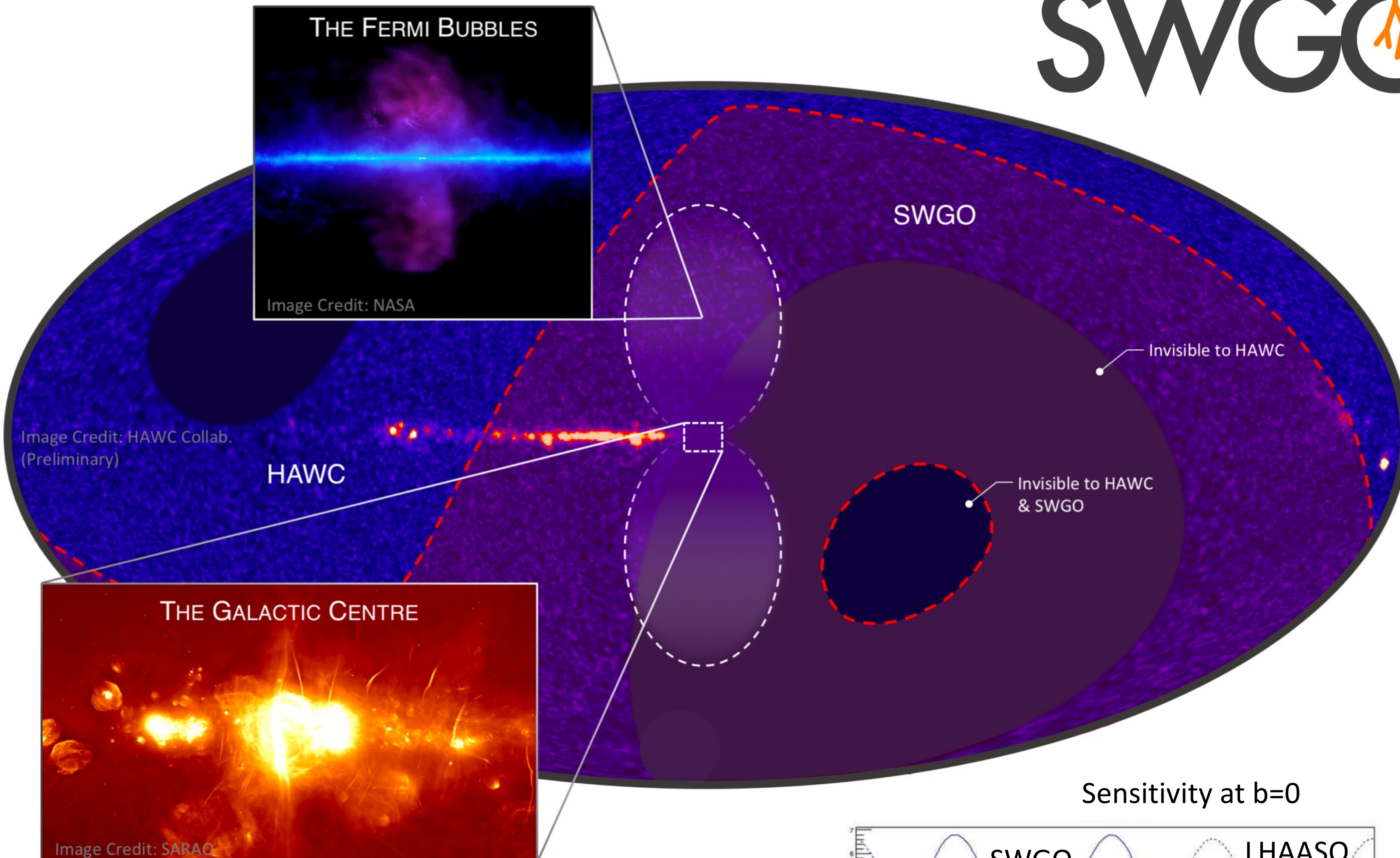
Muon Counting



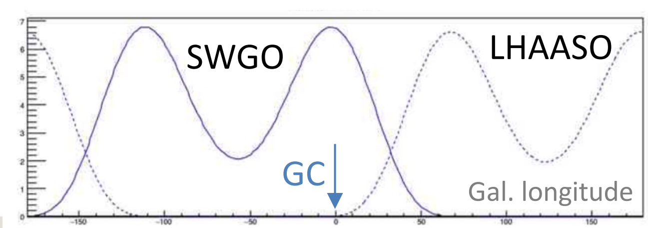




- Jim
- LHAASO

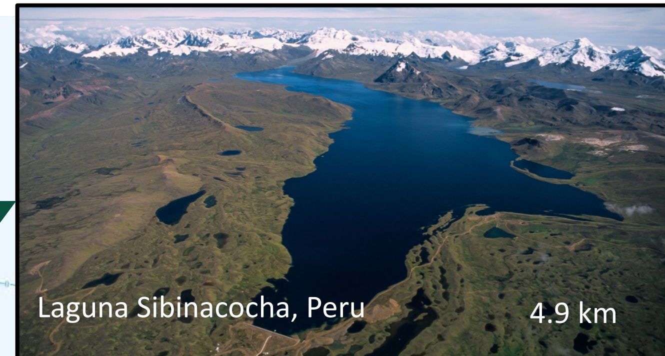


Sensitivity at b=0



Site?

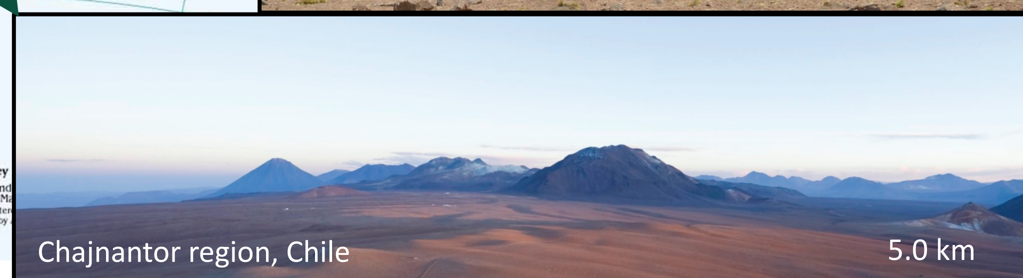
Caribbean Sea
North Atlantic Ocean
South Pacific Ocean
South Atlantic Ocean
VENEZUELA
COLOMBIA
ECUADOR
PERU
BRAZIL
BOLIVIA
PARAGUAY
CHILE
ARGENTINA
URUGUAY
GUYANA
SURINAME
AMAZON BASIN
BRAZILIAN HIGHLANDS
ANDES
Caracas
Bogotá
Quito
Lima
Cusco
La Paz
Asunción
Santiago
Buenos Aires
Montevideo
Manaus
Brasília
Rio de Janeiro
São Paulo
Georgetown
Paramaribo
Cayenne
Scale 1:35,000,000
Azimuthal Equal-Area Projection



Laguna Sibinacocha, Peru
4.9 km

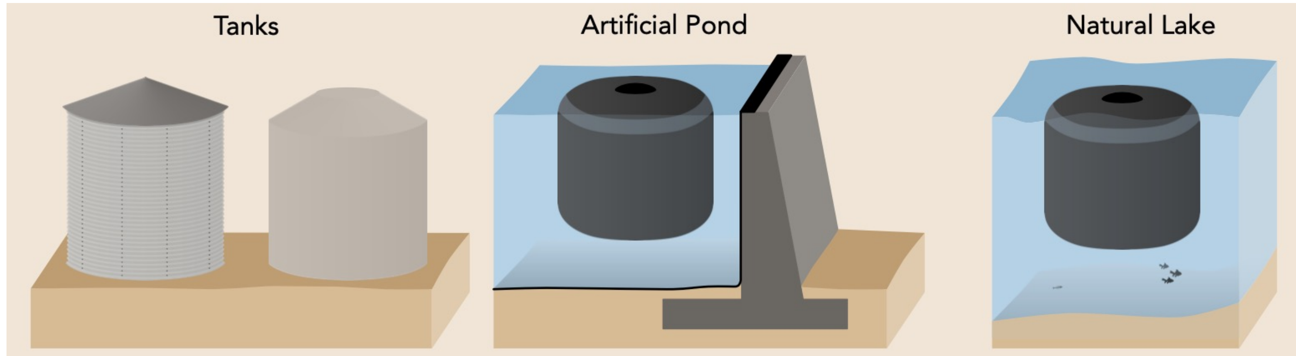
ALPACA site
near Mt Chacaltaya, Bolivia
4.7 km

CUBIC site, Salta, Argentina
4.8 km

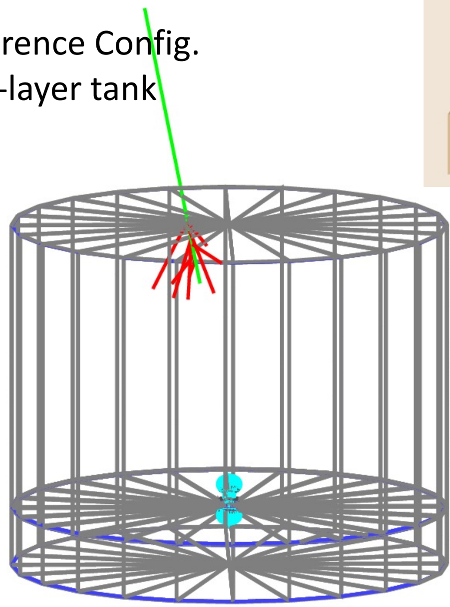


Chajnantor region, Chile
5.0 km

SWGO Design Development

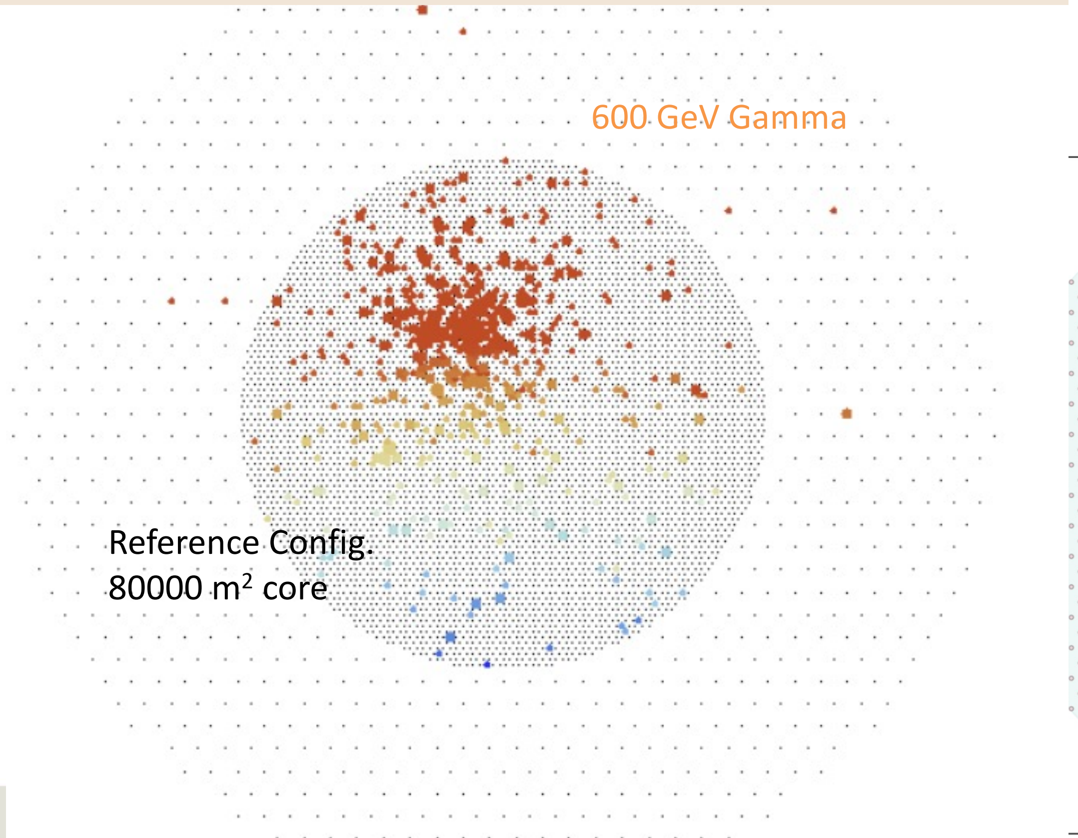


Reference Config.
Two-layer tank

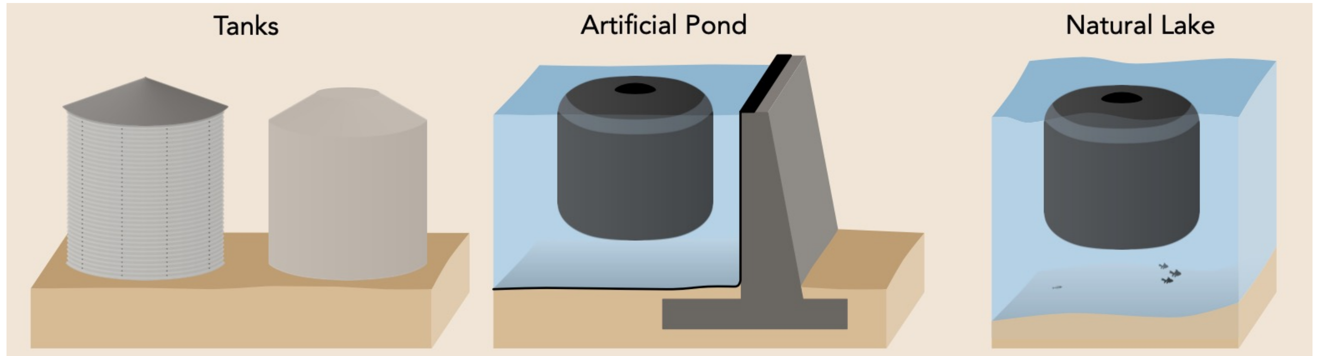


Samridha Kunwar

Muon identification a key element of background rejection



SWGO Design Development



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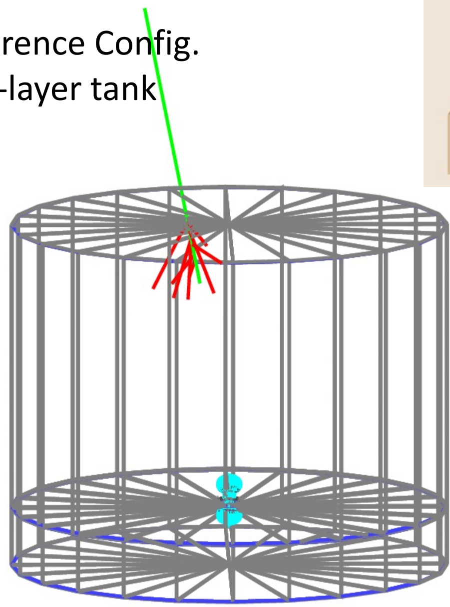
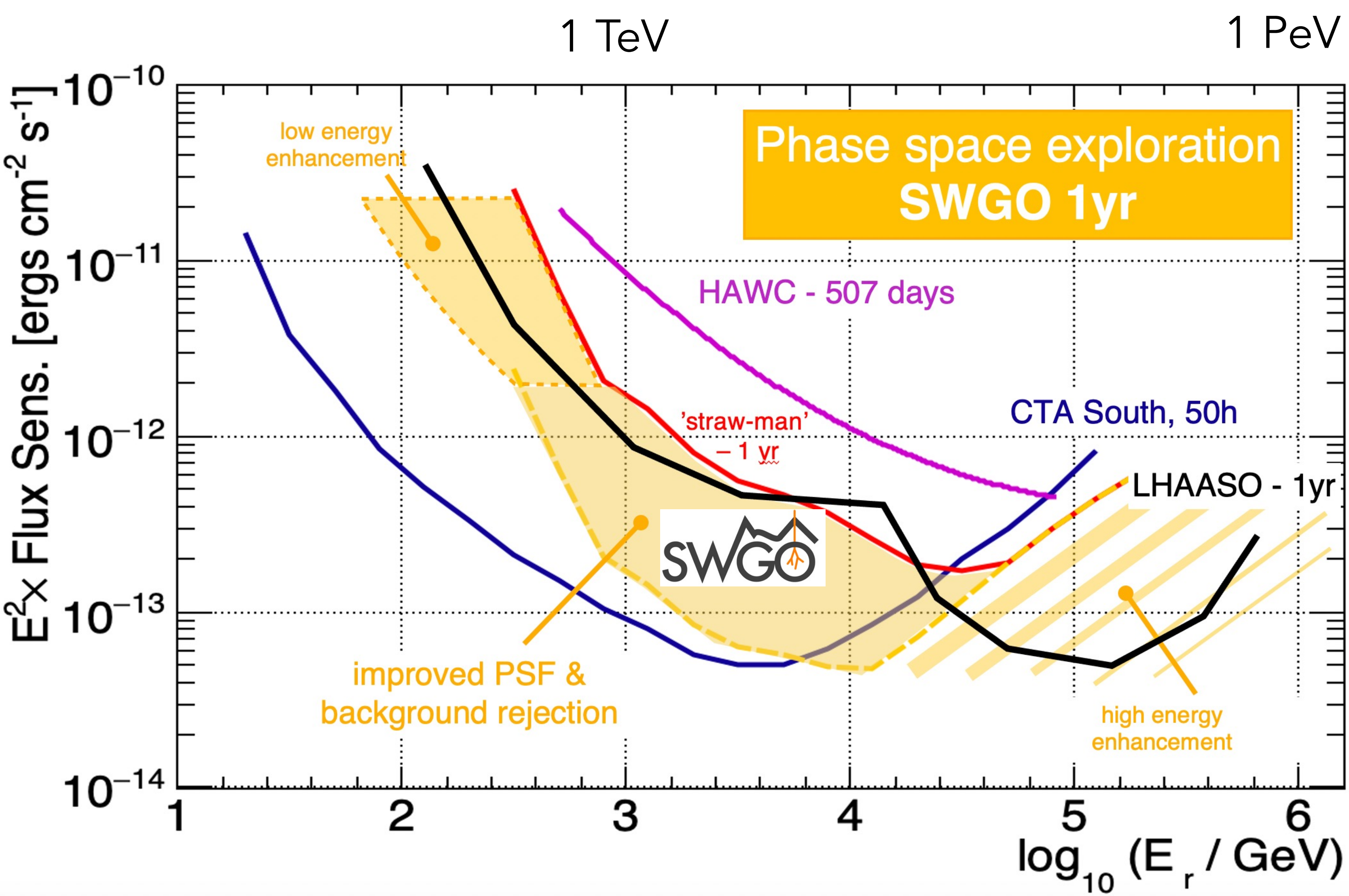
Two-layer tank

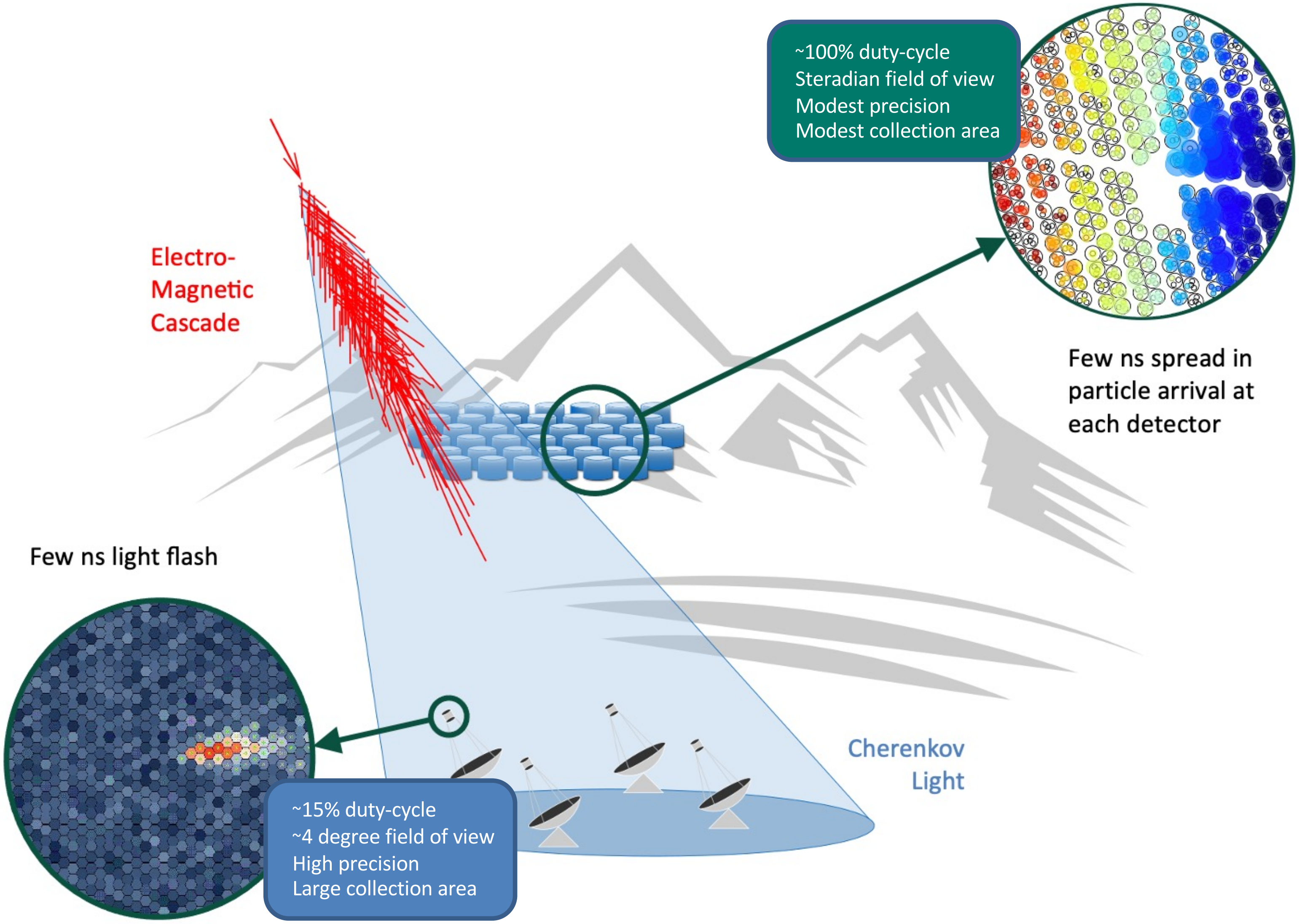


Design+Site Choices **2023**
Engineering Array **2024+**

Reference Config.
80000 m^2 core

Muon identification a key element of background rejection


1 TeV
1 PeV
Phase space exploration
SWGO 1yr
low energy enhancement
HAWC - 507 days
'straw-man' – 1 yr
CTA South, 50h
LHAASO - 1yr
SWGO
improved PSF & background rejection
high energy enhancement
$E^2 \times$ Flux Sens. [ergs cm^{-2} s^{-1}]
$\log_{10}$ (E_r / GeV)

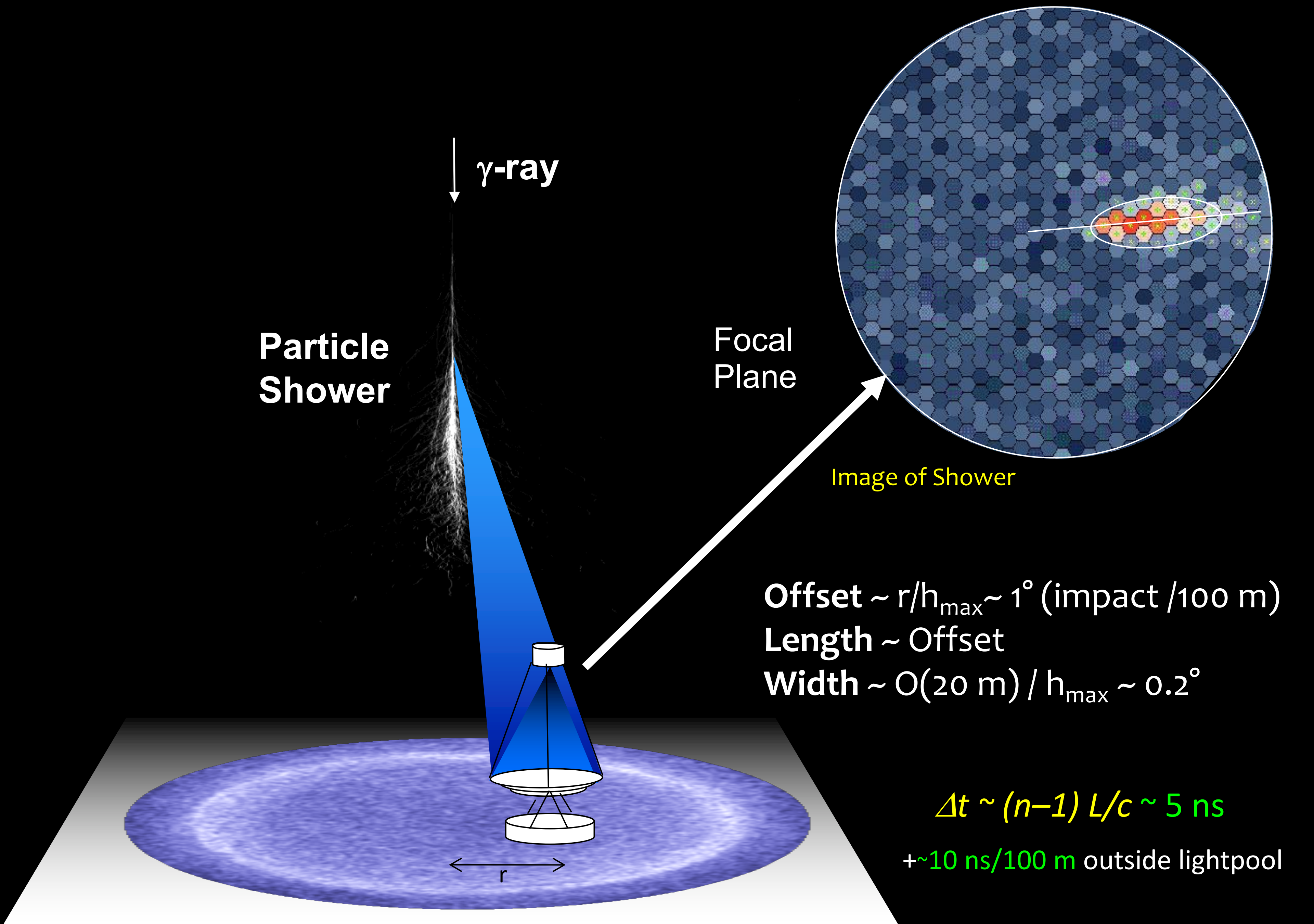

~100% duty-cycle
Steradian field of view
Modest precision
Modest collection area
Electro-
Magnetic
Cascade
Few ns spread in
particle arrival at
each detector
Few ns light flash
Cherenkov
Light
~15% duty-cycle
~4 degree field of view
High precision
Large collection area

IACTs

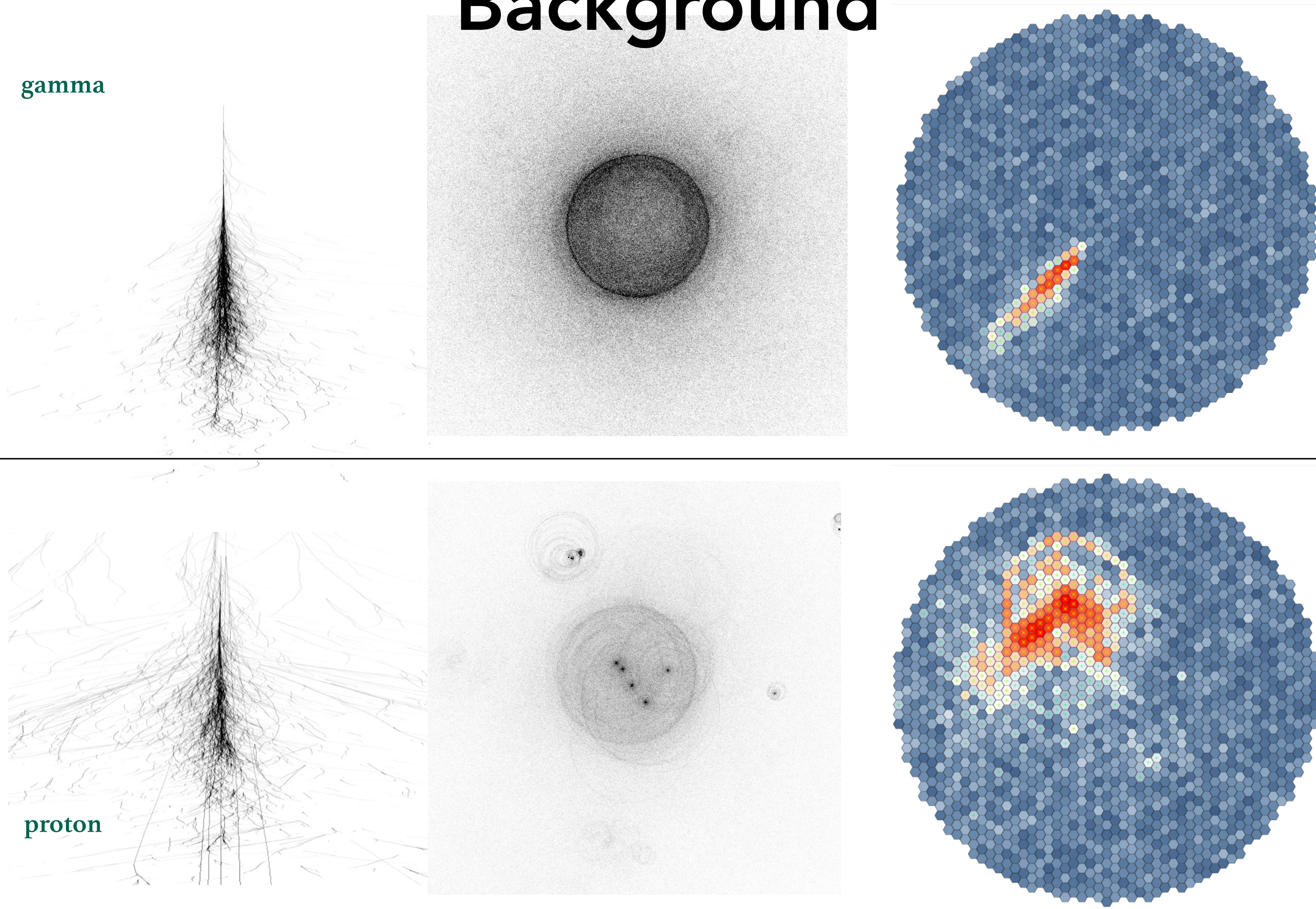
- Whipple, HEGRA, CAT, ++
  - Single telescope → array
  - Finer pixilation
- HESS, MAGIC, VERITAS
  - Arrays of large telescopes, since 2004
- → CTA

NB. Cherenkov light pool ~10^5 m^2
~15% duty cycle, pointed → typ. 50 h of obs.
Exposure O(10^{14} cm^2 s)

→ For 10 events > 100 TeV →**10^{-11} erg cm^2 s**
→ **No known source this bright**
Current IACT spectra to ~80 TeV


γ-ray
Particle Shower
Focal Plane
Image of Shower
Offset ~ r/h_max ~ 1° (impact /100 m)
Length ~ Offset
Width ~ O(20 m) / h_max ~ 0.2°
Δt ~ (n–1) L/c ~ 5 ns
+~10 ns/100 m outside lightpool
r

Background



Muons

Eur. Phys. J. C (2021) 81:1101
https://doi.org/10.1140/epjc/s10052-021-09869-0

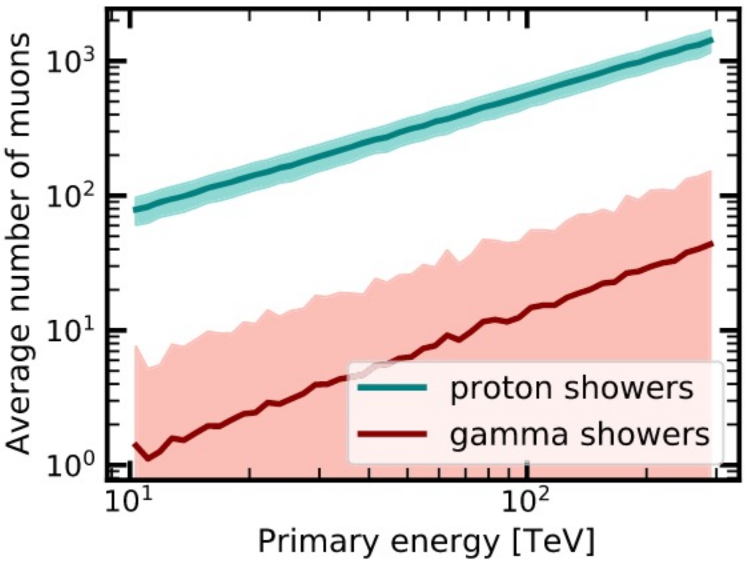
THE EUROPEAN PHYSICAL JOURNAL C

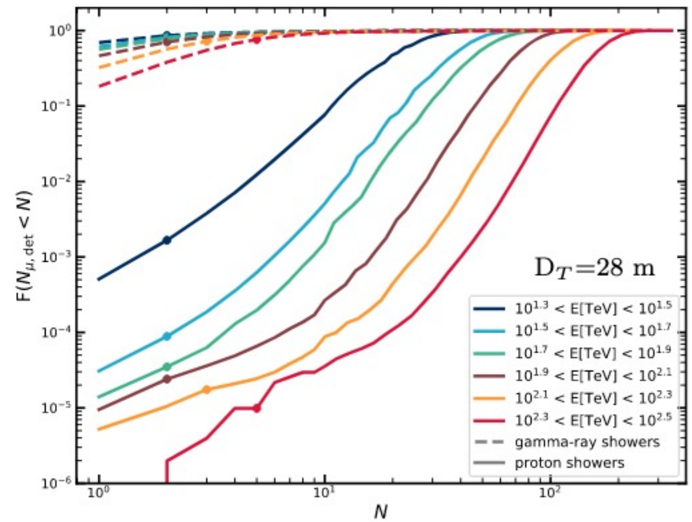
Regular Article - Experimental Physics

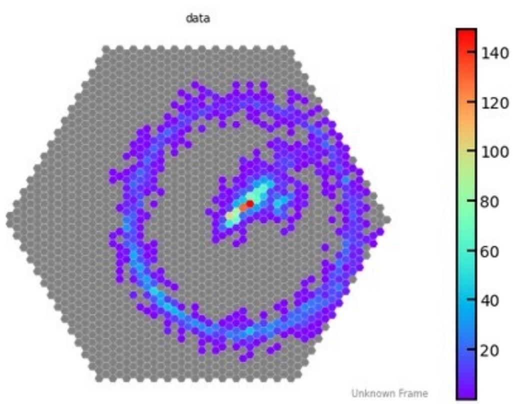
Muons as a tool for background rejection in imaging atmospheric Cherenkov telescope arrays

L. Olivera-Nieto[1,a], A. M. W. Mitchell[2,3], K. Bernlöhr[1], J. A. Hinton[1]

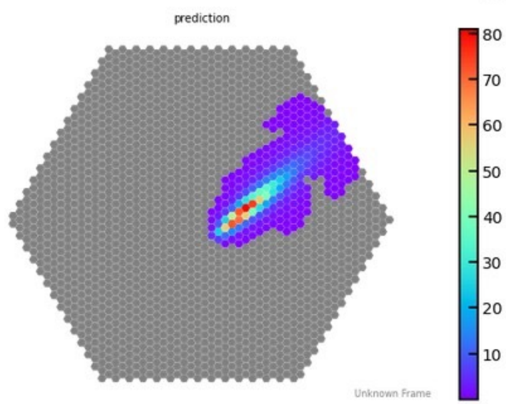
[1] Max-Planck-Institut für Kernphysik, P.O. Box 103980, 69029 Heidelberg, Germany
[2] Department of Physics, ETH Zurich, 8093 Zurich, Switzerland
[3] Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

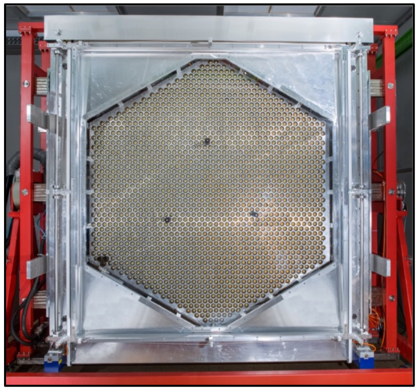




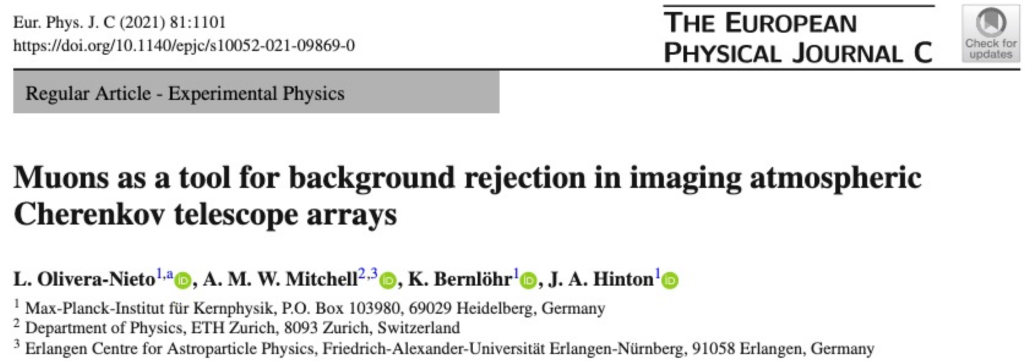


HESS CT5 Camera Images





Muons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Regular Article - Experimental Physics

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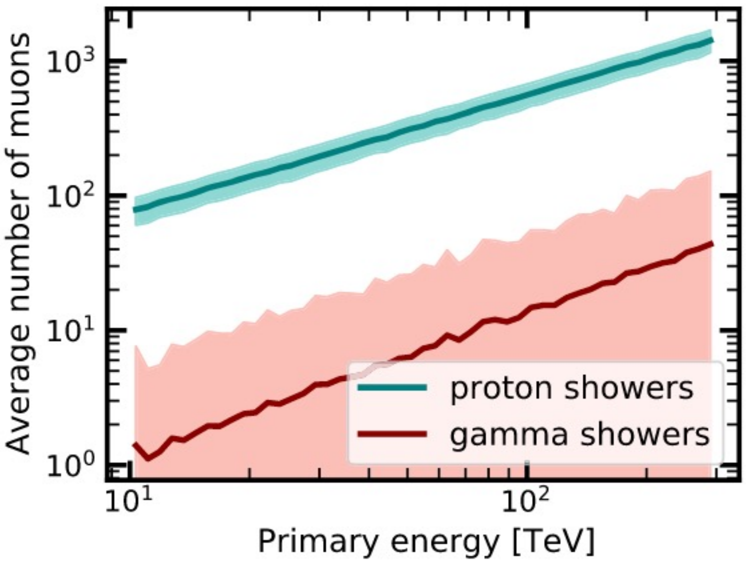
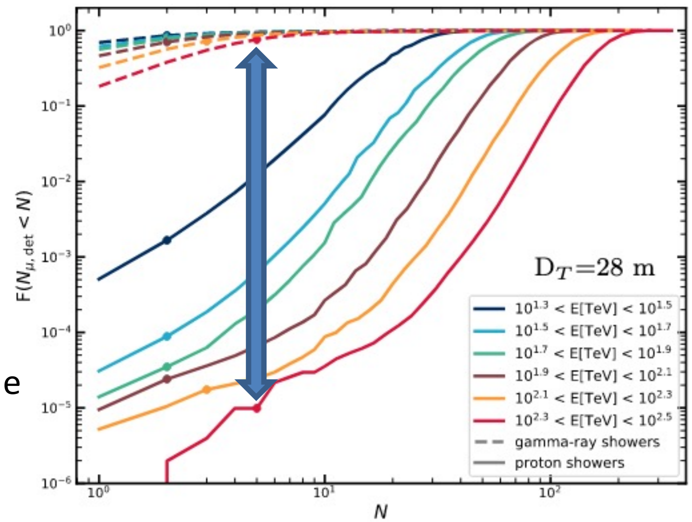
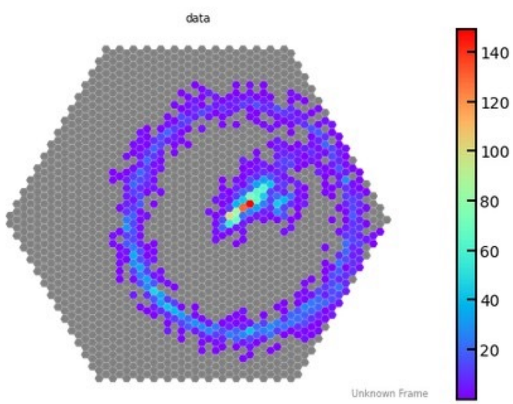
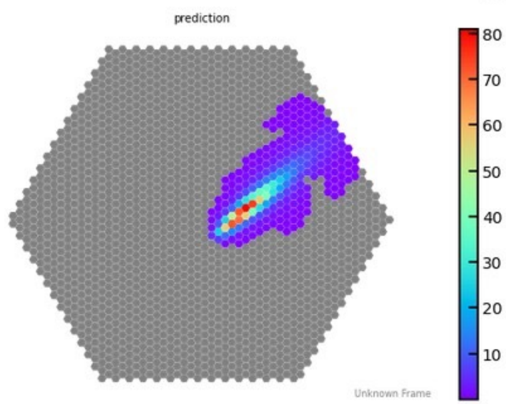


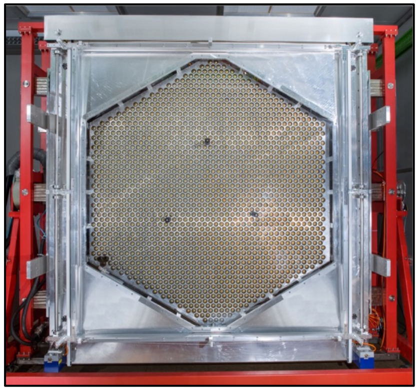
~10^5 rejection
Possible in principle
~200 TeV





HESS CT5
Camera
Images





Muons

Eur. Phys. J. C (2021) 81:1101
https://doi.org/10.1140/epjc/s10052-021-09869-0
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

Muons as a tool for background rejection in imaging atmospheric Cherenkov telescope arrays

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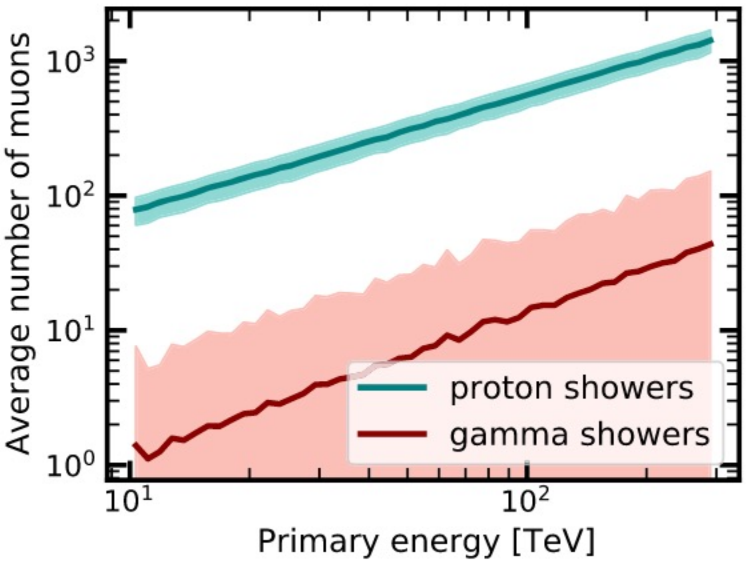
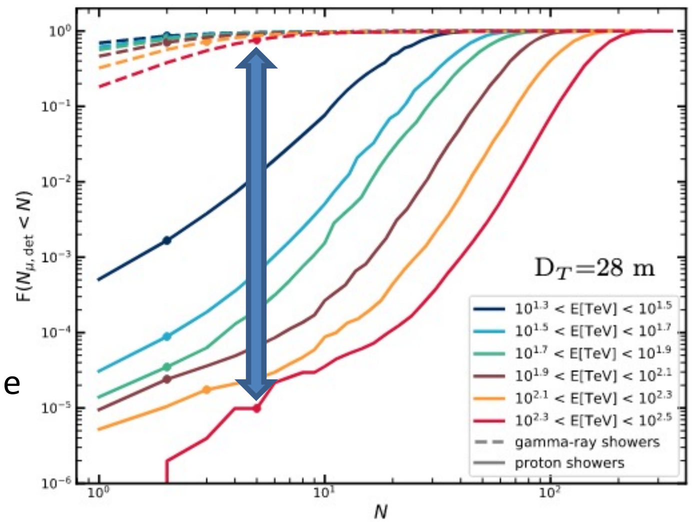
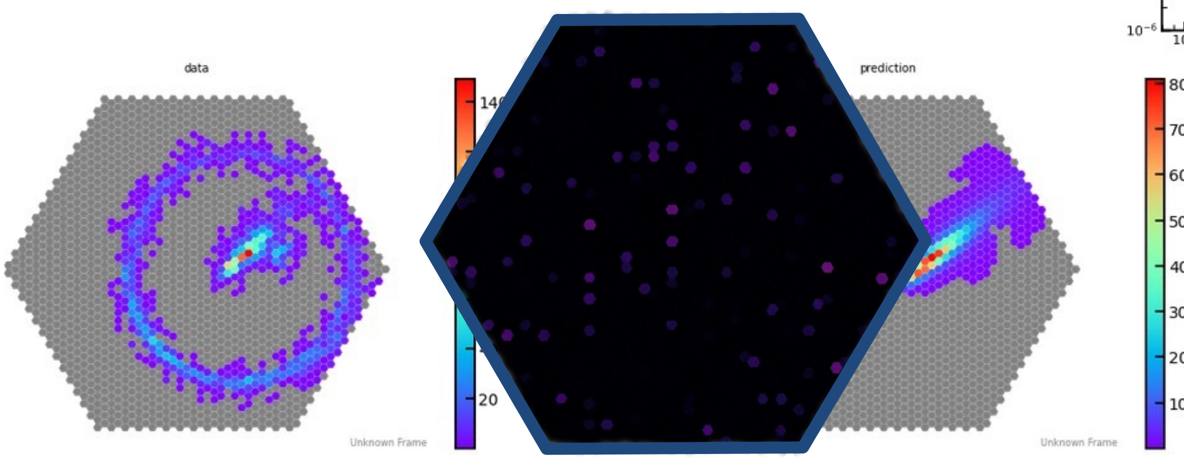
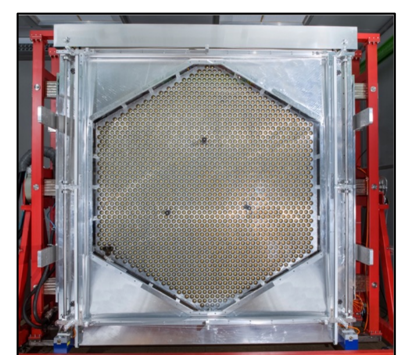
[3] Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany

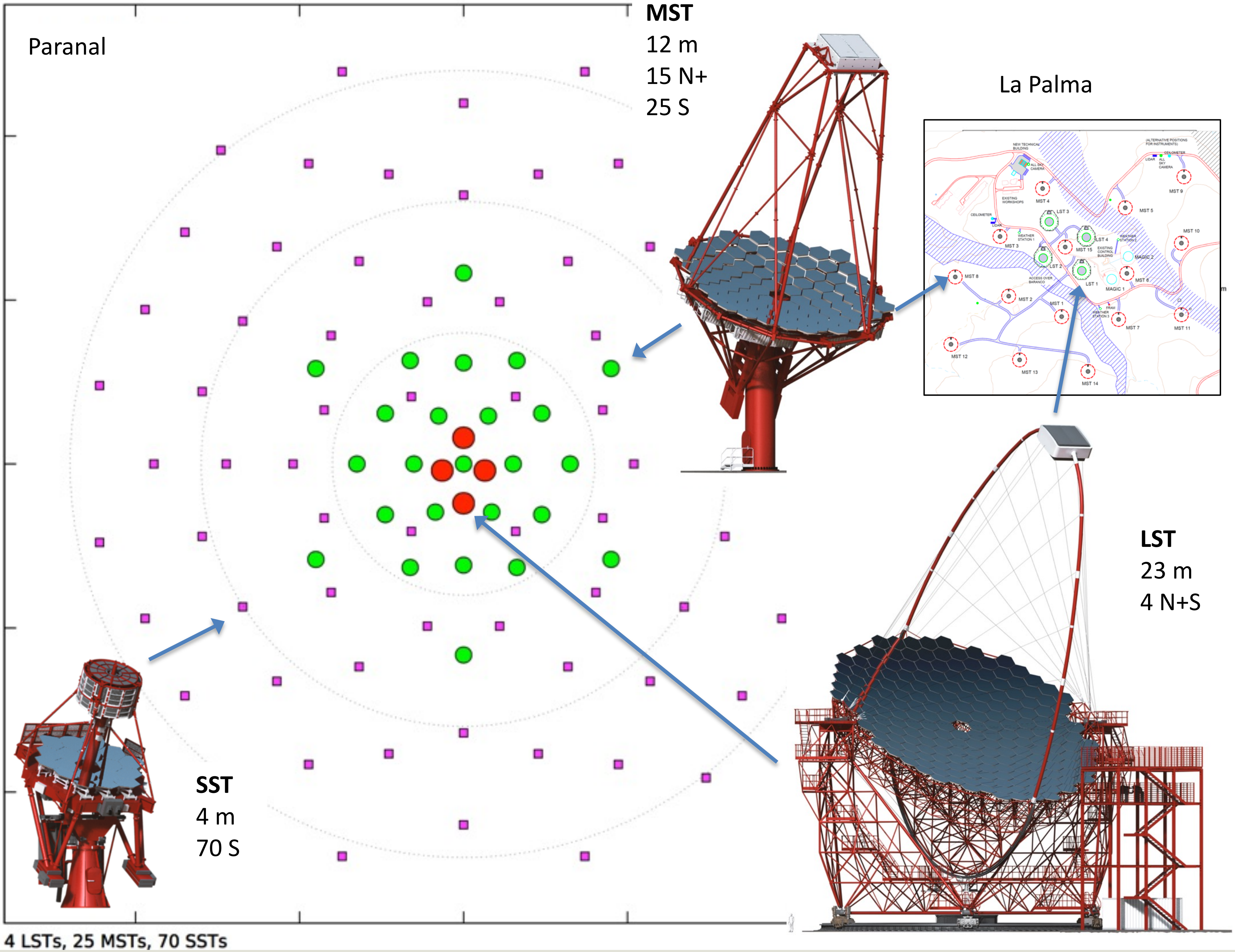


~10^5 rejection
Possible in principle
~200 TeV





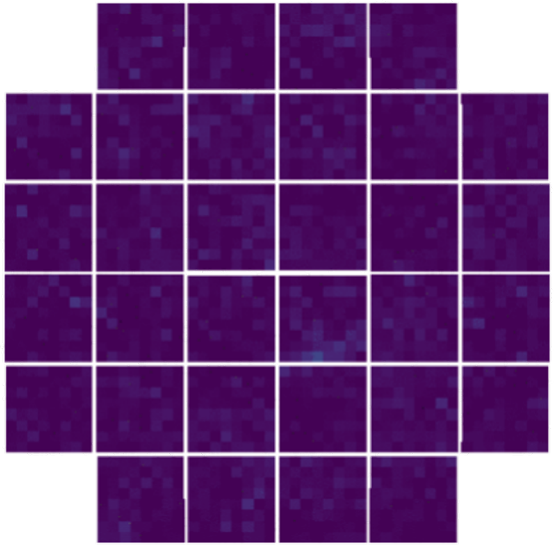


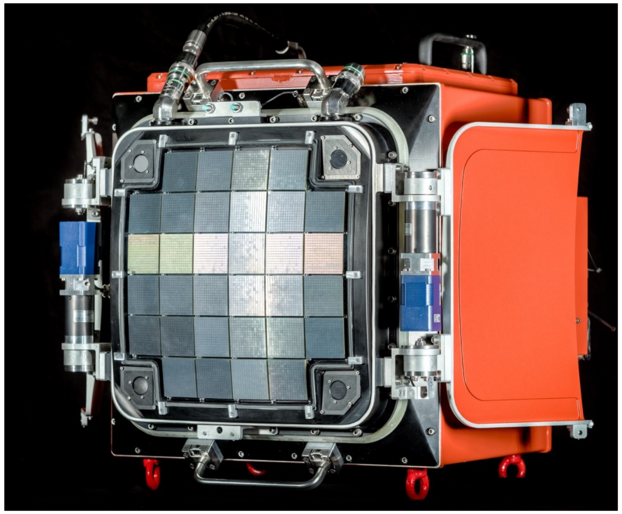


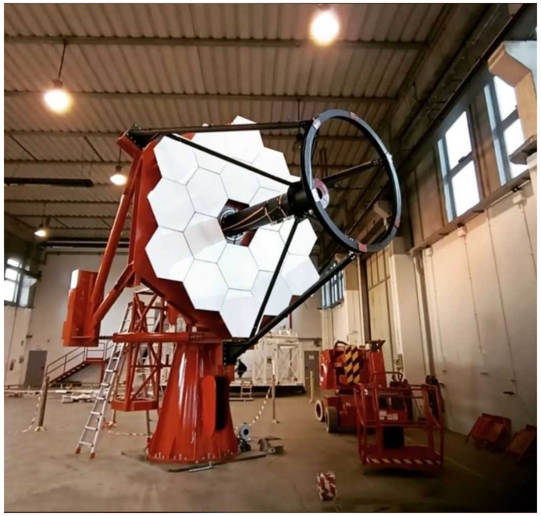
Paranal
MST
12 m
15 N+
25 S
La Palma
LST
23 m
4 N+S
SST
4 m
70 S
4 LSTs, 25 MSTs, 70 SSTs

SST

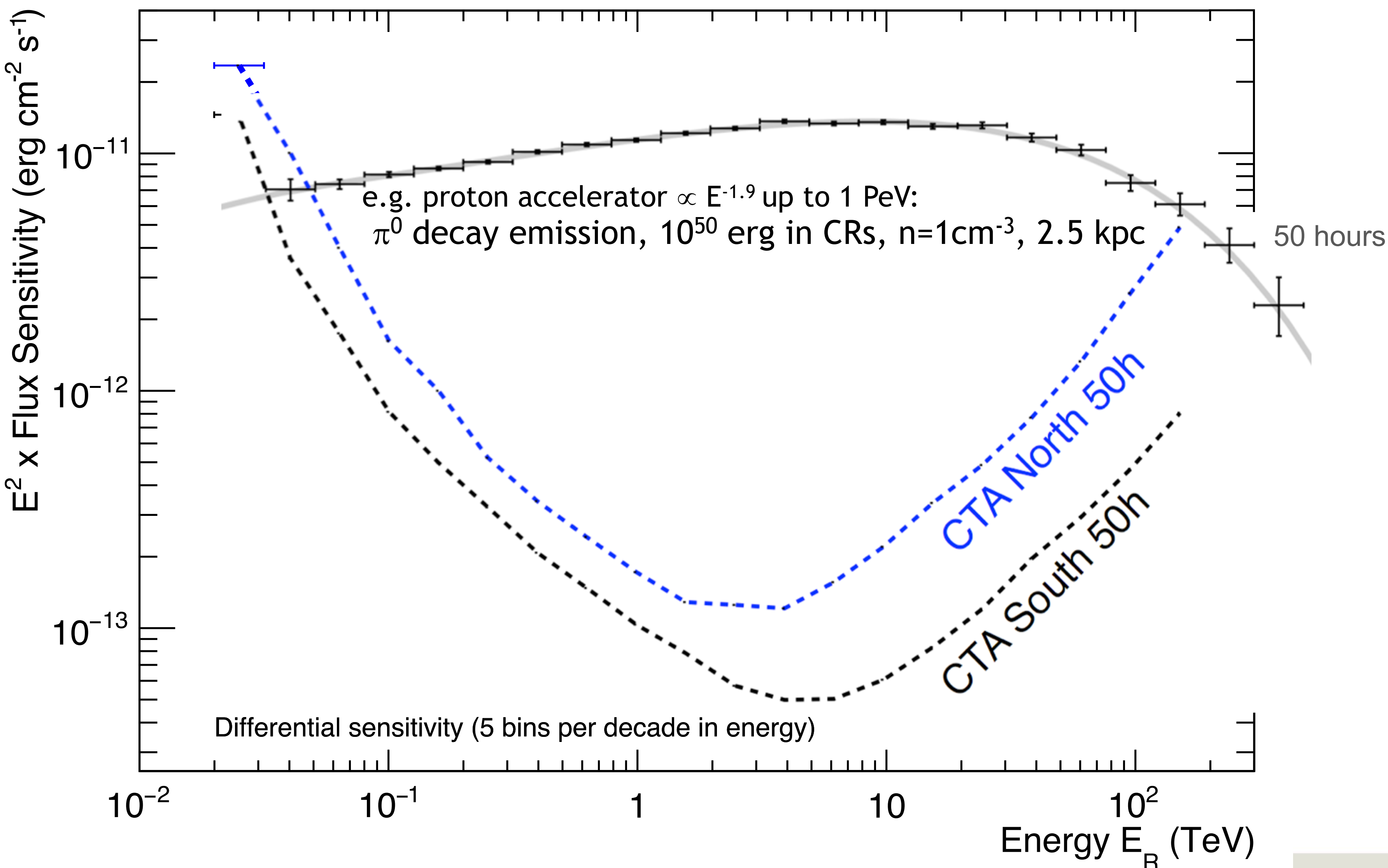
- Design based on ASTRI and CHEC prototypes
  - 9 degree cameras, Gsample/s, 0.17 deg. pixels
- Looking forward to construction in Chile starting soon!
  - ASTRI miniarray in Tenerife in the meantime



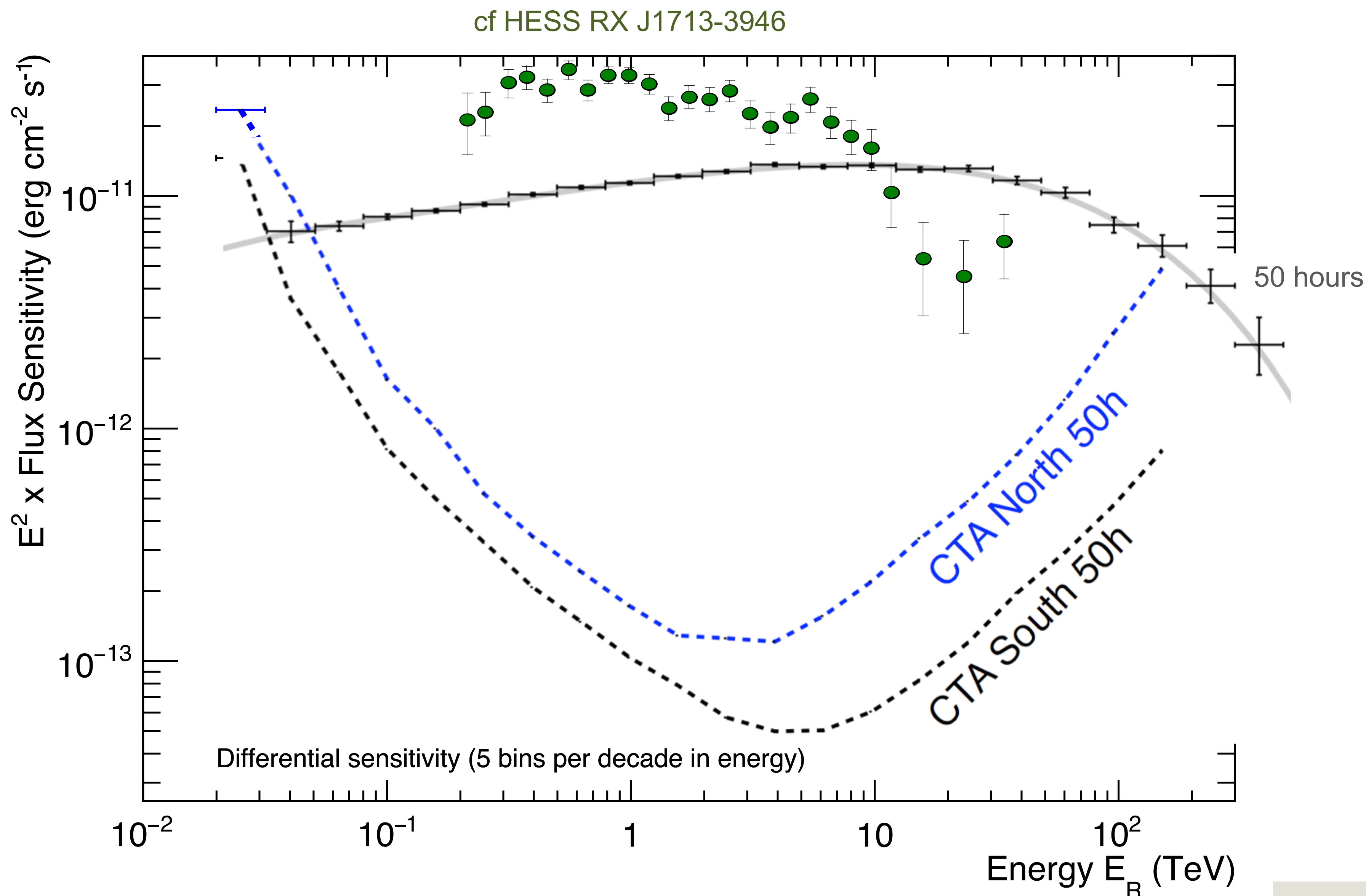




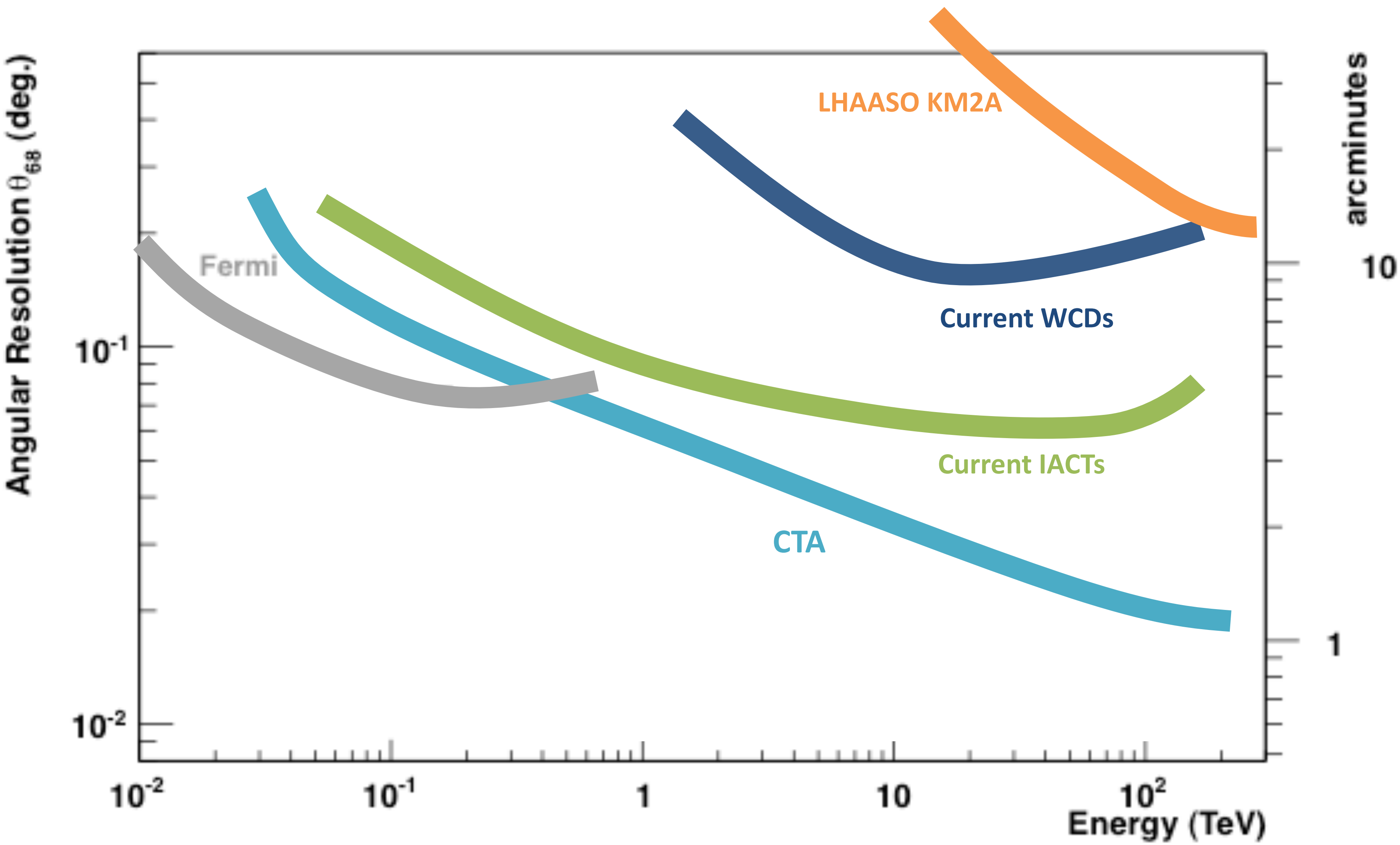
Wide Energy Coverage



Wide Energy Coverage

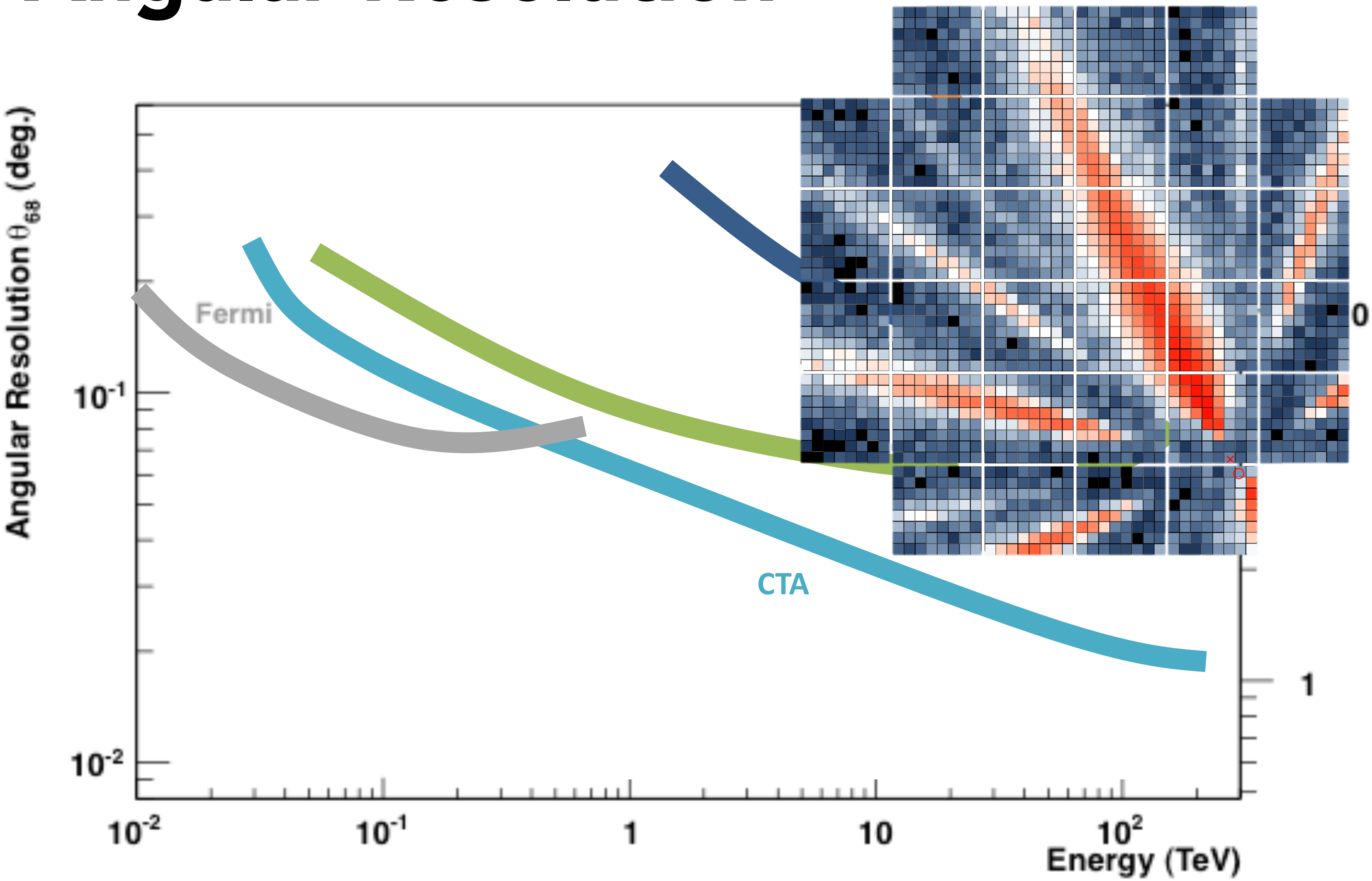


Angular Resolution



Angular Resolution

16 SSTs 300 TeV γ

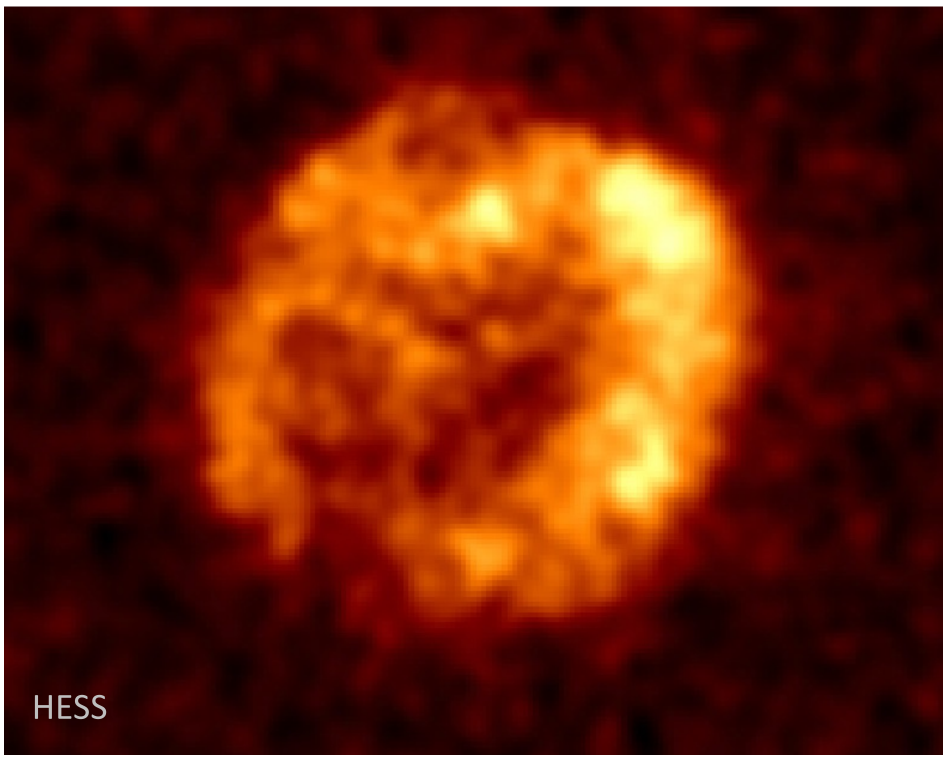


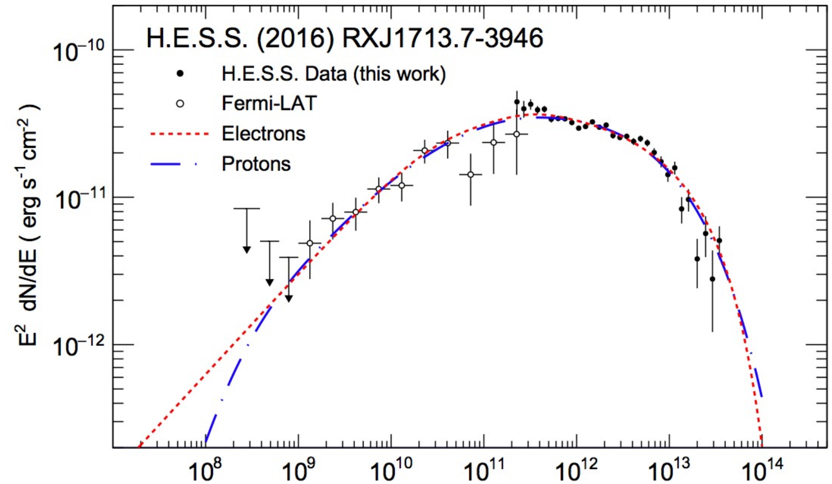
Part 2: Observations

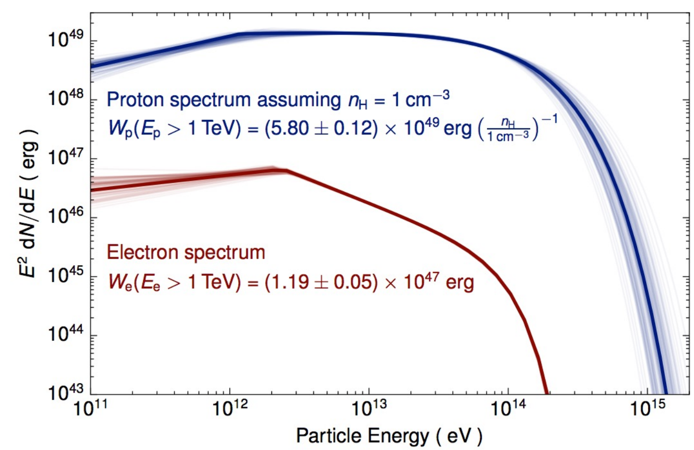
- The usual suspects: SNR
- The LHAASO sources
- Cygnus Cocoon
- Galactic Centre
- Westerlund 1
- SS 433
- A comparison of VHE-UHE spectra

Supernova Remnants?

- Brightest objects are ambiguous in terms of electron v. proton acceleration (e.g. RX J1713 + Vela Junior)

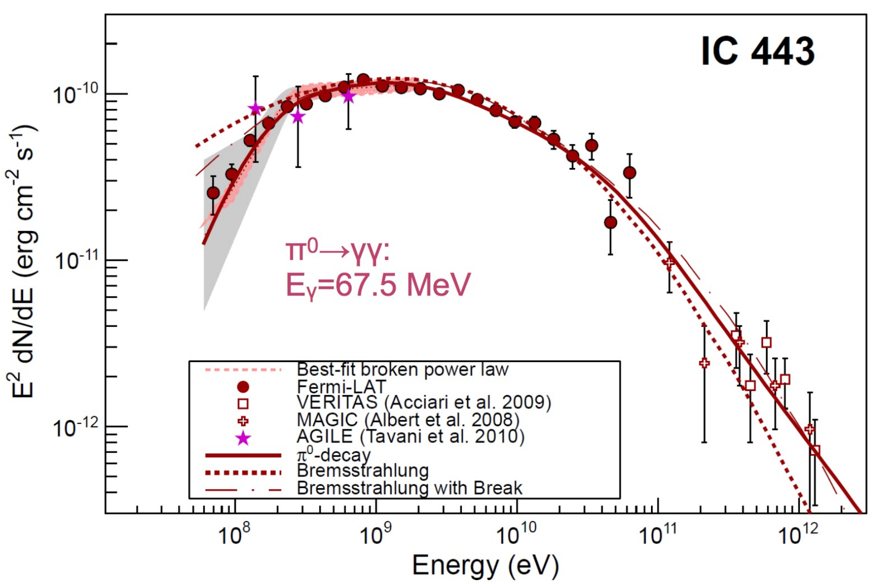




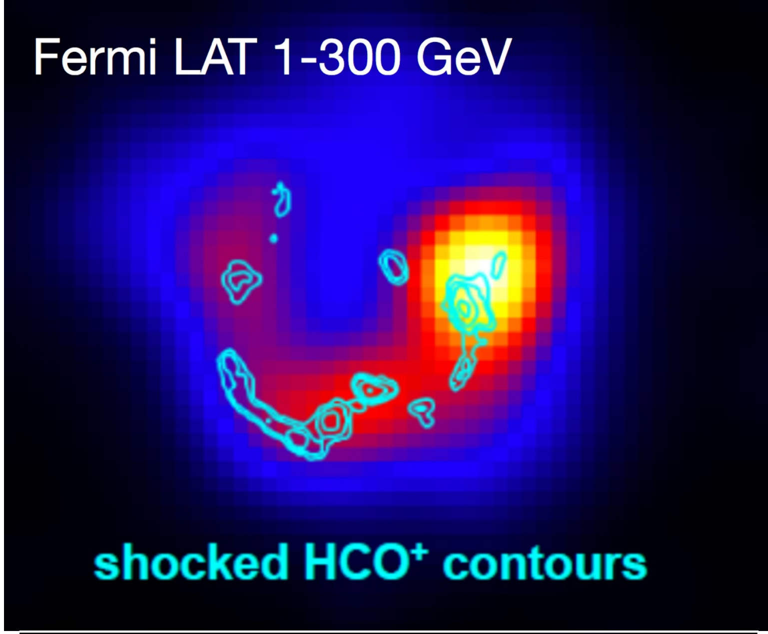


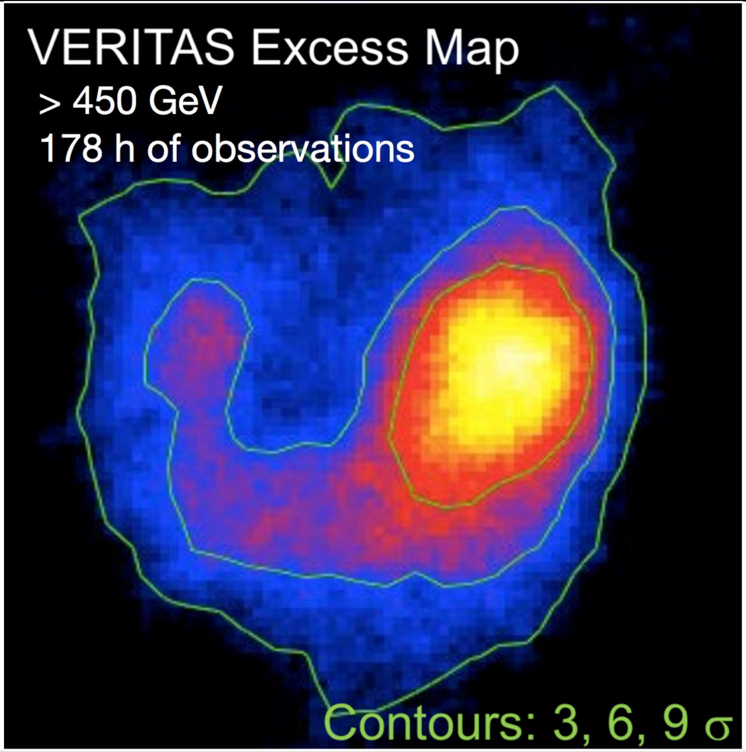
Protons?

- Interacting SNRs
  - Accelerated protons & nuclei interacting in gas clouds
  - But no evidence for protons>100 TeV...



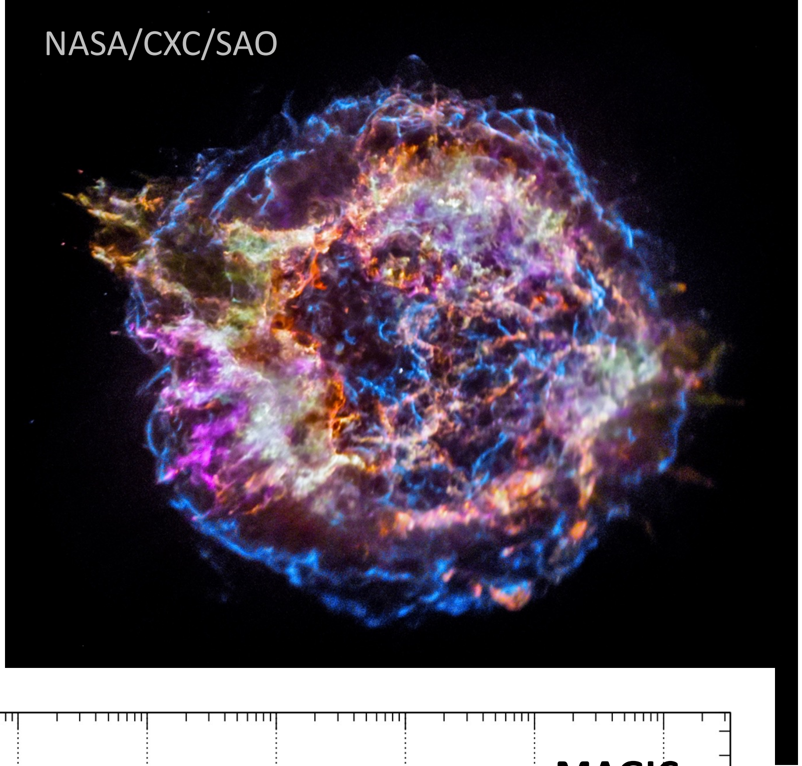
e.g. IC443

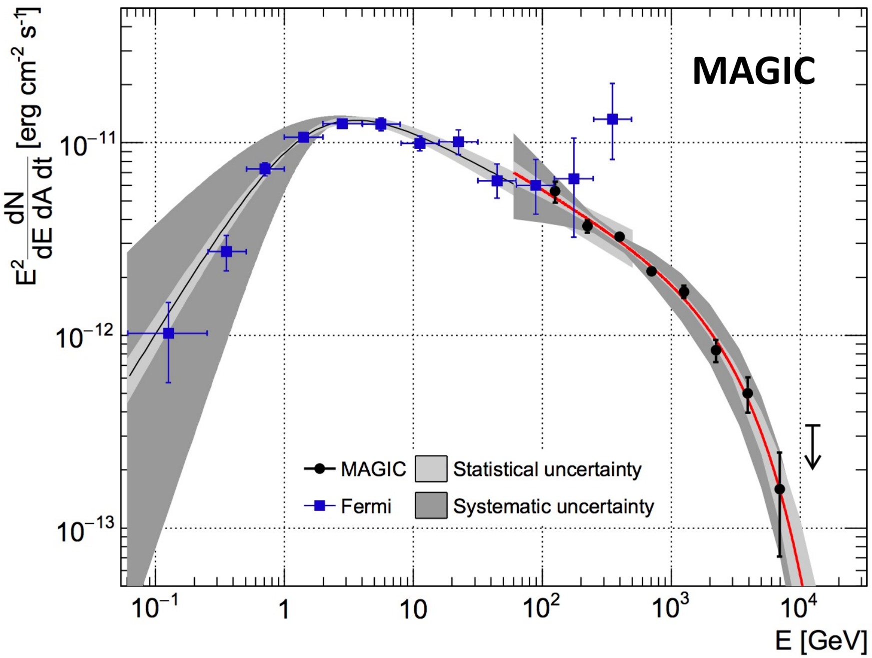




To the Knee?

- Steepening in spectra of all known TeV SNR at <=10 TeV
  - Lack of protons/nuclei > 100 TeV
- e.g. Cassiopeia A
  - Young SNR (~300 years), dense environment – looked like best chance for PeV acceleration…
  - Second component?
- SNRs not the main contributor at/beyond the knee?

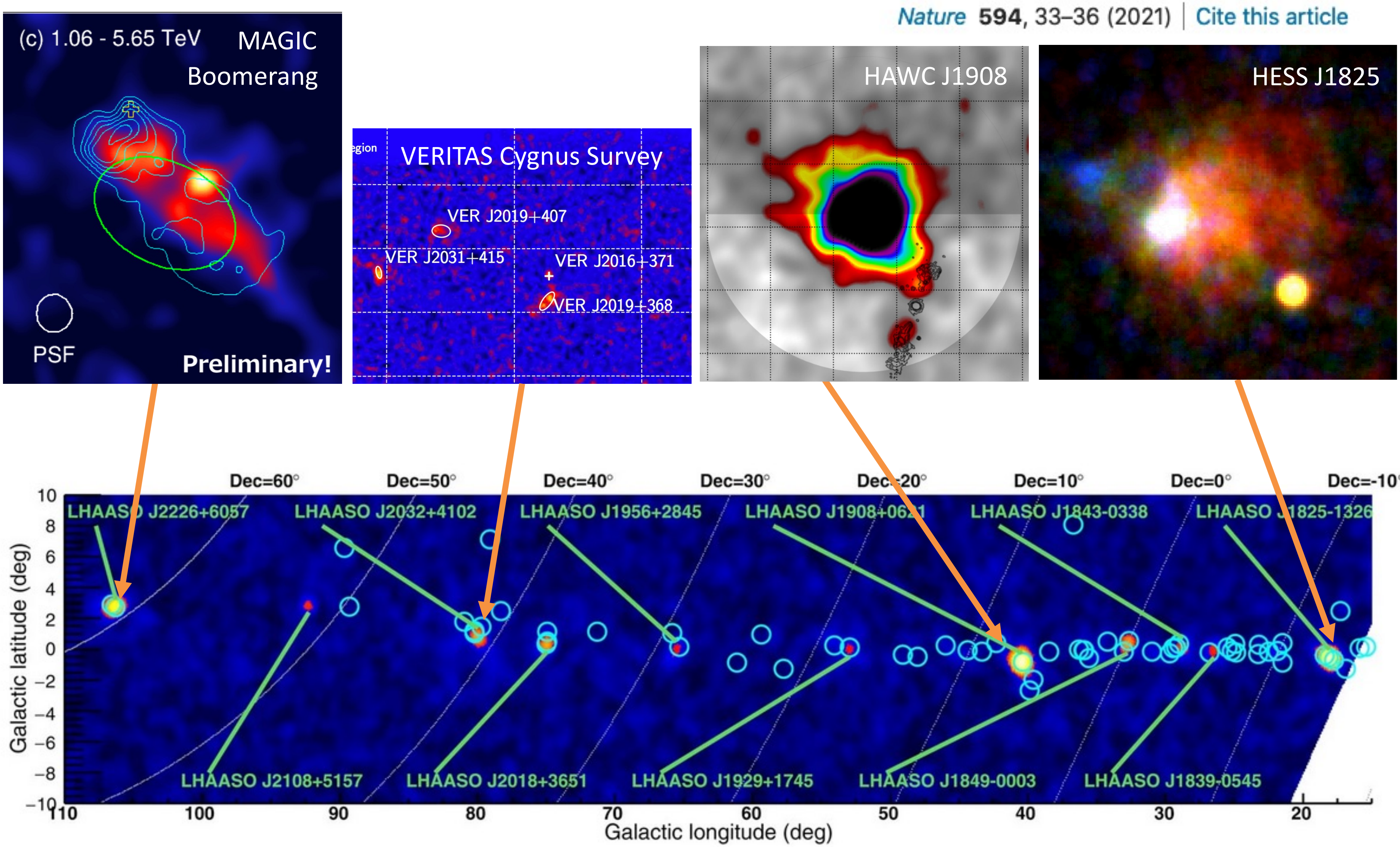




Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

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

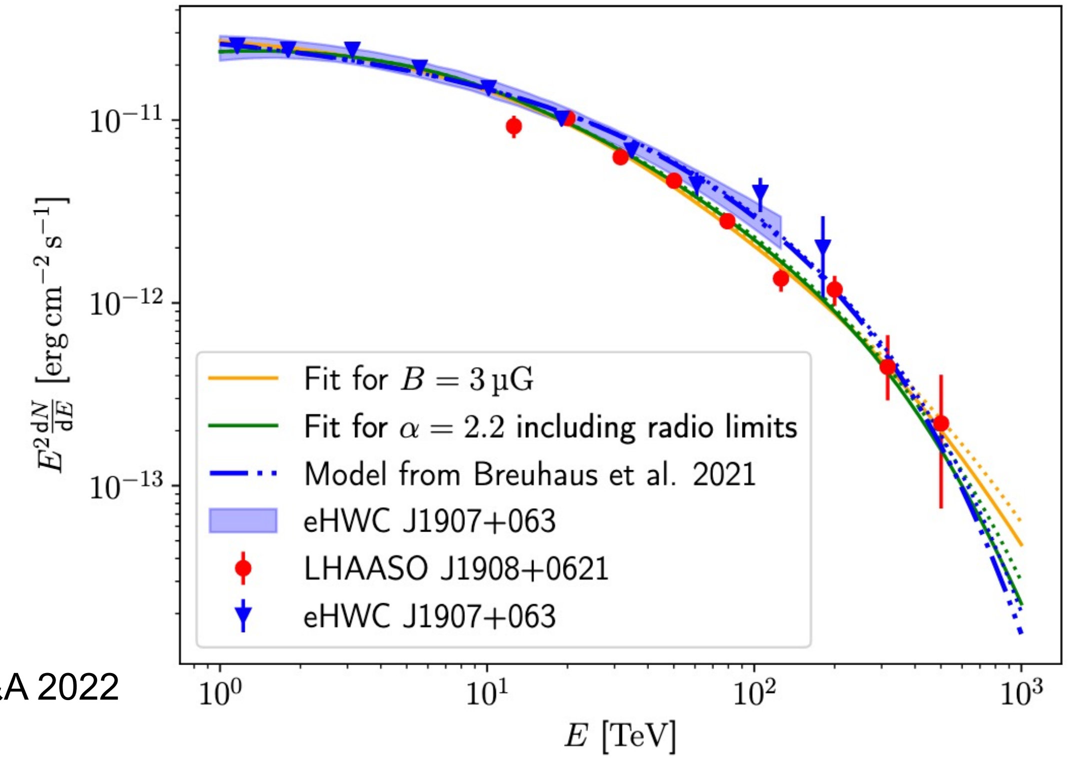
Nature **594**, 33–36 (2021) | Cite this article



Relatively Steep Spectra

- Such that IC interpretation is still possible
- At least in radiation dominated environments
  - Need to separate acceleration and cooling zones

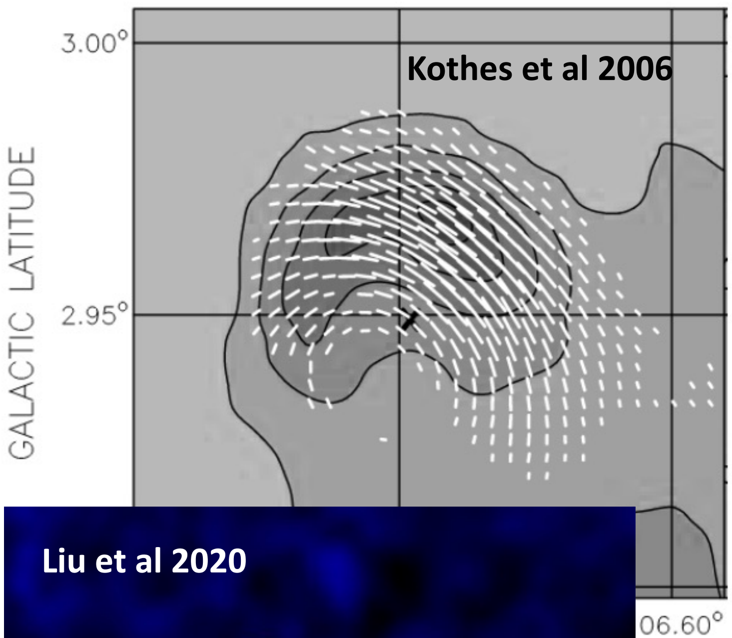
- In general high-powered pulsars can be found nearby

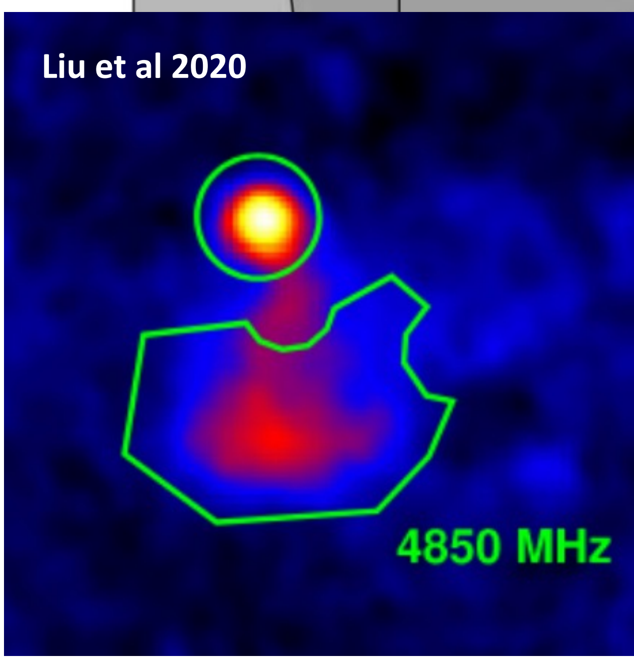


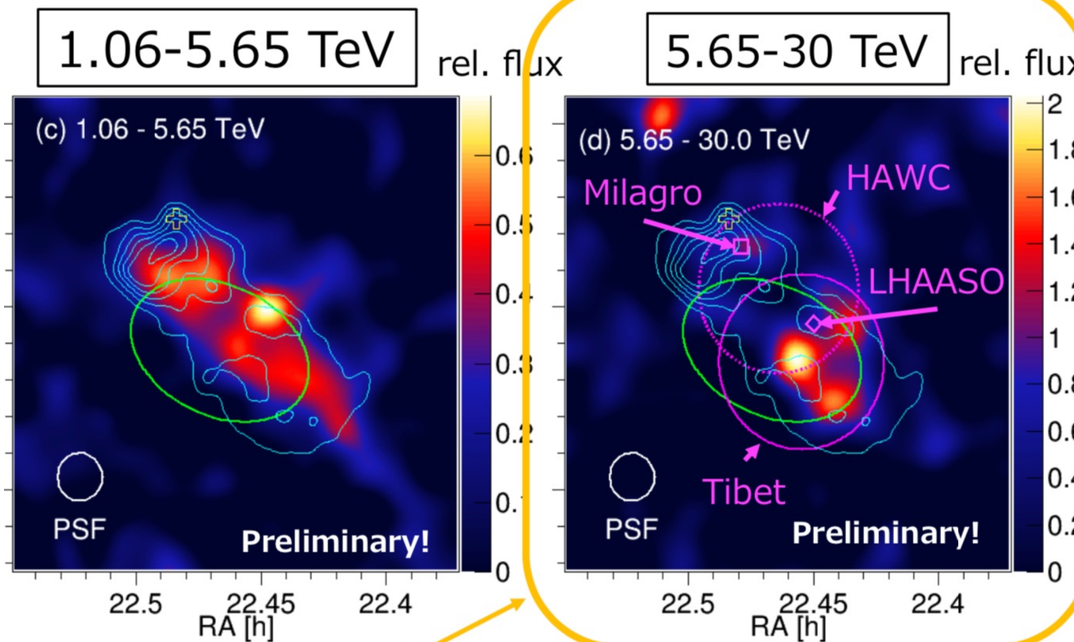
e.g.
M. Breuhaus, B. Reville, J. A. Hinton A&A 2022

The Boomerang (G106.3+2.7)

MAGIC Coll - T. Oka et al. ICRC 2021

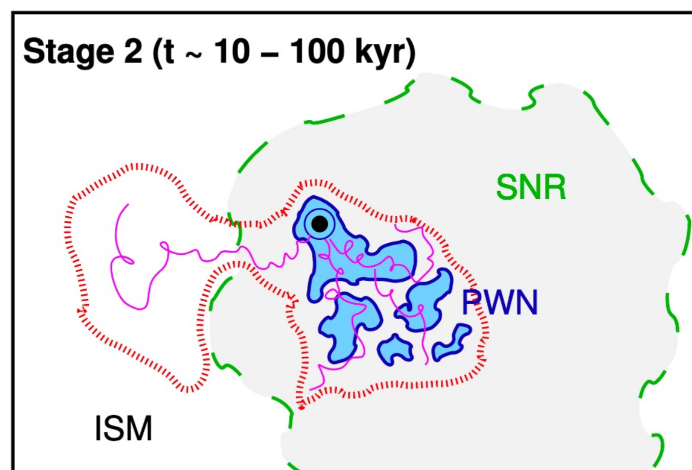






Milagro [Abdo+2009], HAWC [Albert+2020]
Tibet [Amenomori+2021], LHAASO [Cao+2021]

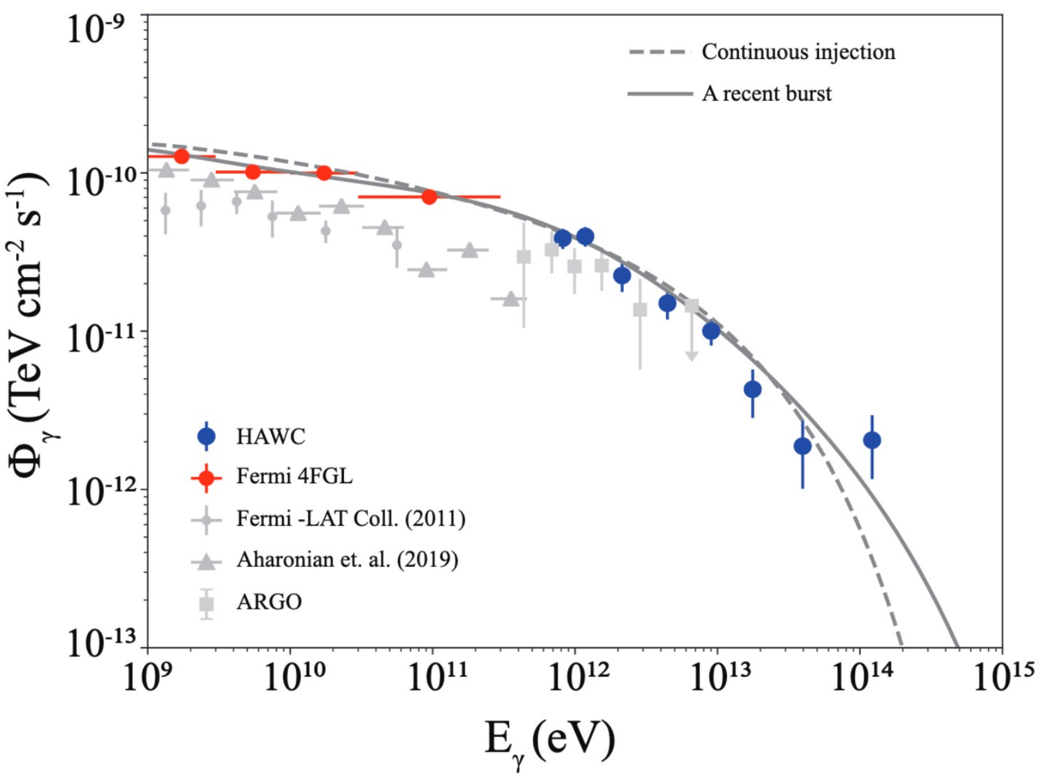
Giacinti et al
A&A 2020

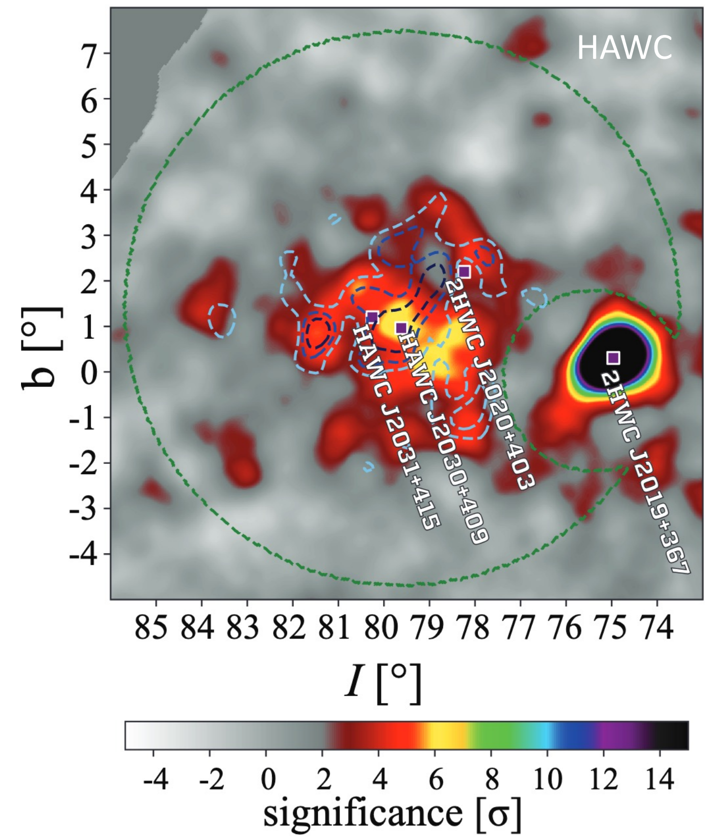


Cygnus Cocoon

HAWC Coll. Nature Astronomy, 2021

See also LHAASO



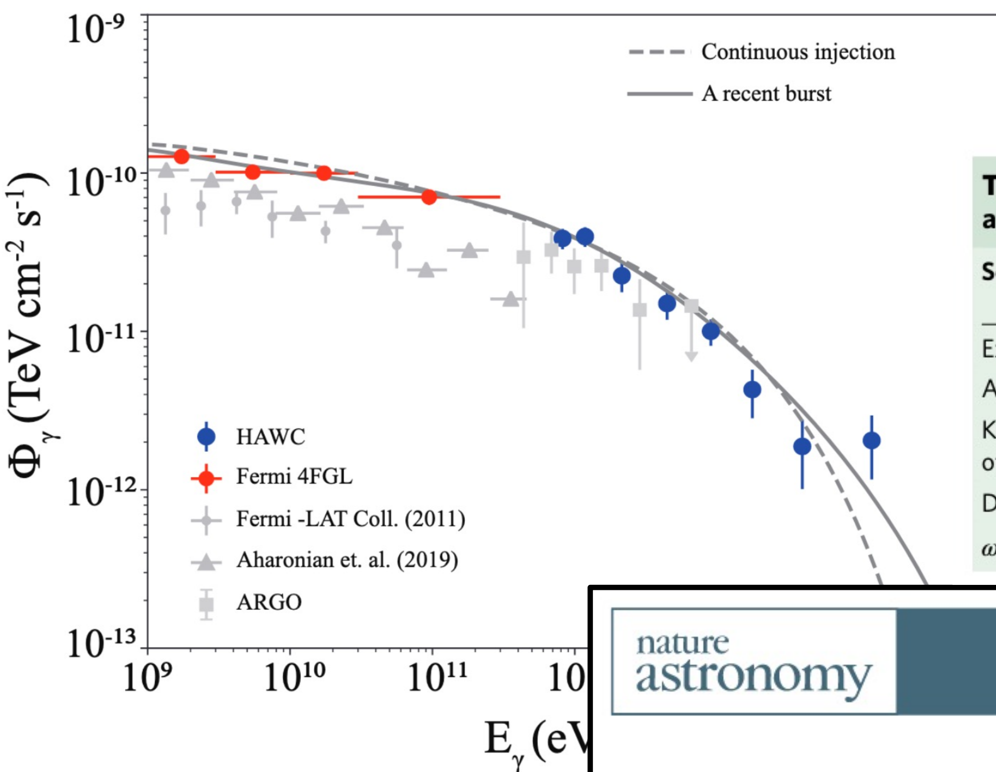


- Large-scale diffuse emission GeV-(almost)PeV around star-forming region Cyg OB2 in Cygnus

Cygnus Cocoon

HAWC Coll. Nature Astronomy, 2021

See also LHAASO



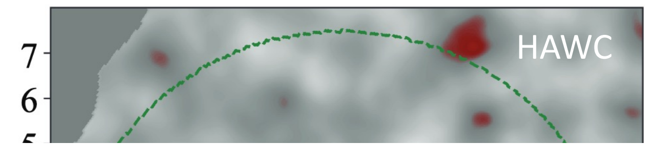


Table 1 | Physical parameters of three extended γ-ray structures and their related stellar clusters

Source	Cygnus Cocoon	CMZ	Wd 1 Cocoon
Extension (pc)	50	175	60
Age of cluster (Myr)[39]	3-6	2-7	4-6
Kinetic luminosity, L_{kin}, of cluster (erg s^{-1})	2×10^{38} (ref. [17])	1×10^{39} (ref. [40])	1×10^{39} (ref. [41])
Distance (kpc)	1.4	8.5	4
ω_0 (>10 TeV) (eV cm^{-3})	0.05	0.07	1.2

nature astronomy
ARTICLES
https://doi.org/10.1038/s41550-019-0724-0

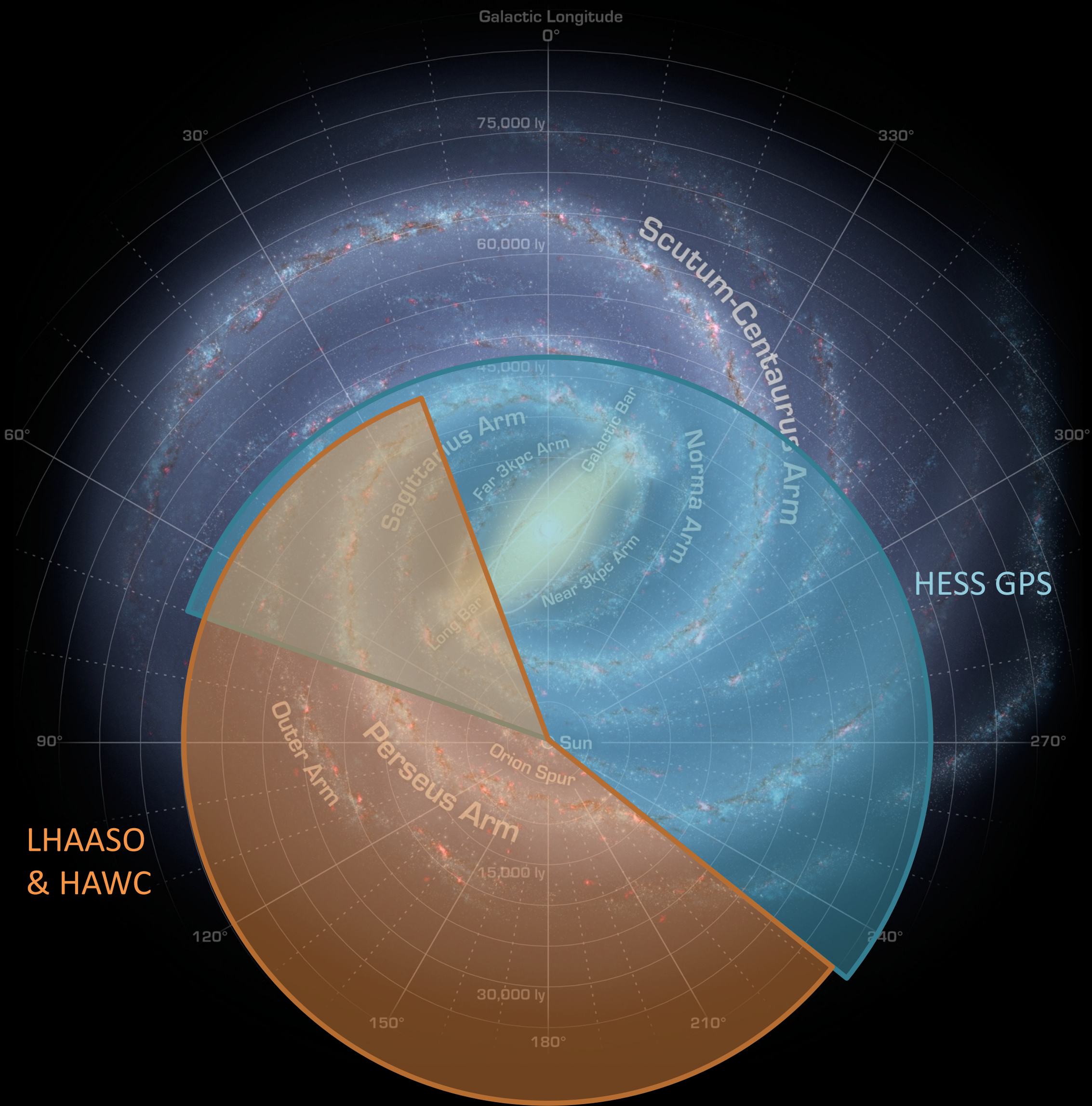
Massive stars as major factories of Galactic cosmic rays

Felix Aharonian[1,2,3,7], Ruizhi Yang[2,7*] and Emma de Oña Wilhelmi[4,5,6,7]

NATURE ASTRONOMY | VOL 3 | JUNE 2019 | 561-567 | www.nature.com/natureastronomy

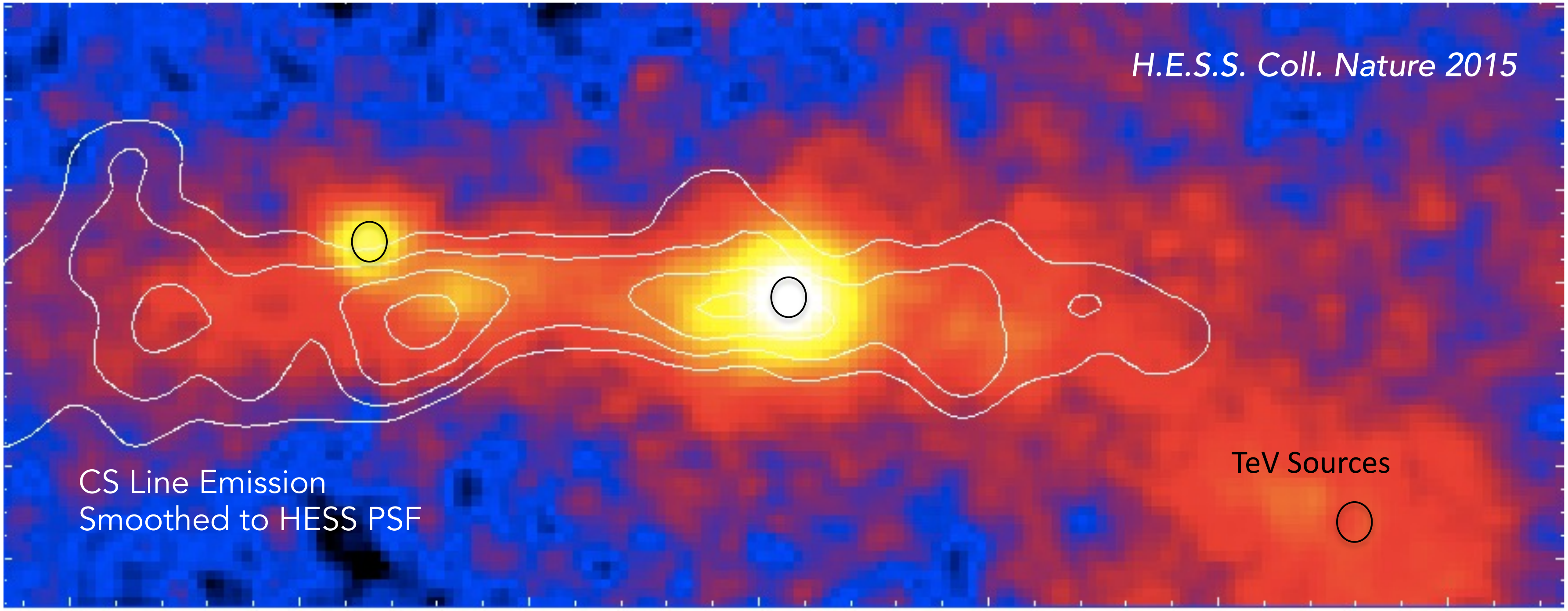
- Large-scale diffuse
forming region in C

A Tale of Two Hemispheres



NASA/JPL-Caltech/R. Hurt

The Central Molecular Zone



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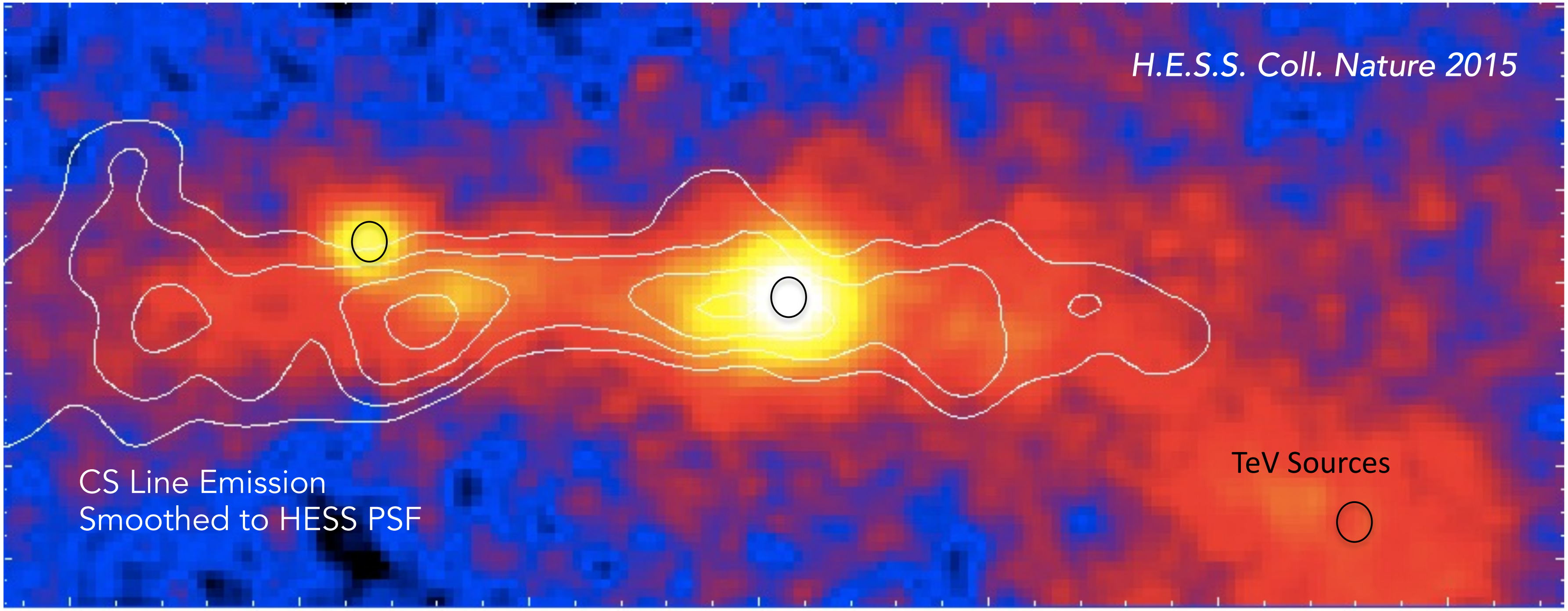
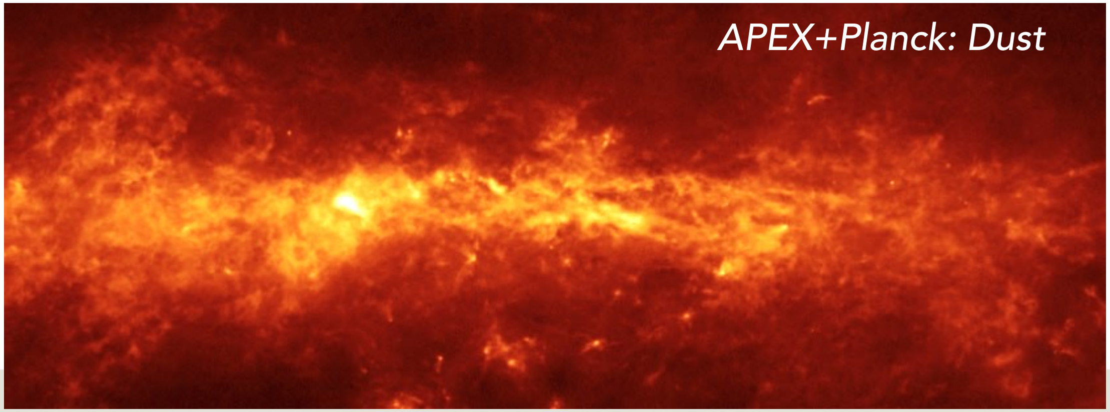
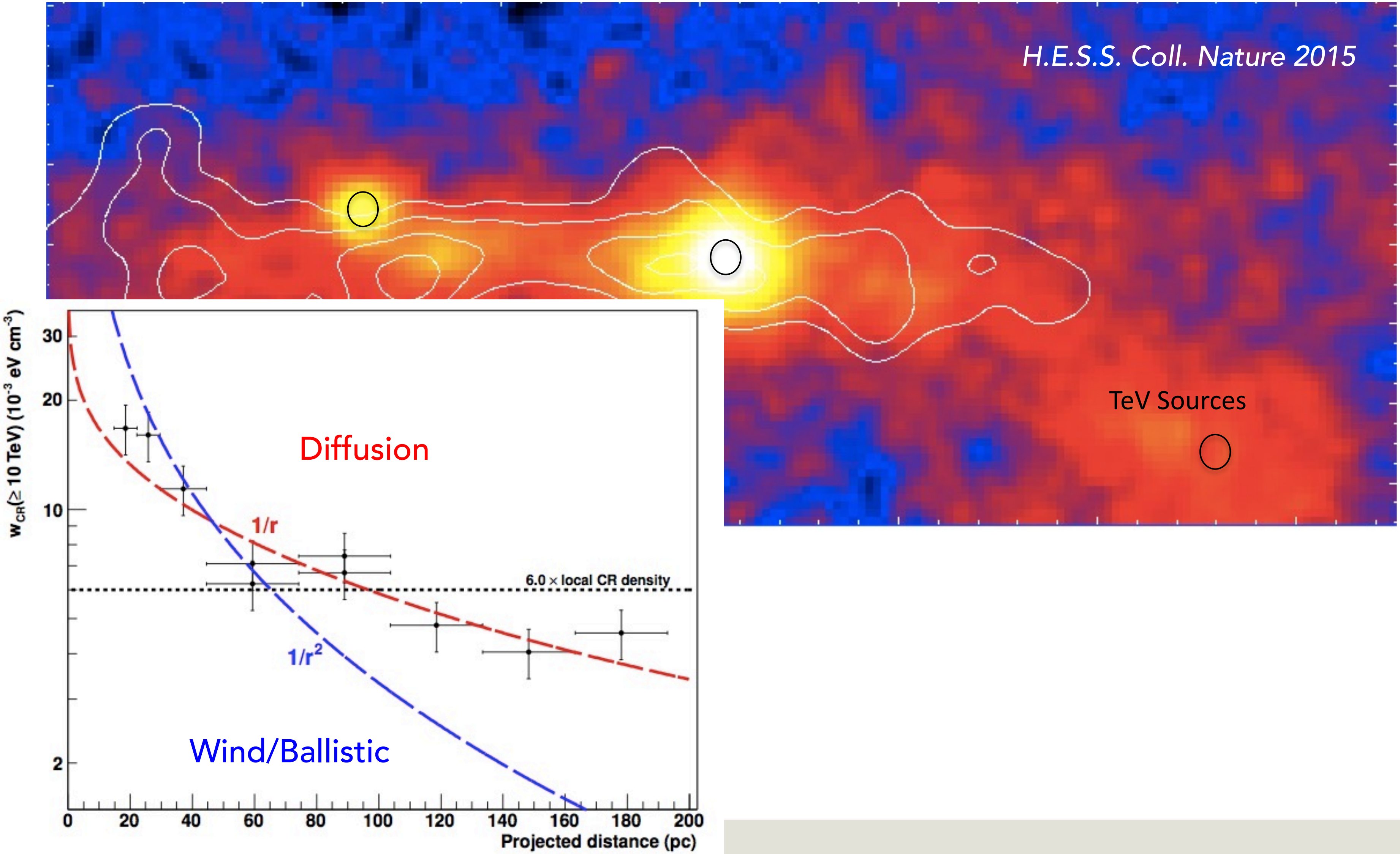


- Diffuse emission correlated with molecular gas + a few individual objects



The Central Molecular Zone

- Ratio of gamma-ray emission to target material → cosmic ray density



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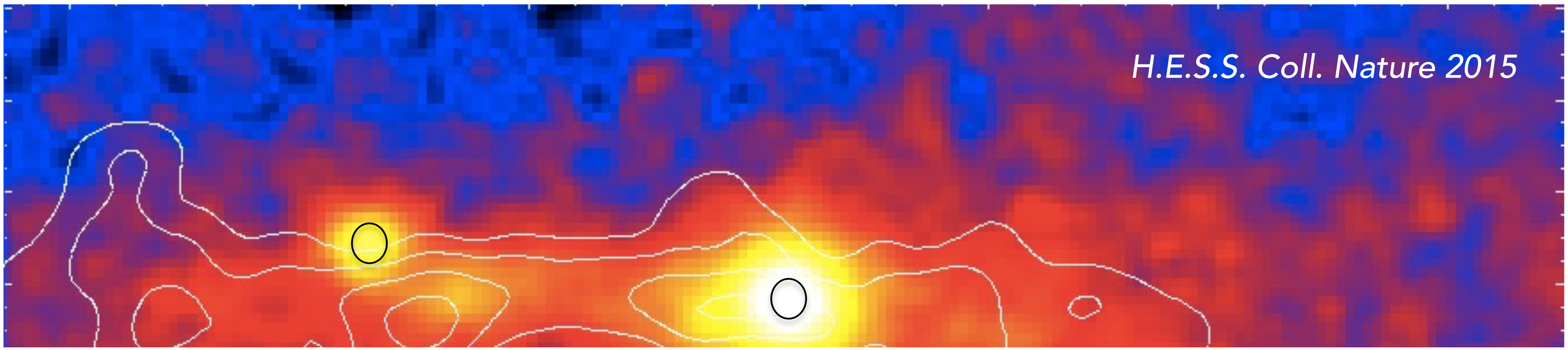

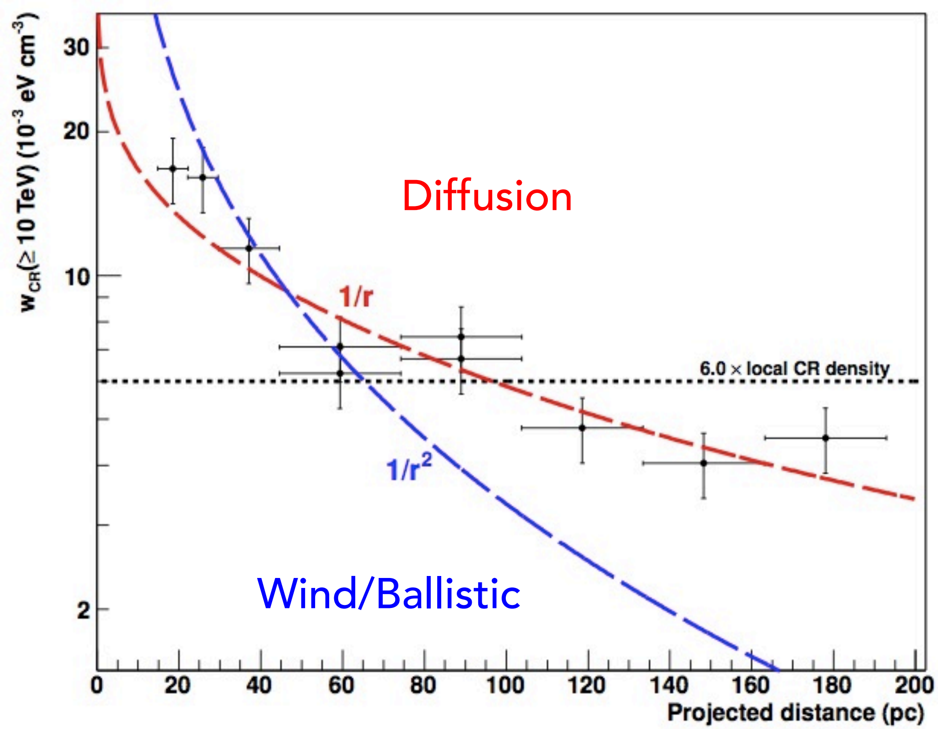

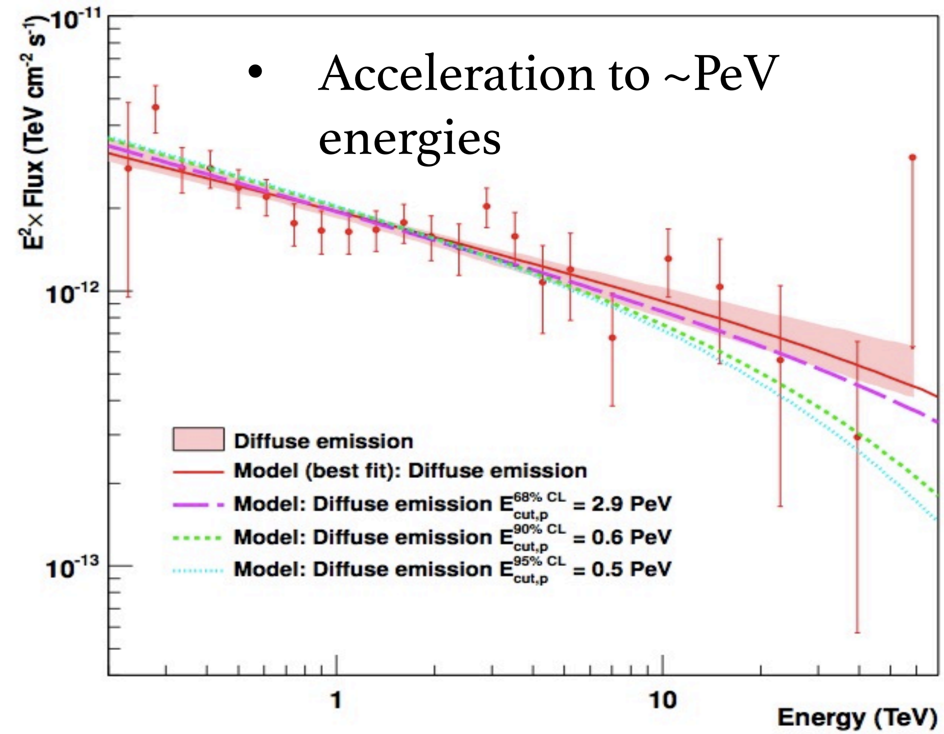

Westerlund 1

HESS Coll ICRC 2021

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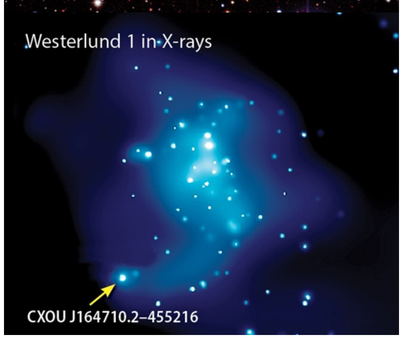
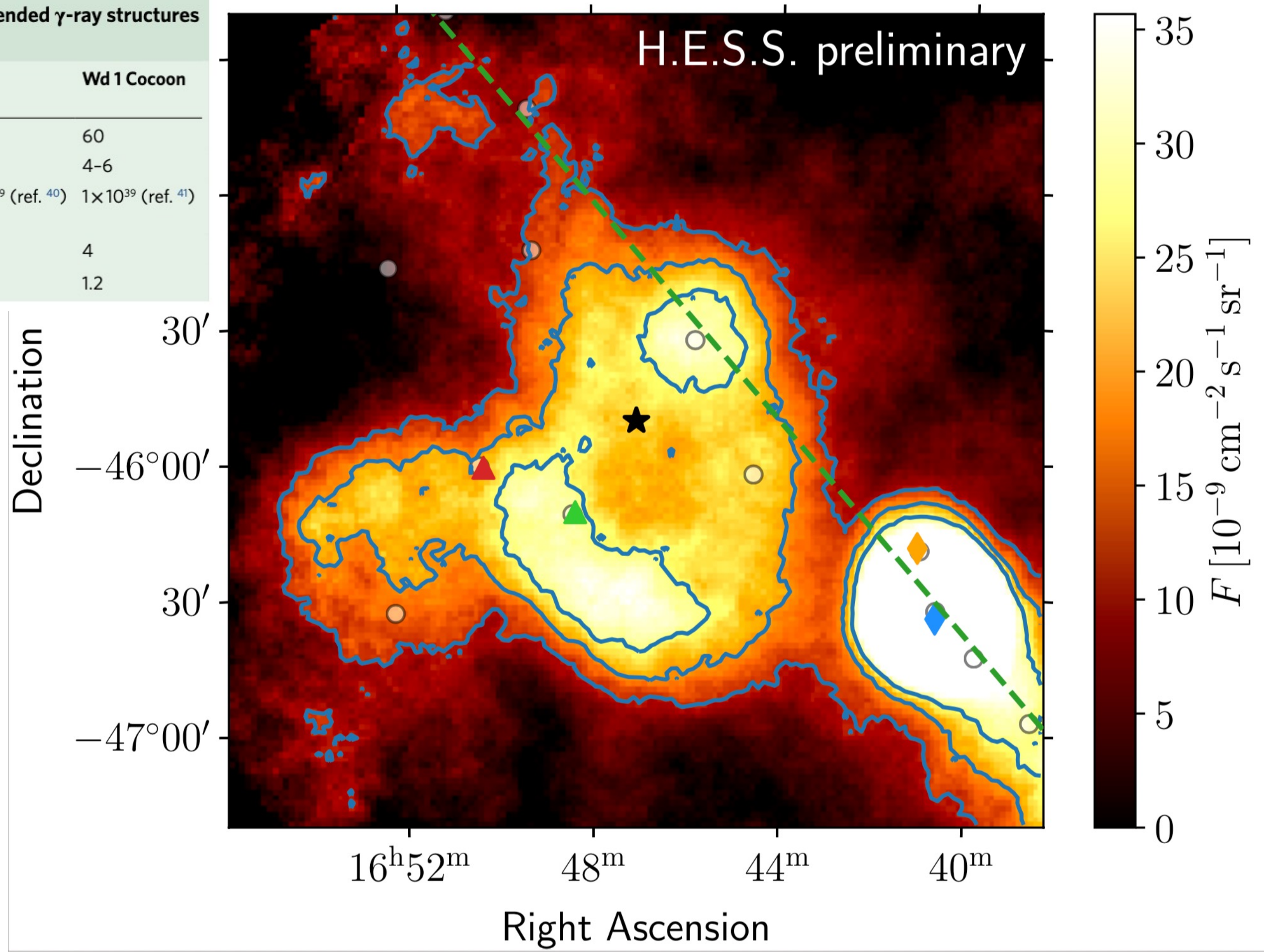
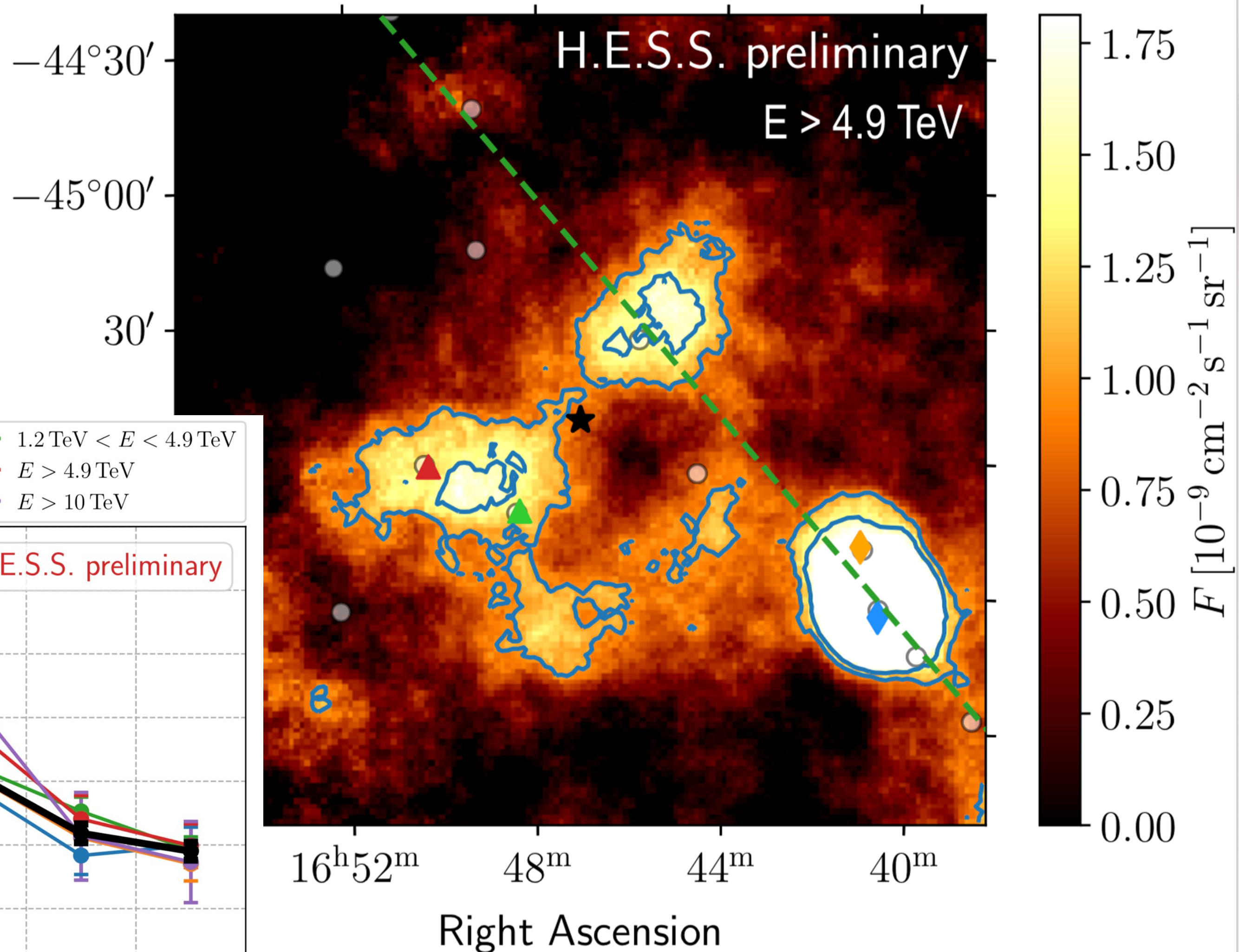


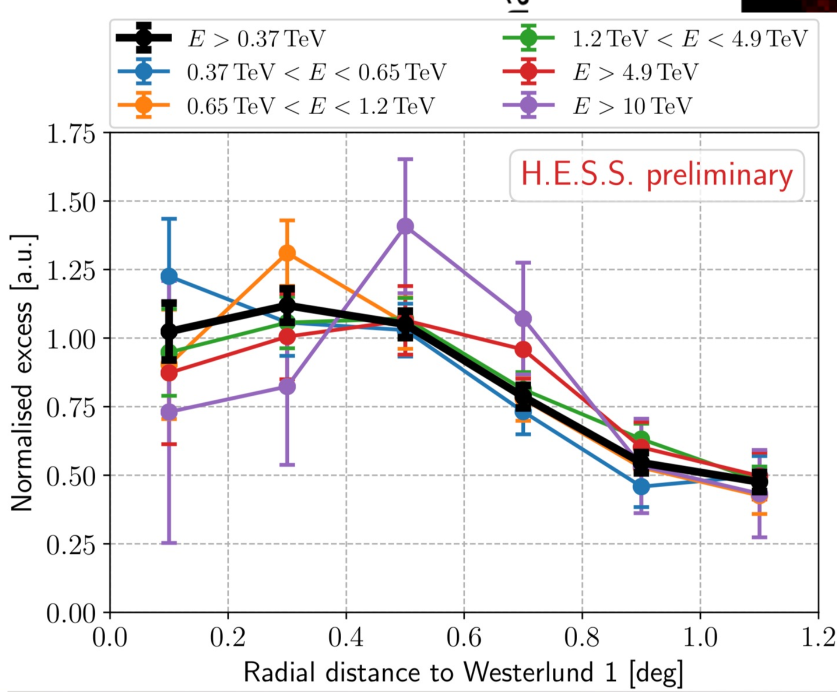


Westerlund 1

HESS Coll ICRC 2021

No clear E-dep. morphology

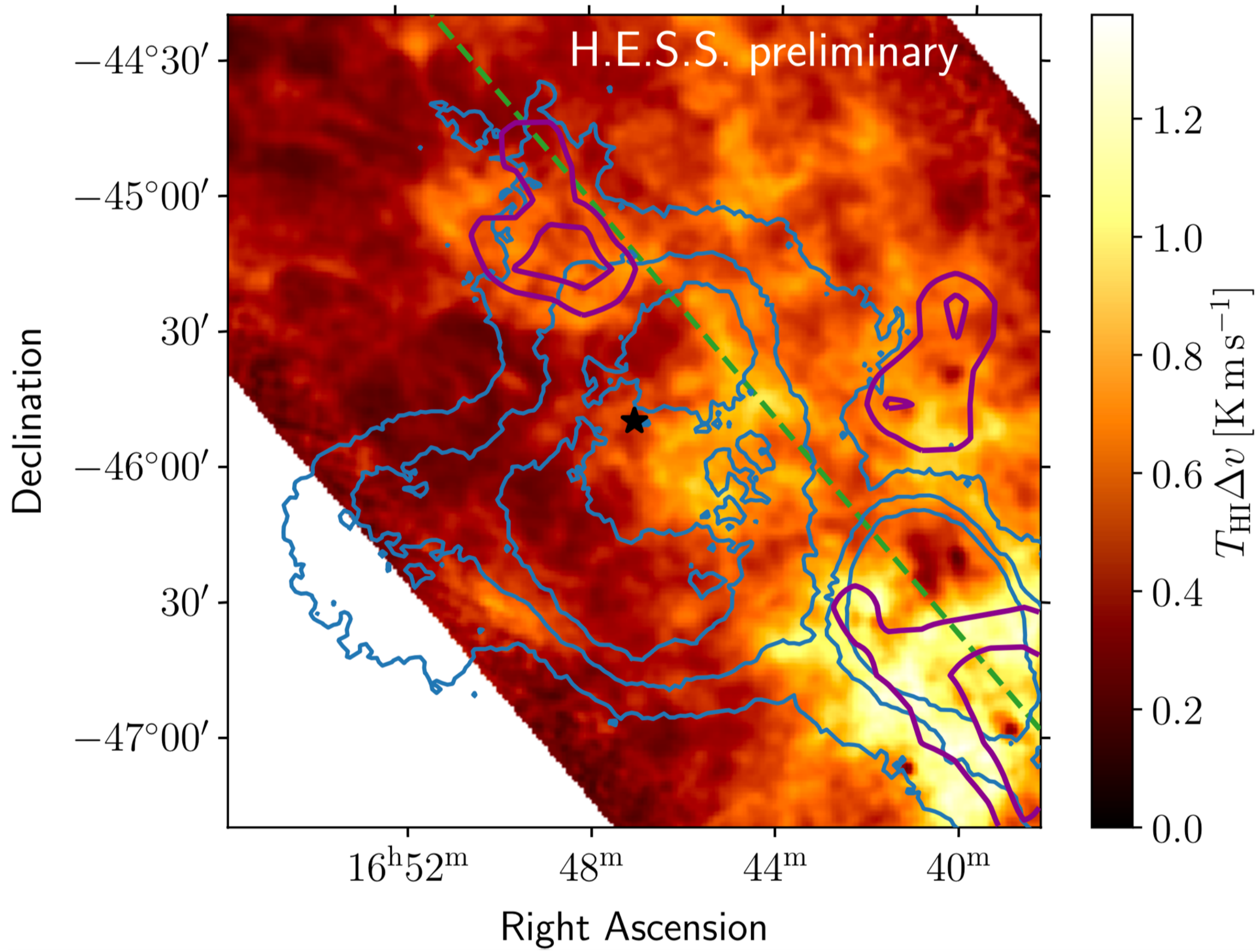




Westerlund 1

HESS Coll ICRC 2021

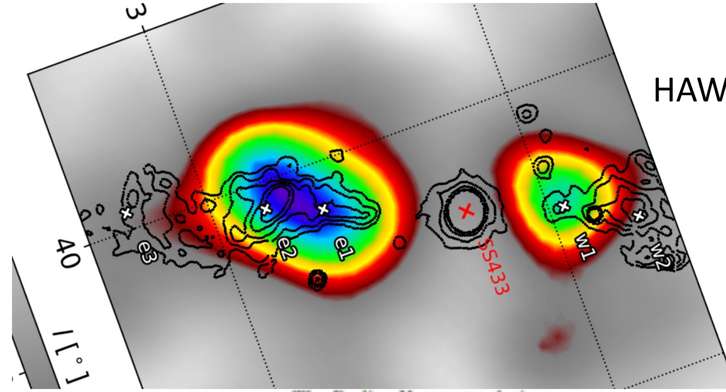
- No correlation with target material
  - Low density target – inside bubble – or
  - IC emission

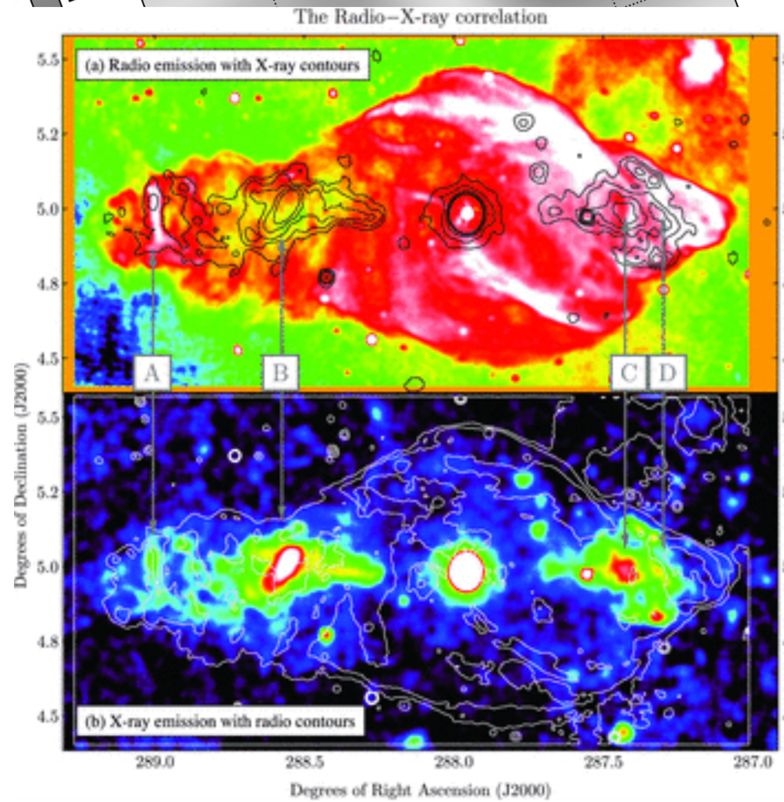


SS 433

Watch this space!

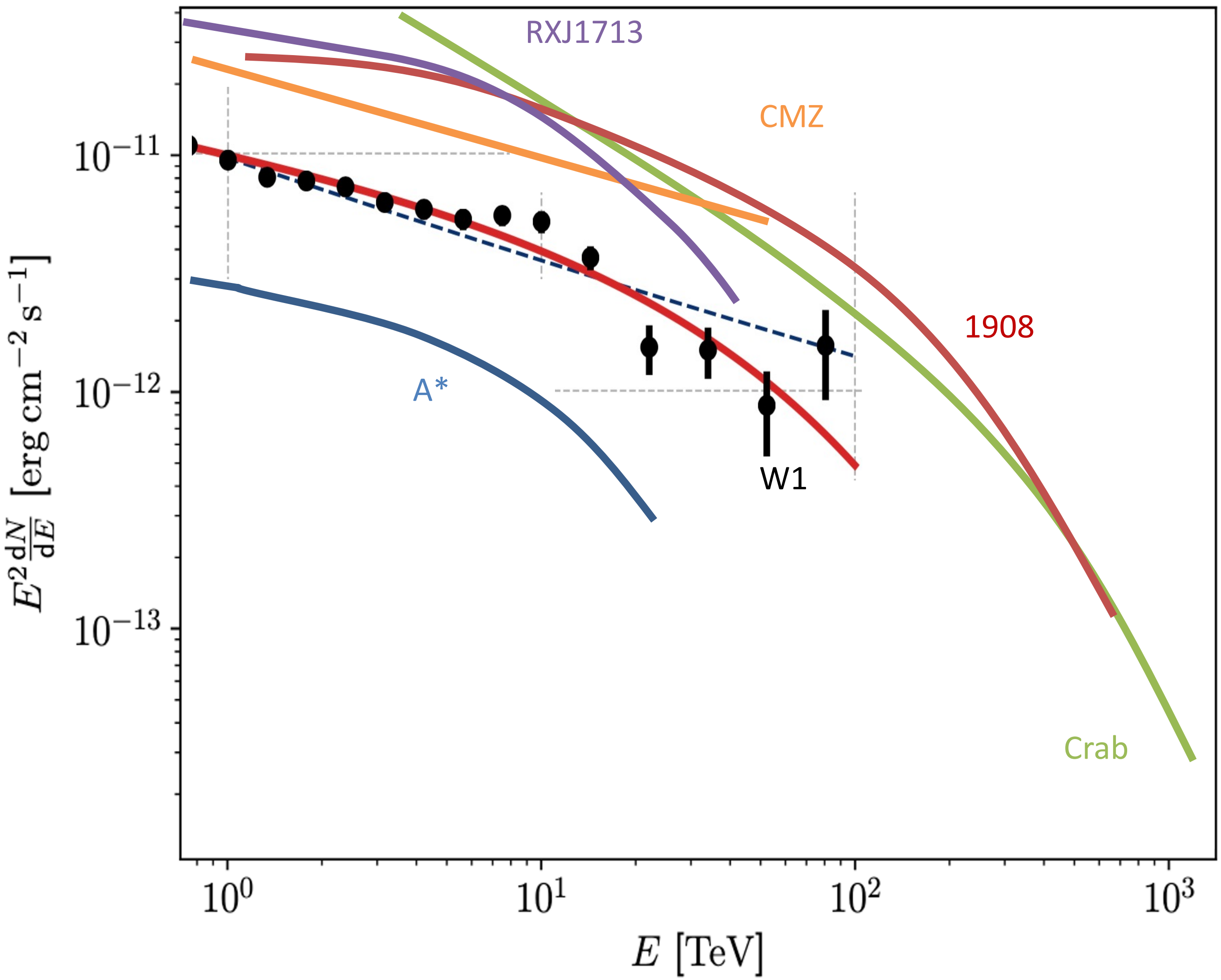
- 20 TeV gamma-ray emission with hard spectrum
  - From zones where jets are thought to decelerate
- A very high energy accelerator
- IC origin seems likely
  - cf X-ray synchrotron
  - density likely low in these regions
- BUT
  - Very plausible (unavoidable?) that **protons** are co-accelerated to <u>at least</u> the same energies!
  - Plenty of power and v=0.3 c shock !





Goodall et al MNRAS 2011

VHE→UHE Spectra



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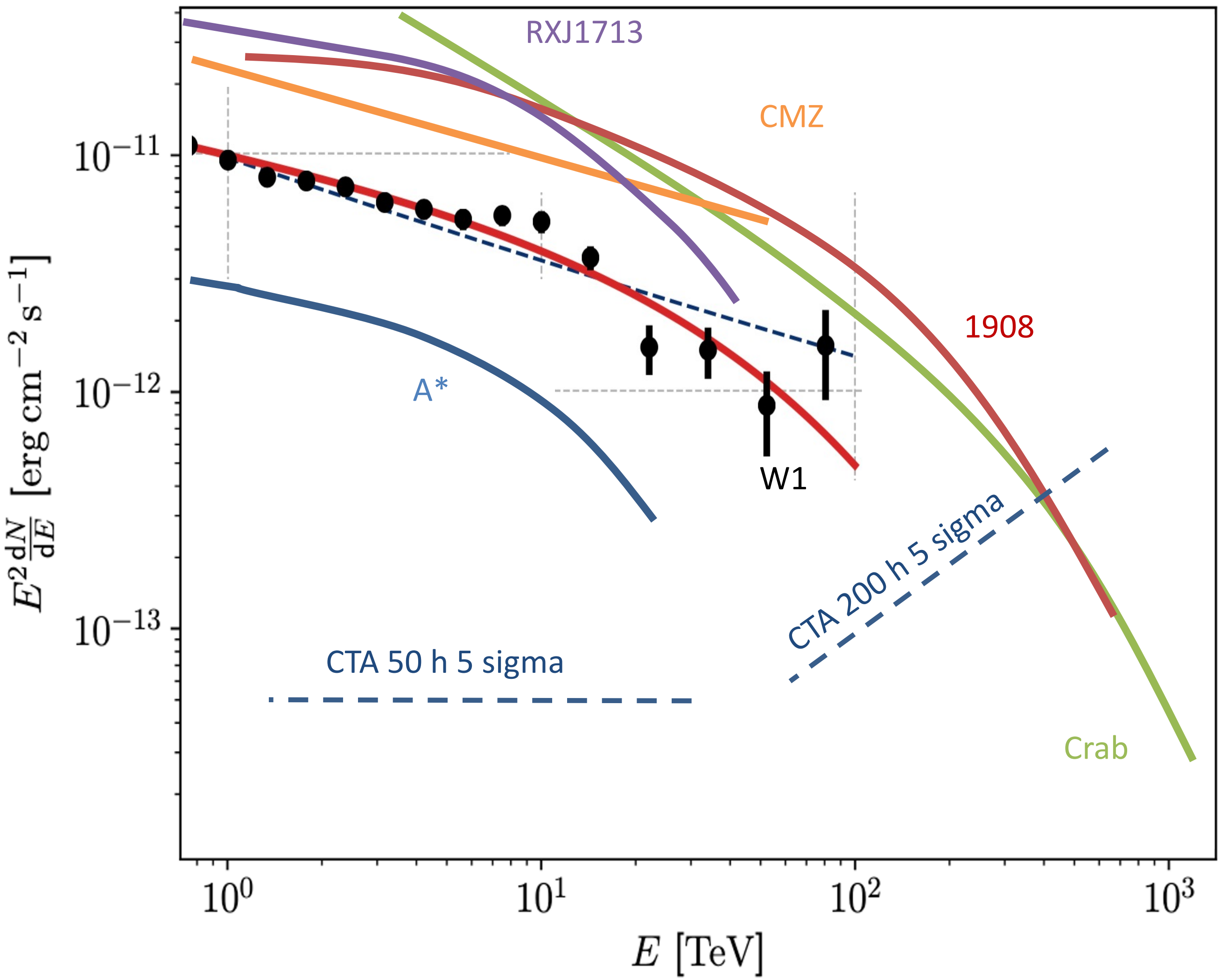
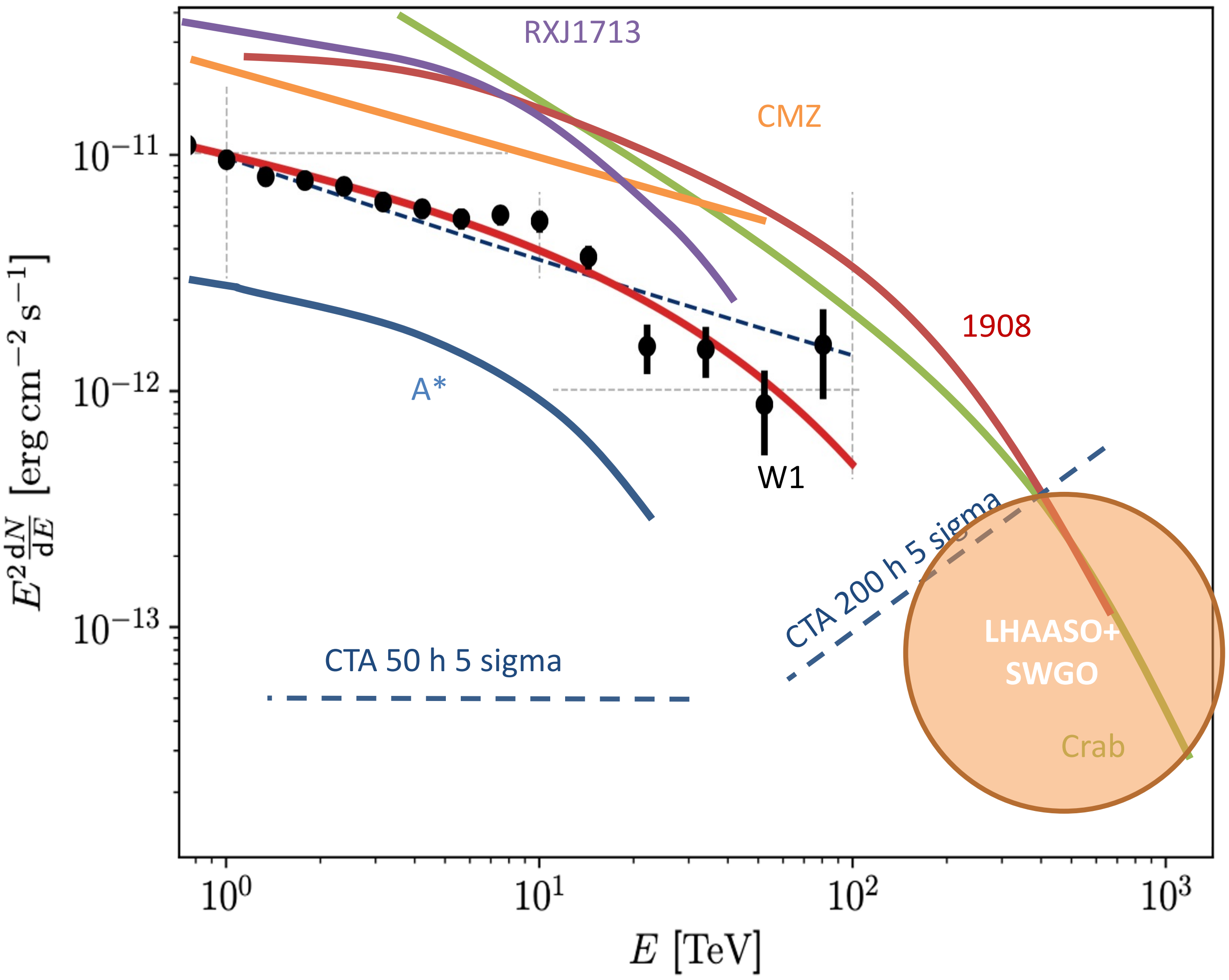


VHE→UHE Spectra



Conclusions

- Gamma-ray VHE-UHE measurements are a powerful tool for understanding particle acceleration up to and beyond PeV
  - Huge step forward in sensitivity at UHE with LHAASO
- Need for southern hemisphere measurements up to PeV!
  - CTA South – in particular the SSTs
  - SWGO
  - (HESS is not dead yet!)
- Need for wide-band coverage and excellent resolution as well as UHE sensitivity