L International Meeting on Fundamental Physics and XV CPAN Days
2 — 6 October 2023
Palacio de la Magdalena · Santander (Spain)

γ ray experiments

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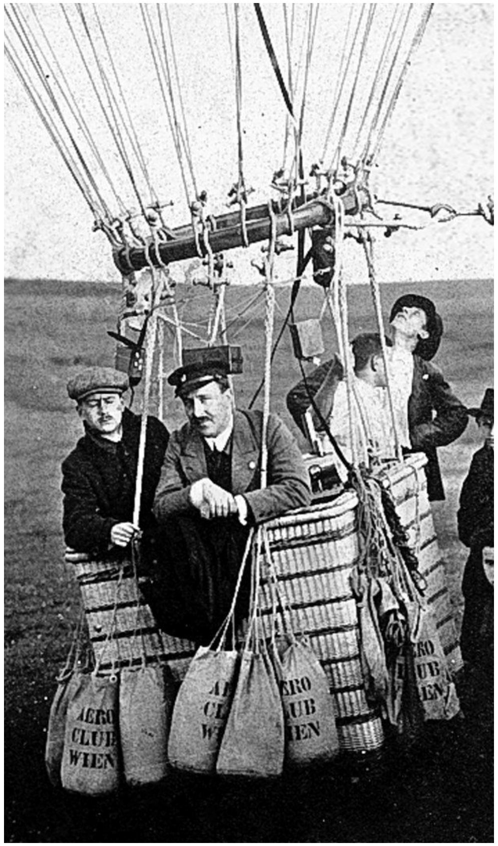
Instituto de Astrofísica de Canarias

Santander. October 2 – 6, 2023

INSTITUTO DE ASTROFISICA DE CANARIAS · IAC ·

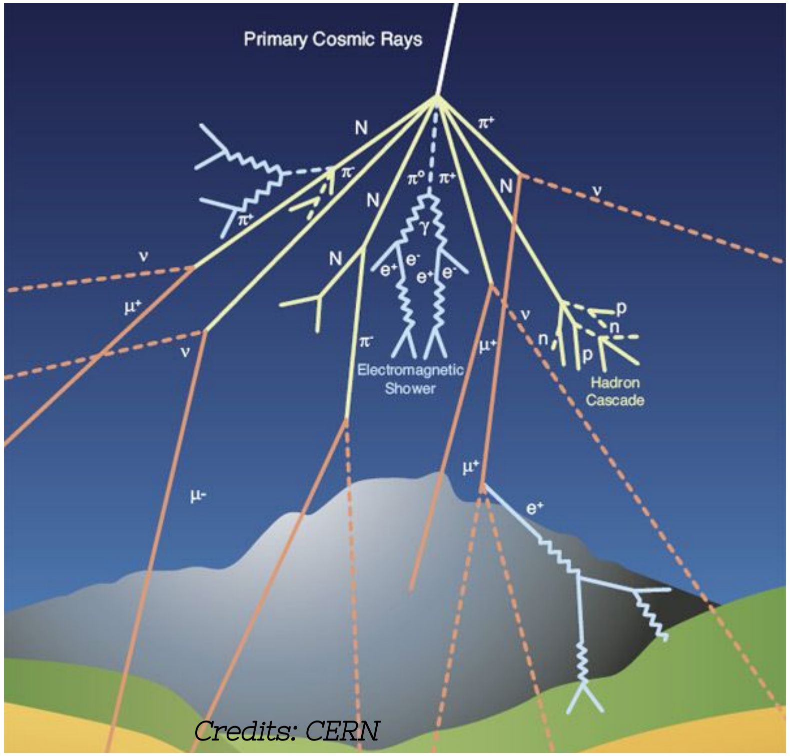
Cosmic rays: origins



Victor Hess (1912): probed Ionizing radiation increasing with altitude with a balloon → space origin. Nobel Prize for Physics in 1936

also: **D. Pacini**, **T. Wulf**.

high-energy particles (*of natural origin*) coming from outer-space which produce particle showers in the atmosphere.



<u>98% hadronic</u>

- 87 % protons
- 12 % helium
- 1% other nuclei

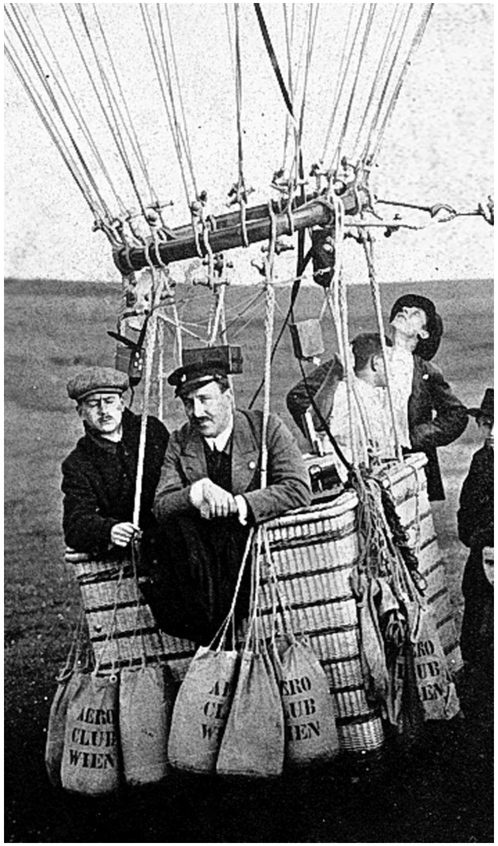
<u>2% electrons</u>

<u>< 1% other species</u>

- antiparticles
- neutrinos
- γ rays

Secondaries: $e^{\pm}$, $\mu^{\pm}$, $K^{\pm}$ ...

Cosmic rays: origins



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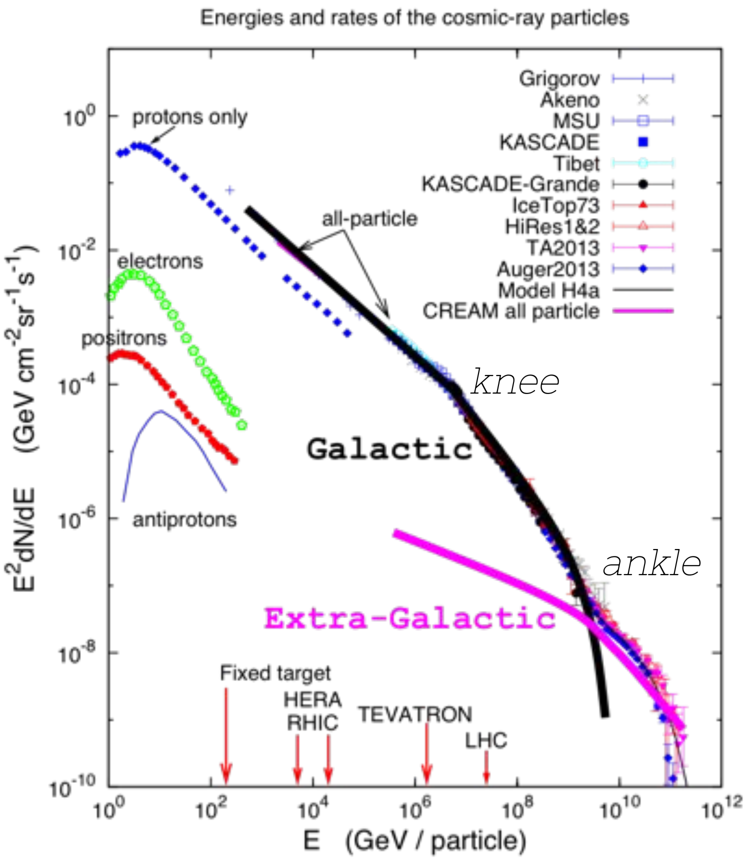


The origin of galactic cosmic rays
Astron.Astrophys.Rev, 21, 70 (2013)

98% hadronic

- 87 % protons
- 12 % helium
- 1% other nuclei

2% electrons

< 1% other species

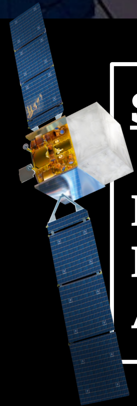
- antiparticles
- neutrinos
- γ rays

CR rates:

knee: ~ 1 / m^2 / yr

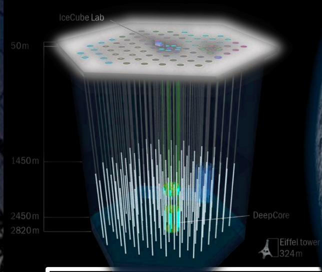
ankle: ~ 1 / km^2 / yr

Cosmic rays & Multi-messenger: current experiments



Satellites

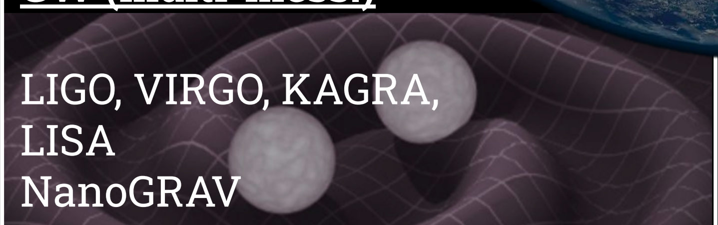
Fermi-LAT
DAMPE
Agile



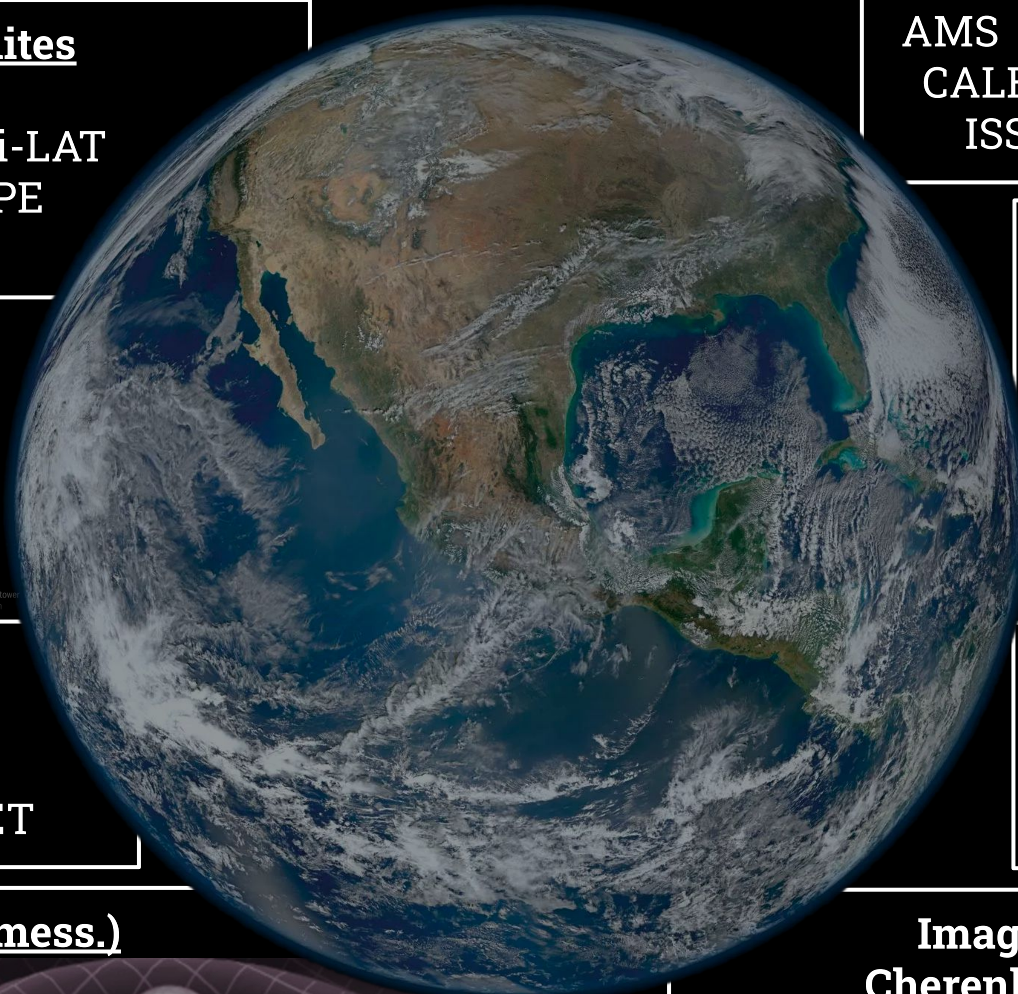
Neutrinos

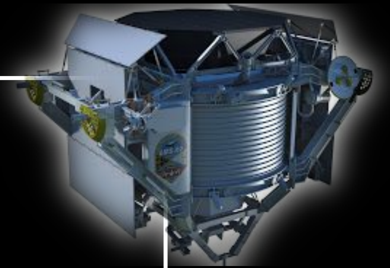
IceCube
KM3NET

GW (multi-mess.)



LIGO, VIRGO, KAGRA,
LISA
NanoGRAV





ISS

AMS
CALET
ISS CREAM

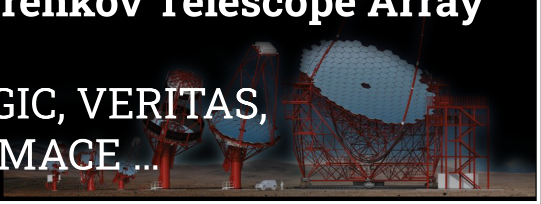
UHECR / Air shower & hybrid arrays

Telescope Array
Auger
ALPACA
LHAASO

Water Cherenkov

HAWC
SWGO

Imaging Atmospheric Cherenkov Telescope Array



H.E.S.S., MAGIC, VERITAS,
CTA, ASTRI, MACE ...

(Ground-based) γ-ray telescopes

Whipple Telescope → 1968

1968–1976 → upper limits

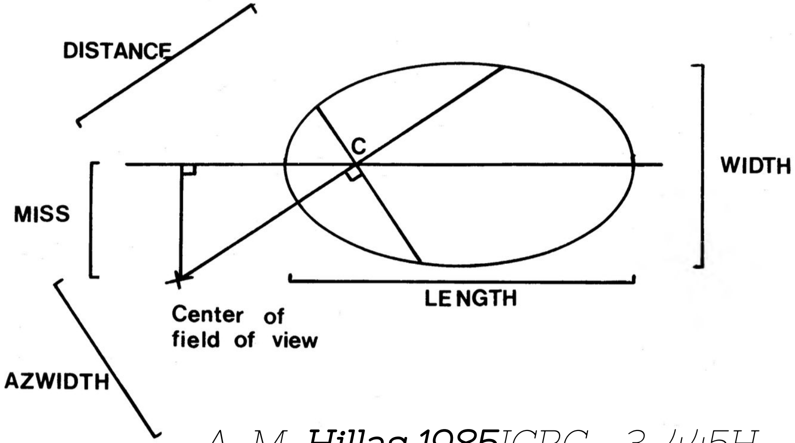
1976–1982 → 'Dark ages'

1st multi-PMT camera → 1982 (Whipple)

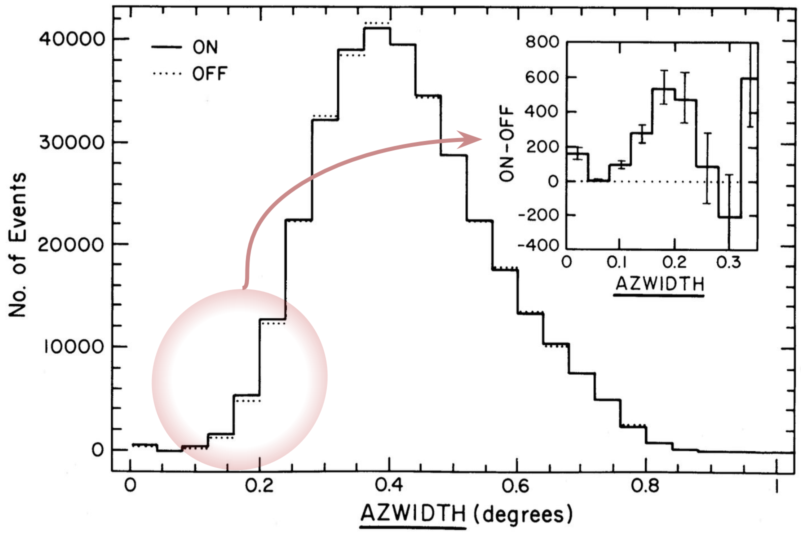
1st source → Crab Nebula (Whipple). Announced (1985 ICRC), published: *Weekes et al. ApJ 379 (1989)*

" Observation of TeV Gamma Rays from the Crab Nebula using the Atmospheric Cherenkov Imaging Technique "

1st (hybrid) array → HEGRA Cherenkov Telescopes CTs. 1995 – 2002

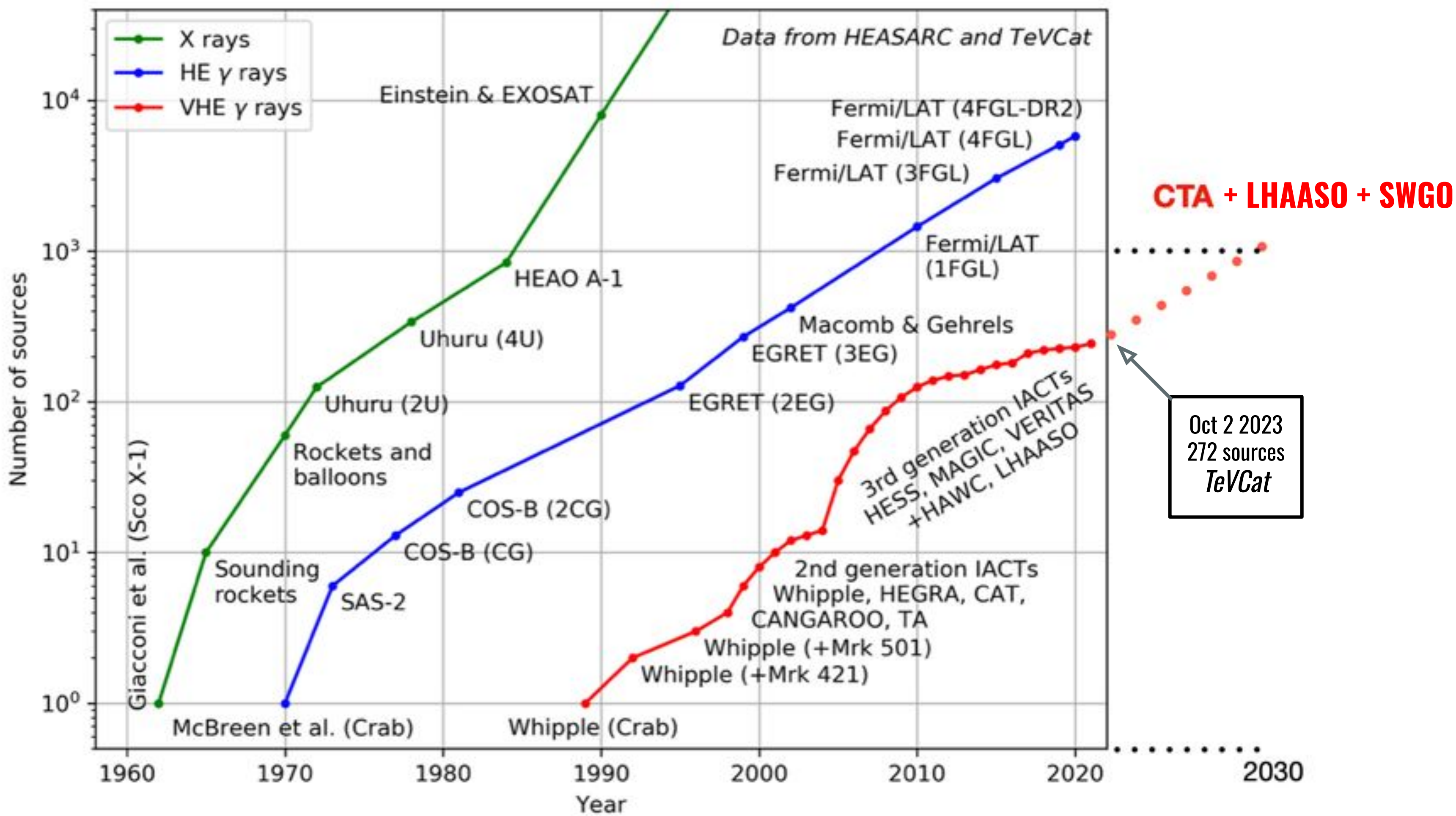


A. M. ***Hillas 1985****ICRC....3..445H*
(parametrization of shower images)



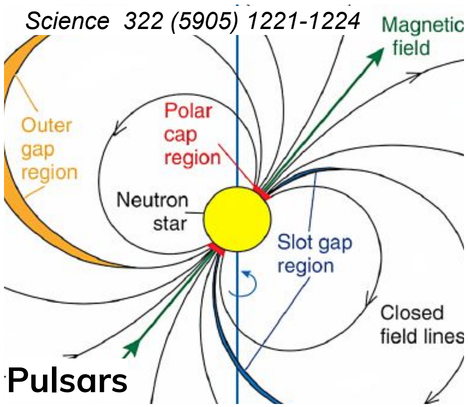
Many discoveries

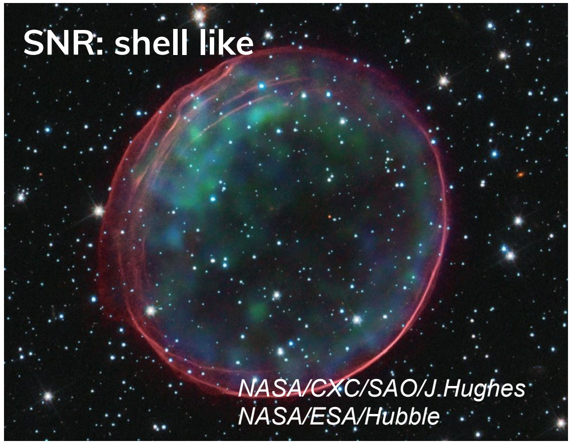
Number of detected astronomical sources vs time

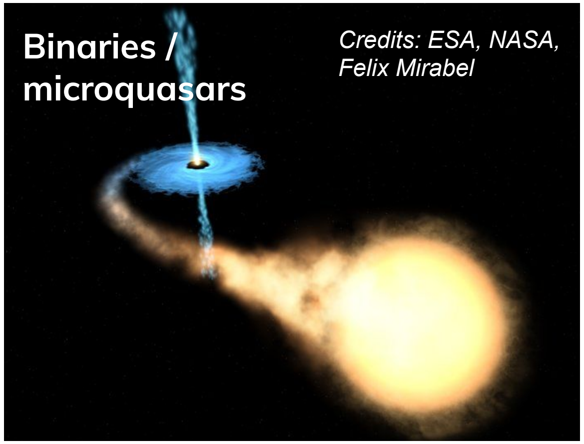


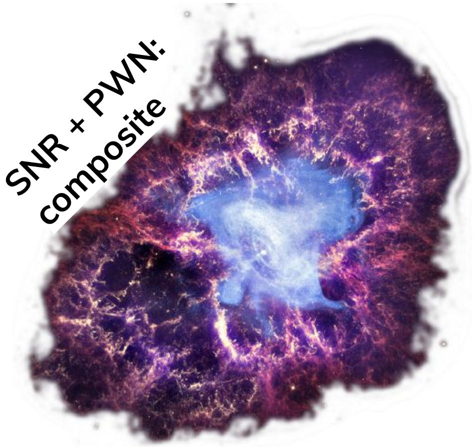
Many discoveries

Galactic γ ray sources



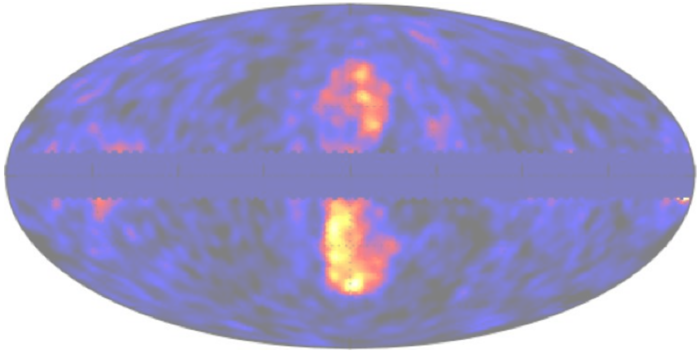






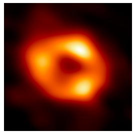
Credits: NASA, ESA, JPL-Caltech

Fermi bubbles: (Galactic lobes)



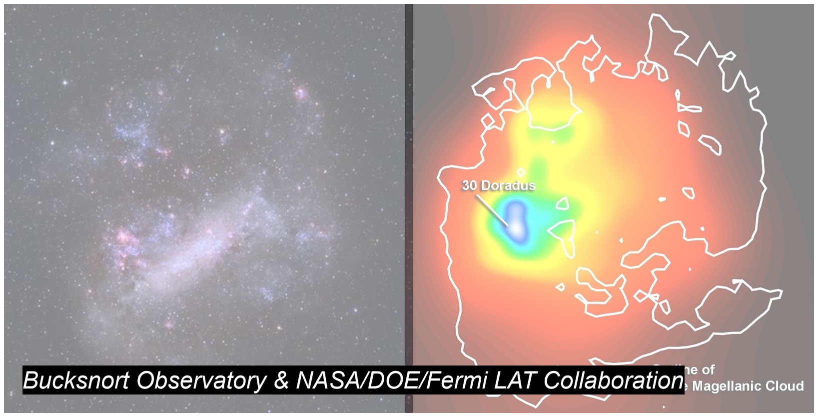
Credits: NASA, ESA, JPL-Caltech

+ Sgr A*



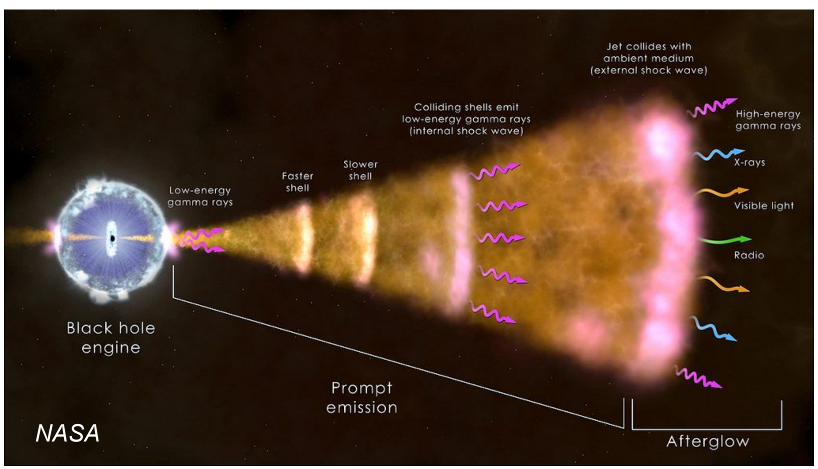
Many discoveries

Extragalactic γ ray sources



Bucksnort Observatory & NASA/DOE/Fermi LAT Collaboration

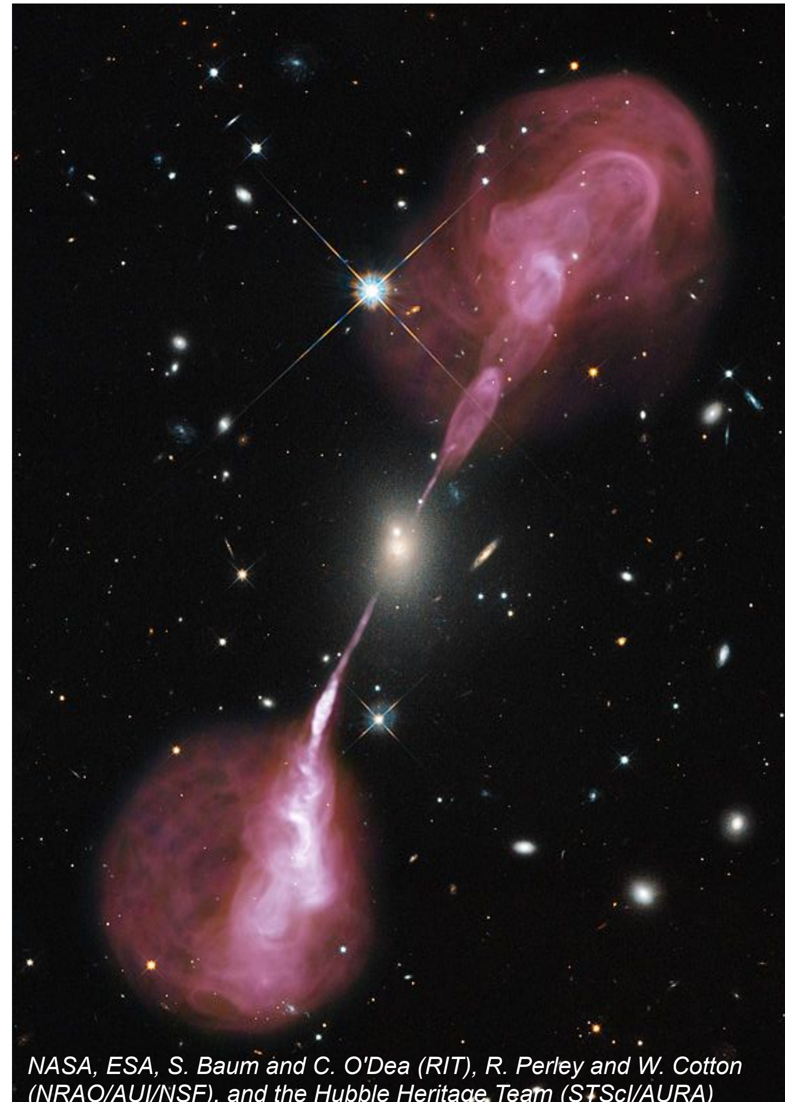
Local galaxies: LMC, SMC, M31 and M33.
Individual sources in LMC (30 Doradus region)



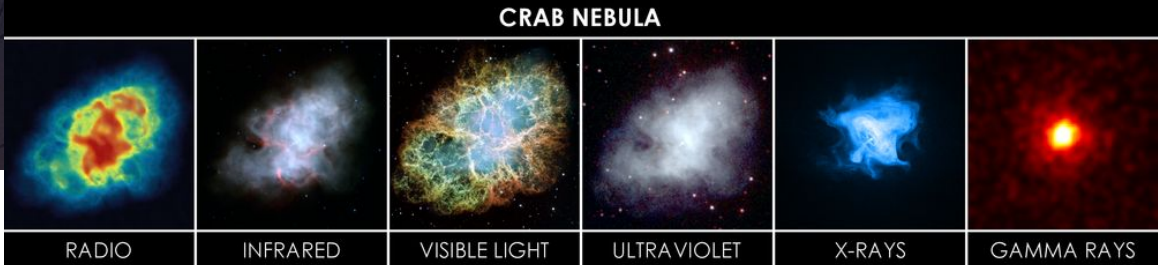
NASA

GRBs: Fireball model. Several detected in VHE

Active Galactic Nuclei

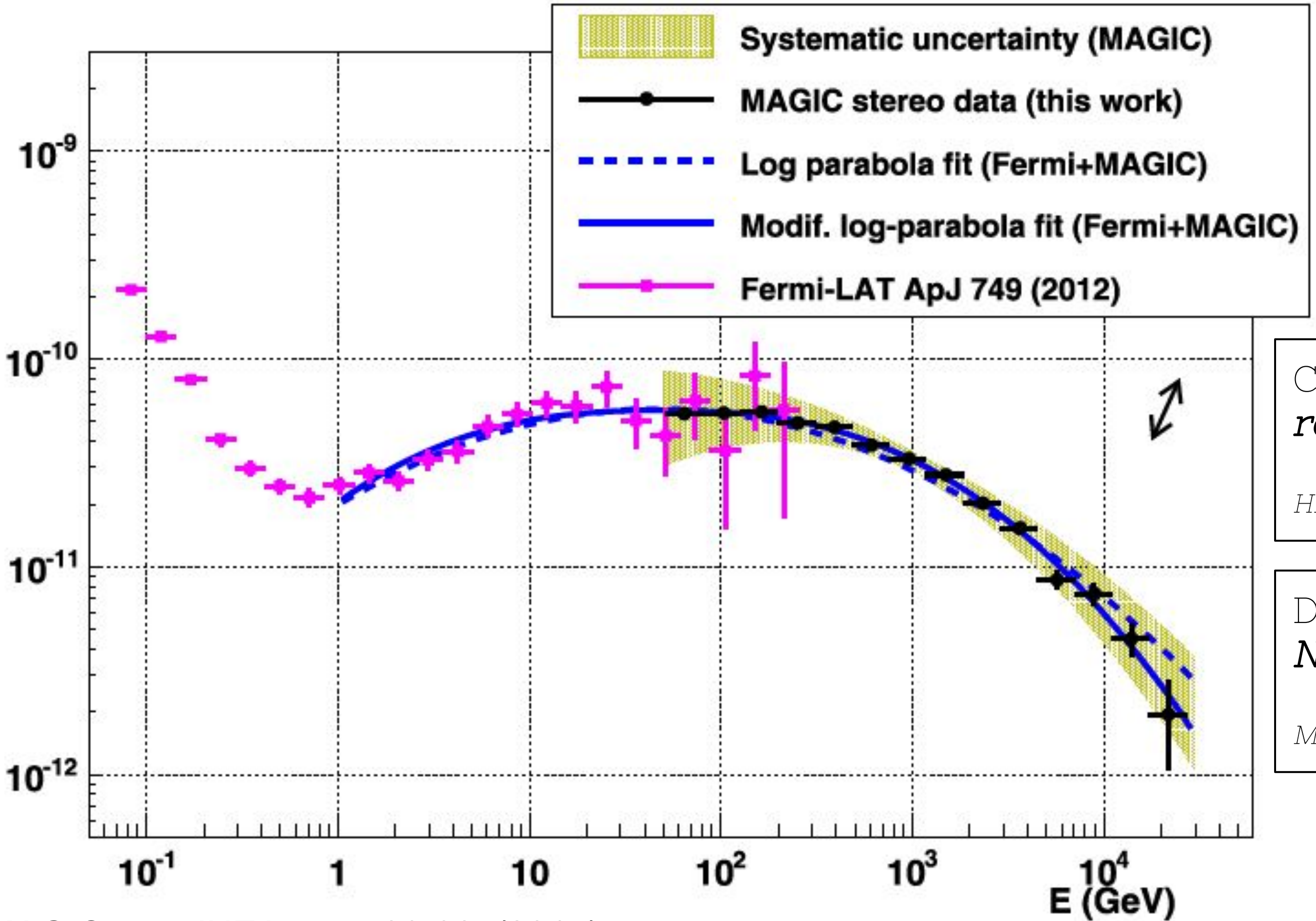

NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA)

Many discoveries



Crab Nebula

‘standard candle’ and benchmarking tool for VHE instruments



MAGIC coll. JHEA, 5, p. 30-38. (2015)

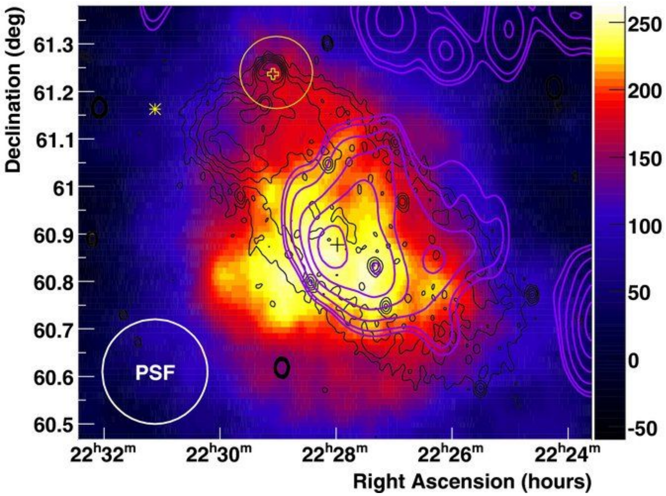
Crab Nebula ***spatially resolved*** in the TeV band

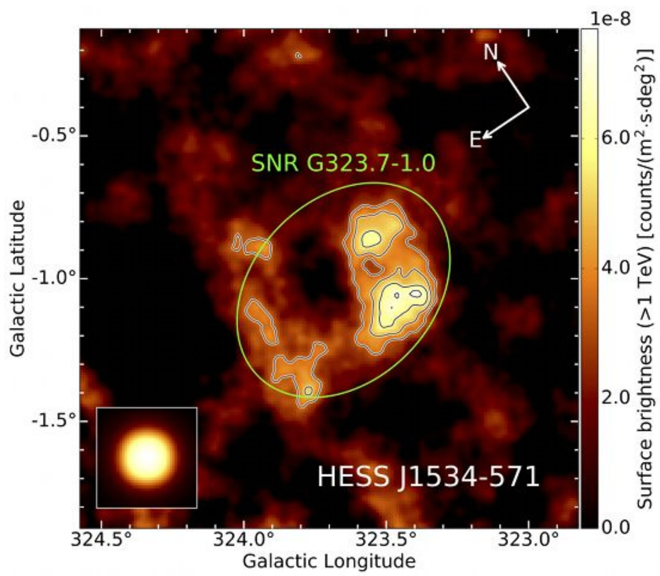
HESS coll. Nature 4, 167–173 (2020)

Detection of the ***Crab Nebula*** up to ***~ 100 TeV***

MAGIC coll. A&A, 635, A158 (2020)

Many discoveries





Particle accelerators

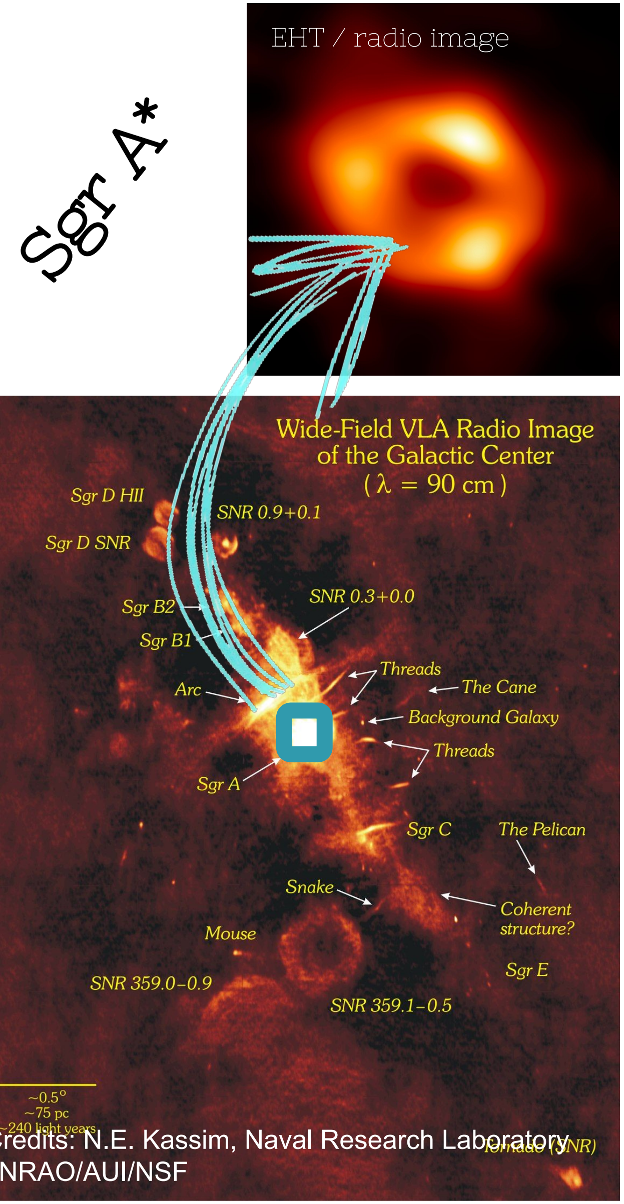
CRs up to the knee from Galactic origin, but ... which sources?

Candidates (emission beyond ~100 TeV):

- ❑ Supernova Remnants (SNR):
  - SNR G106.3+2.7 (*NatAst 5, 460–464*) ...

(*LHAASO* has now detected ***43 srcs at E>100 TeV*** !)

Many discoveries

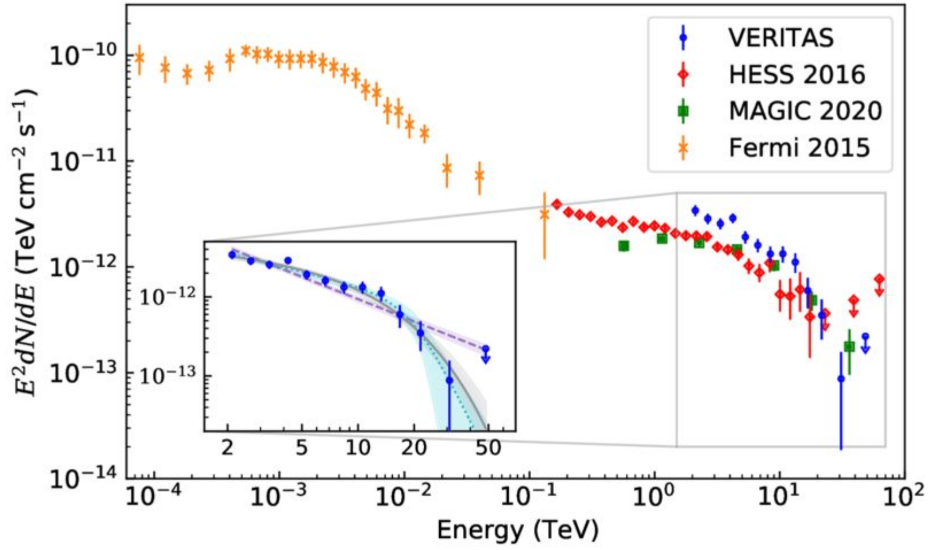


Particle accelerators

CRs up to the knee from Galactic origin, but ...
which sources?

Candidates (emission beyond ~100 TeV):

❑ Galactic center / Sgr A* (*JCAP 4, 37; Nature 531, 476–479*). Emission up to 50 TeV, from π^0 – decay



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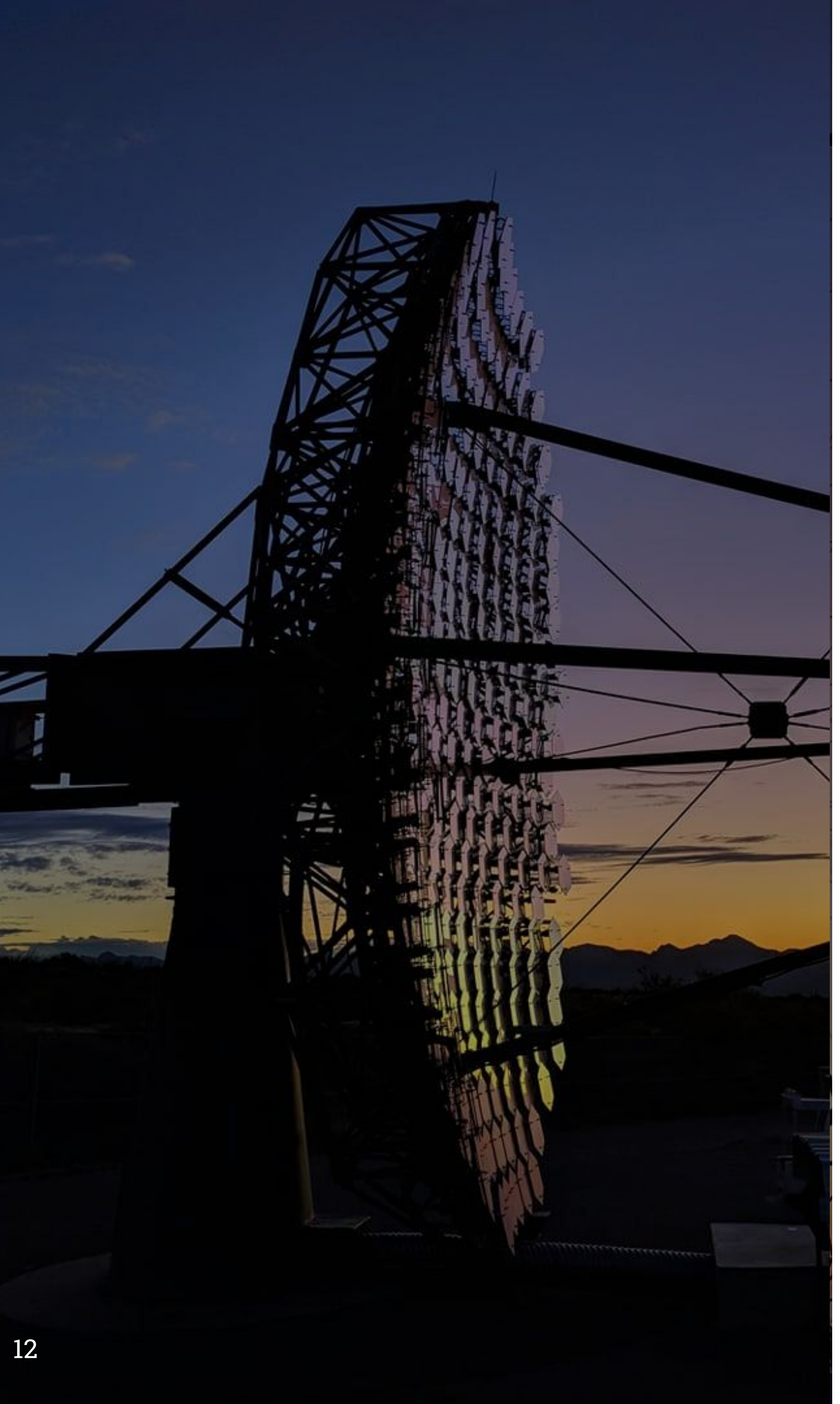


Current
γ ray instruments

High Energy (HE) gamma-rays, E > 100 MeV

Predecesor: **EGRET** (onboard ***CGRO***)

<u>Fermi-LAT</u> (~ 100 MeV – 100 GeV).

- **Large FOV**: 20% sky instantaneously
- **Survey mode**: full sky every 3 hours.
- **Self-triggers** (LAT, GBM)
- **Small collection areas** (< 1 m²)

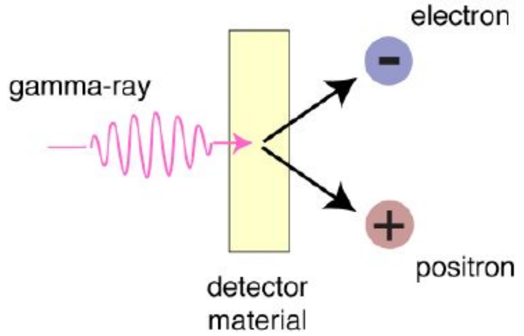
Components:

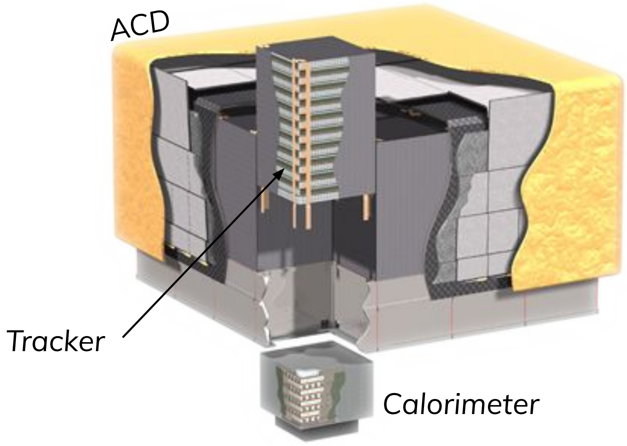
❏ **Tracker** (direction)
❏ **Calorimeter** (energy)
❏ **ACD** (charged particle veto)

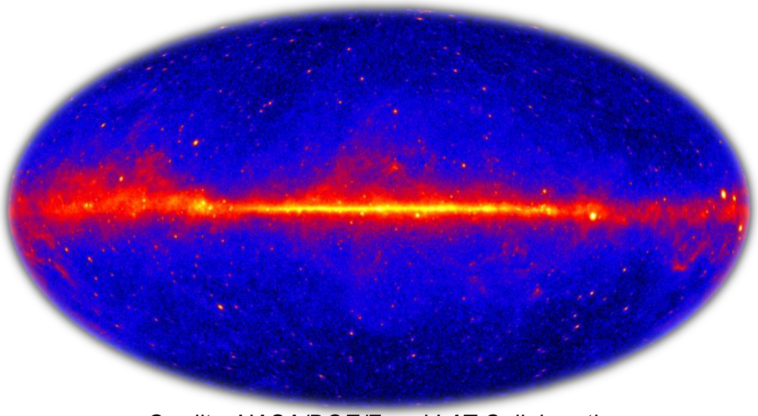
Some LAT catalogs:

★ **4FGL**: 7194 sources (DR4, 14 years)
★ **4LAC**: 3814 extragalactic sources (DR3, 12y)
★ **3FHL**: 1556 sources (above 10 GeV)
★ **1FLE**: 187 sources (below 100 MeV)

<u>Public data, used by many.</u>





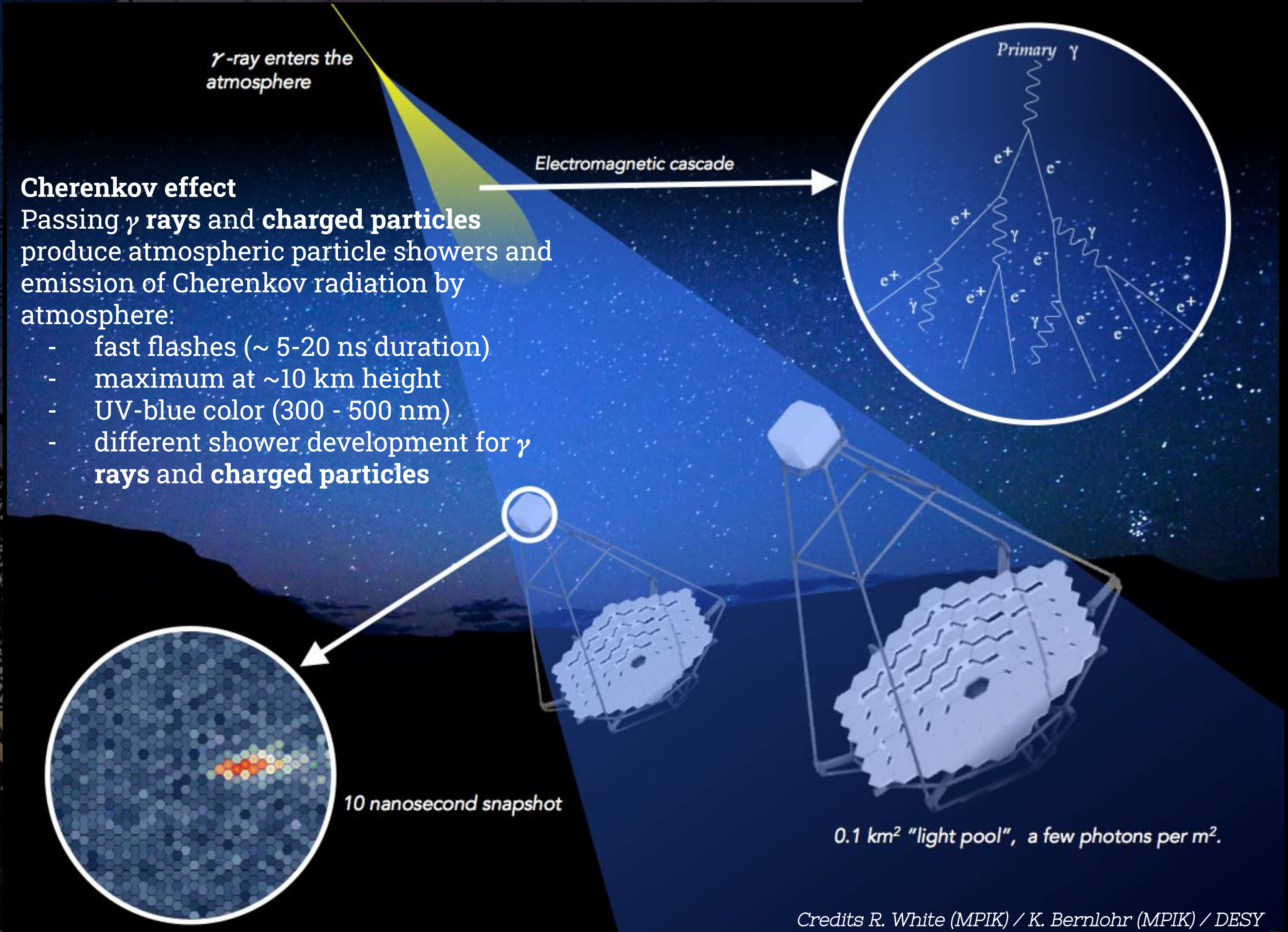


Credits: NASA/DOE/Fermi LAT Collaboration

Imaging Atmospheric Cherenkov Telescopes (IACTs)

Cherenkov effect
Passing γ **rays** and **charged particles** produce atmospheric particle showers and emission of Cherenkov radiation by atmosphere:

- fast flashes (~ 5-20 ns duration)
- maximum at ~10 km height
- UV-blue color (300 - 500 nm)
- different shower development for γ **rays** and **charged particles**



Credits R. White (MPIK) / K. Bernlohr (MPIK) / DESY

IACTs: major instruments

H.E.S.S. *Khomas Highland, Namibia*

Telescopes: 4 × 12m + 1 × 28m

Since 2004, major upgrade 2015-2016

MAGIC *ORM, La Palma, Spain*

Telescopes: 2 × 17m

Since 2004, major upgrade in 2011.

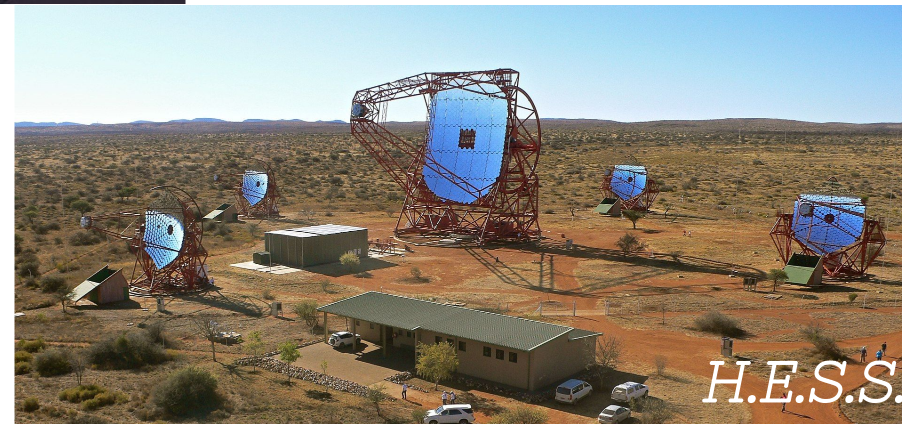
VERITAS *FLWO, Arizona, US.*

Telescopes: 4 × 12m

Since 2007, major upgrade in 2012

Arrays *of 2-5 telescopes, with ~ 500-1000 PMT* ***pixelized cameras****.*

Effective areas: ~ 10^5 m^2
Sensitivity: < 1% Crab Nebula flux (50h)
Field of view: ~ 3-5°
Angular resolution: ~ 0.1°
Energy resolution: ~ 15%
Pointing observation, limited surveys.



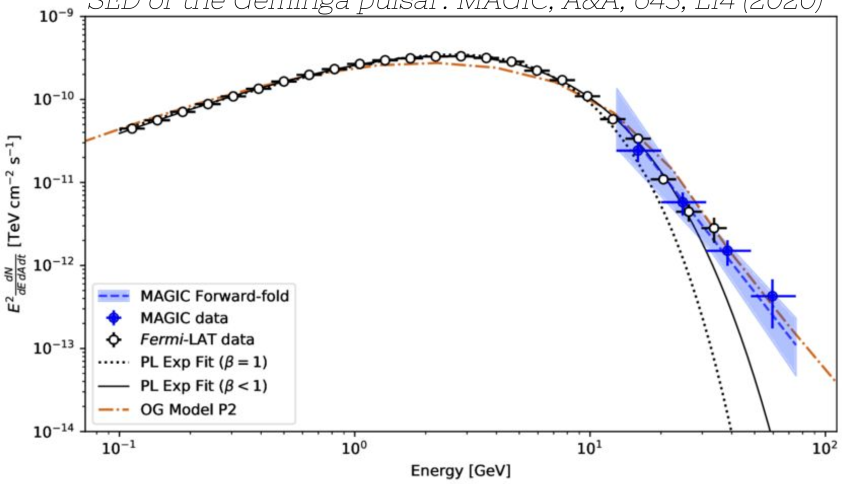
IACTs: results / Galactic

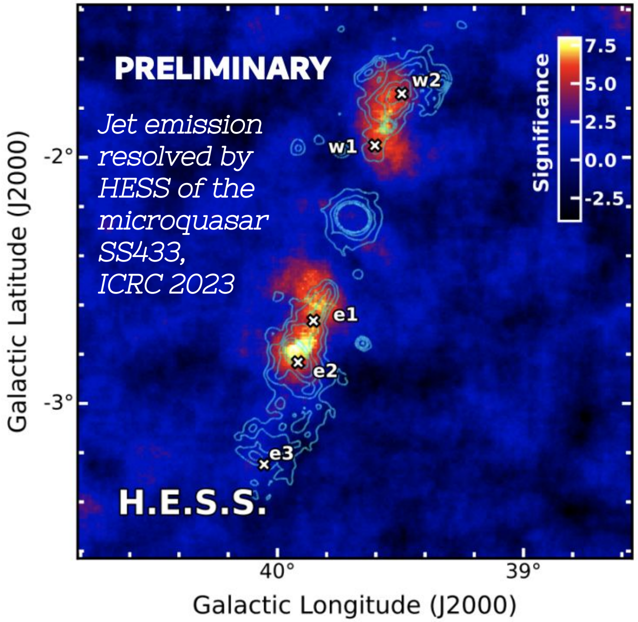
Pulsars:
- ❑ Crab (up to 2 TeV). Vela (HESS), Geminga (MAGIC, LST-1). Cutoff + PWL at VHE.

Binaries:
- ❑ SS 433: spectral modelling, morphology.
- ❑ PSR B1259-63 (binary pulsar)

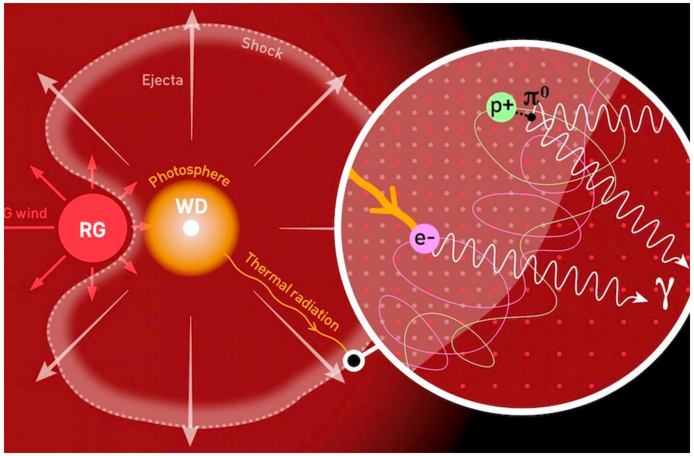
Galactic center: Dark matter origin? PeVatron?

SED of the Geminga pulsar: MAGIC, A&A, 643, L14 (2020)





Novae:
- ❑ **RS Ophiuchi**: symbiotic nova detected in 2021 by HESS, MAGIC, LST-1. Proton acceleration. *Sci 376, 6588; NatAst, 6, 689-697*)



IACTs: results / Extragalactic

Starburst galaxies

- Updated measurements of the emission from **M82** (VERITAS). Integrated emission from PWNe? responsive for the bulk of the extragalactic γ ray background?

Active galaxies

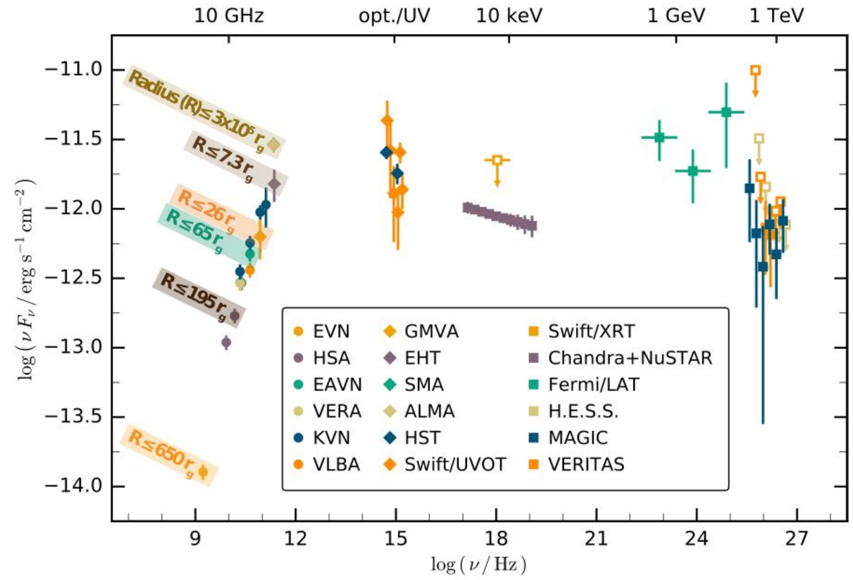
New or updated catalogs

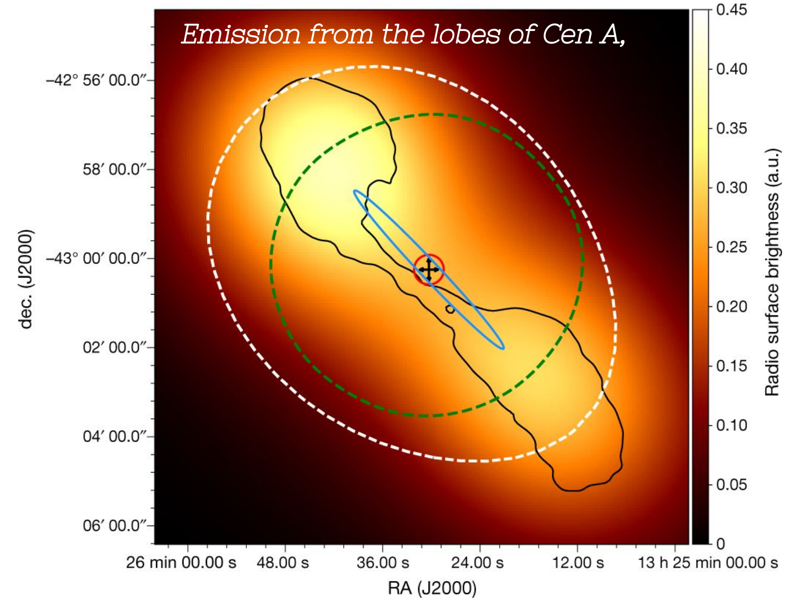
- **TeVCat:** http://tevcat.uchicago.edu/
- **GammaCAT:** https://gamma-cat.readthedocs.io/
- **STeVECAT** ***(released in 2023)***: https://zenodo.org/record/8152245

Radio galaxies

- **M87:** deep MWL campaigns following EHT observations.
- **Centaurus A:** break in VHE emission. Lower energies from core, Higher energies from lobes
  Nature, 582, 7812, p.356–359

M87 broadband spectrum (EHT coll. + MWL partners, ApJL 911 L11 2021)





IACTs: results / Extragalactic

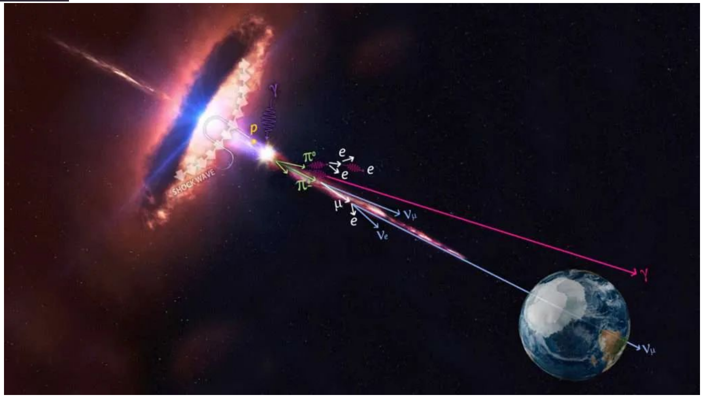
Blazars

Too many new advances to list here

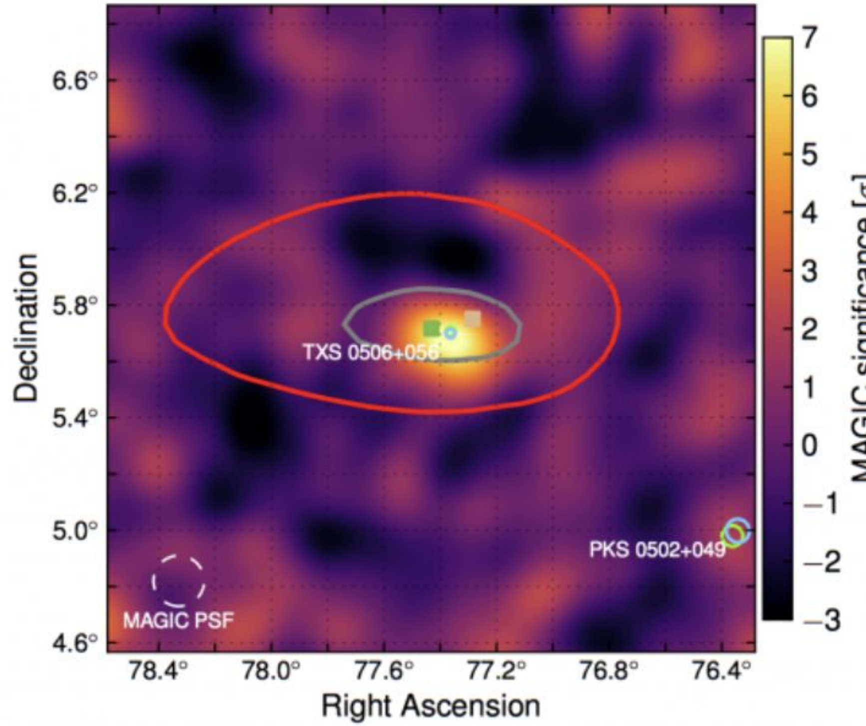
- **Theory**: more detailed models and simulations of structured jets, lepto-hacronic, multi-zone and jet-ISM interactions.
- **~ 85 blazars** detected in VHE. Most are BL Lacs, a few FSRQs.
- **Hot topics:** extreme blazars, binary systems (e.g. PG 1553+113), etc.
- **Multi-wavelength & Multi-messenger** are hot topics:

  TXS 0506+056 / IceCube-170922A detection (*Science, 361, 6398*)

Credit: IceCube/NASA



Detection of the blazar TXS 0506+056 coincident with IceCube-170922A

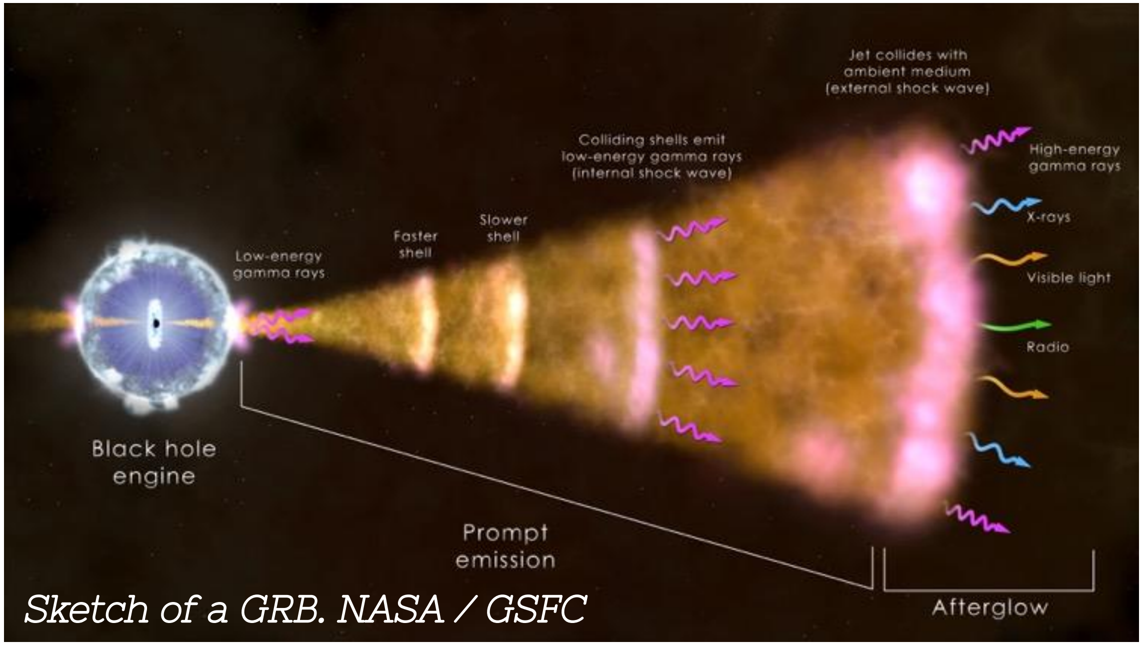


IACTs: results / Extragalactic

Gamma-ray bursts (GRBs)

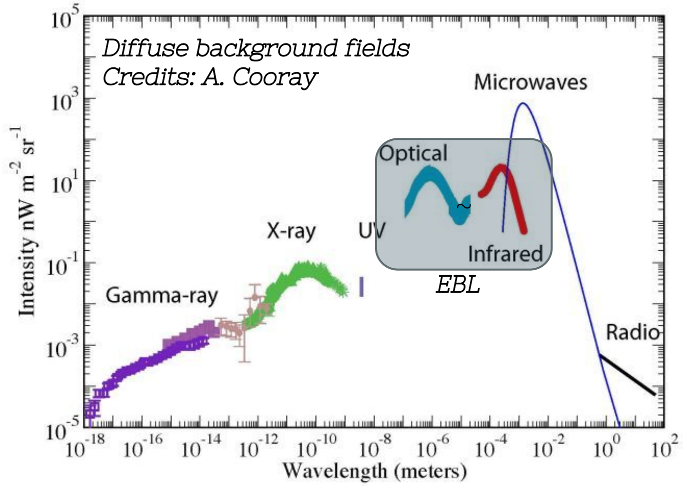
- ❑ New source class in VHE (since 2019).
- ❑ 5 GRBs detected:
  - ❑ GRB 180720B (H.E.S.S.), GRB 190114C (MAGIC), GRB 190829A (H.E.S.S.), GRB 201216C (MAGIC), ***GRB 221009A*** (LHAASO, ***B.O.A.T.***)

★ Many open questions: progenitors? afterglow plateau phase? how is the VHE emission produced?



Sketch of a GRB. NASA / GSFC

IACTs: results / EBL

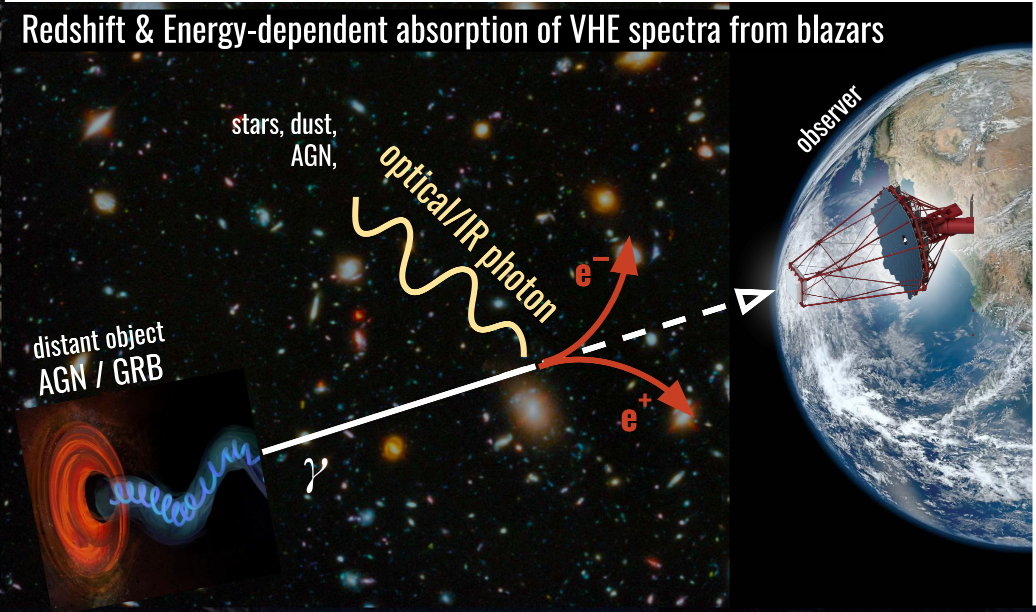


Extragalactic background light (EBL)

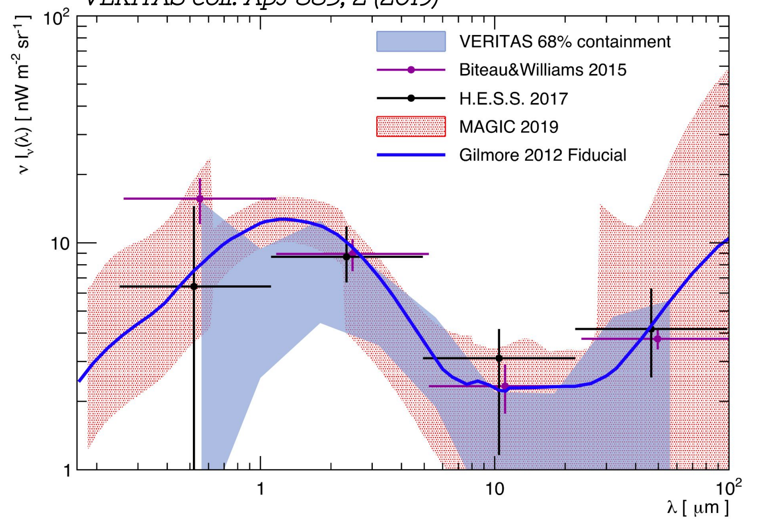
New models: Saldana-Lopez ‘21, Finke ‘22, etc.

Updated measurements by the 3 major IACTs:

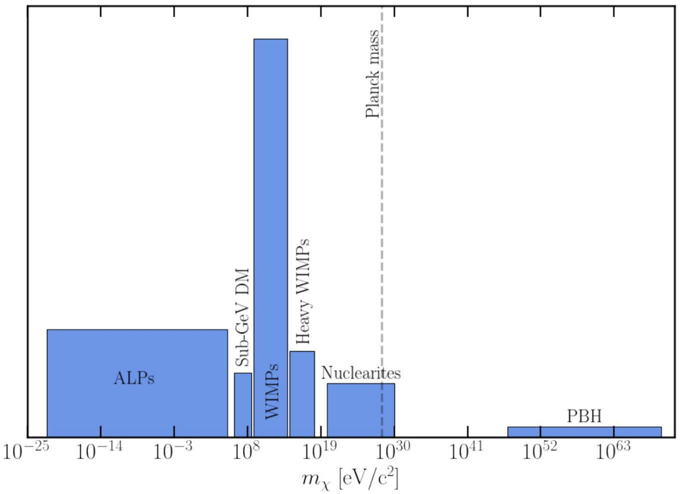
- HESS. A&A 606, A59 (2017)
- MAGIC. MNRAS, 486, 3 (2019)
- VERITAS. ApJ 885, 2, 150 (2019)
- recent projects (*all presented at ICRC 2023*):
  - Anisotropy searches (EBL skymaps)
  - Combining all existing data (better limits)
  - EBL as a tool: blazar distance estimation & cosmology (H_0, Ω_M)



EBL spectrum in the NIR (‘the dusty Universe’)
VERITAS coll. ApJ 885, 2 (2019)



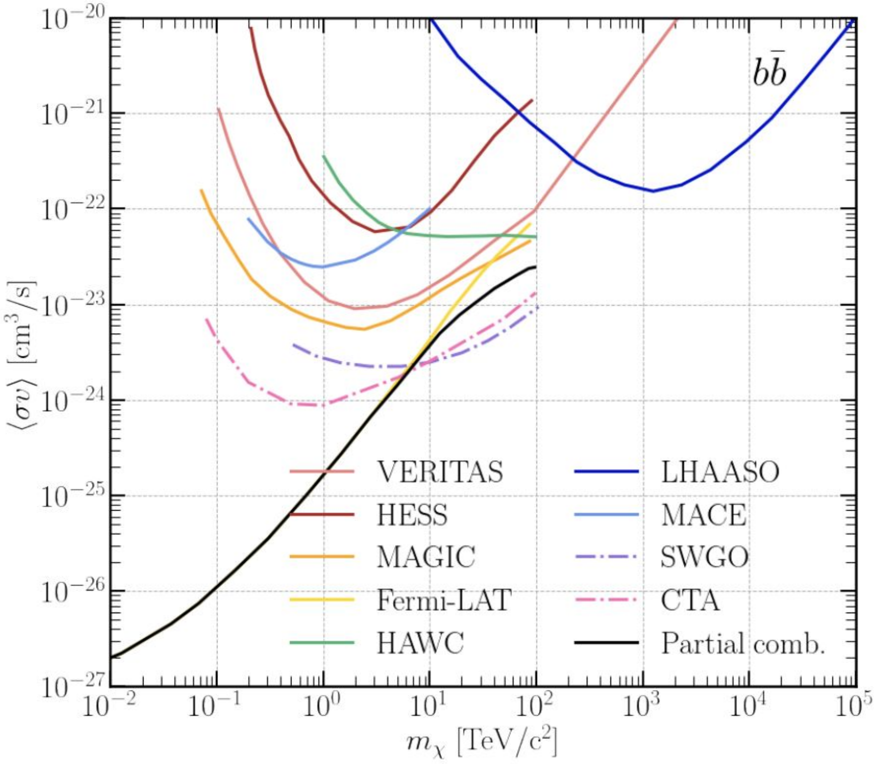
IACTs: results / Dark Matter

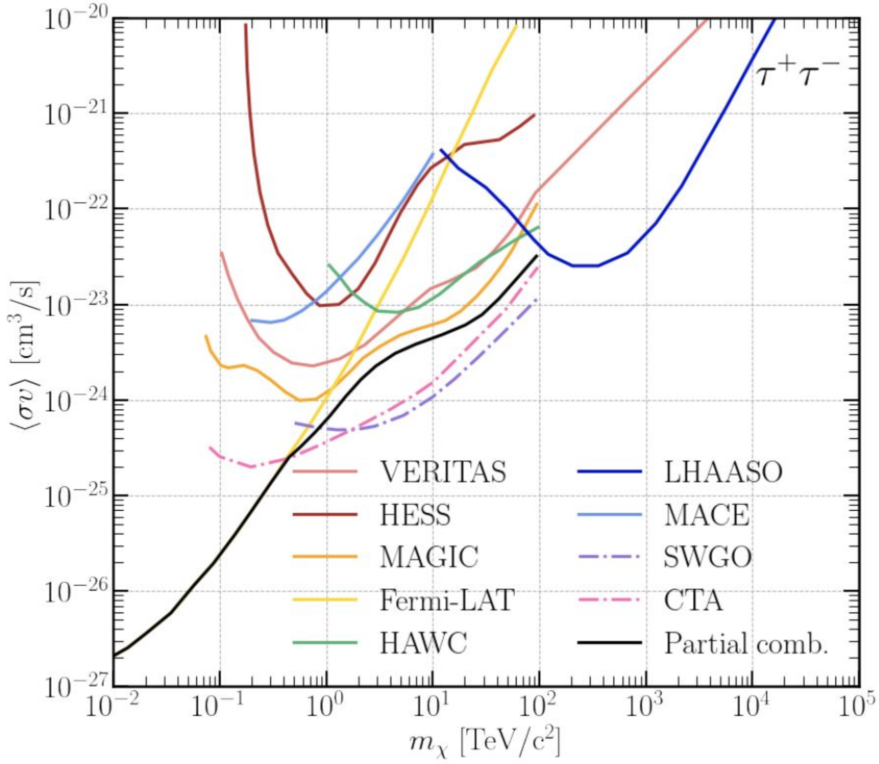


M. J. Zurowski (ICRC 2023)

Targets:

- Galactic centre
- Galactic halo
- galaxy clusters
- Sun and surroundings
- dwarf spheroidals:





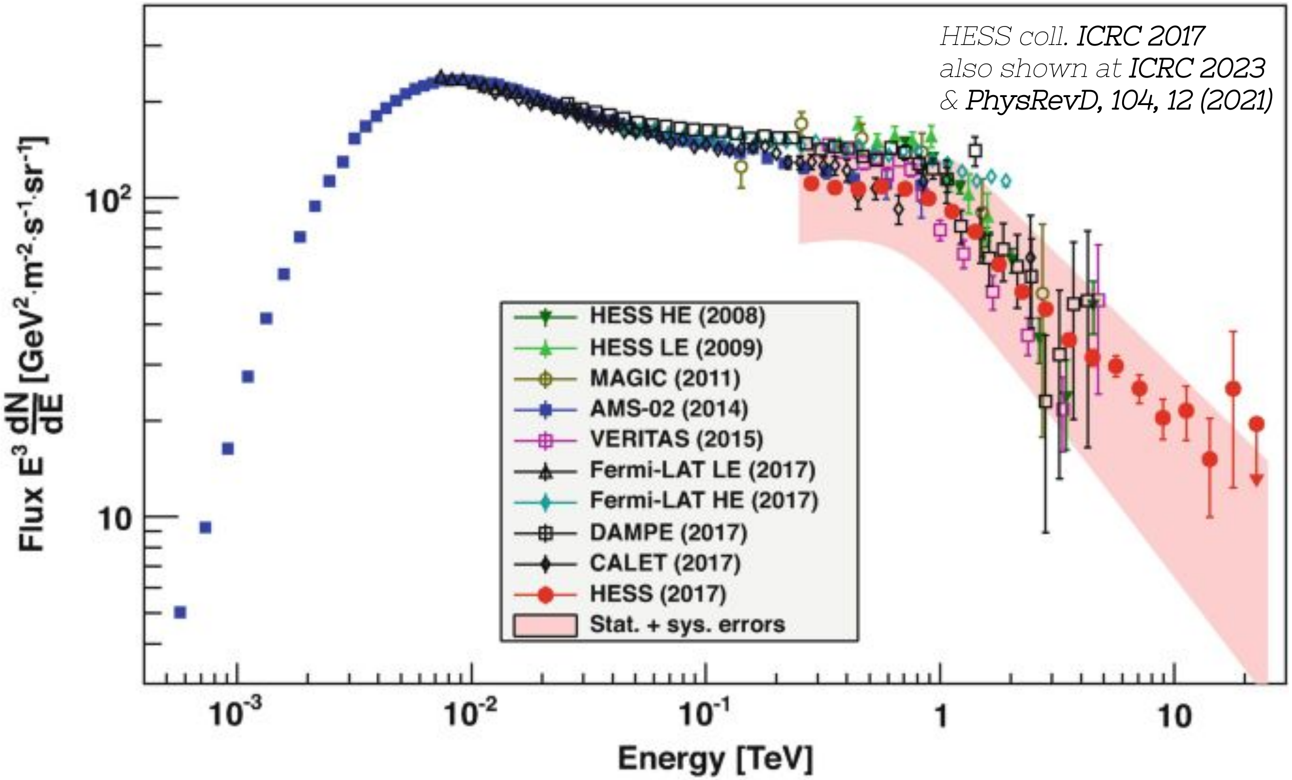
IACTs: results / Cosmic Rays

Electron spectrum.

Measurement from all 3 major IACTs.

- Break at ~ 1 TeV used for energy-scale calibration !

PRELIMINARY



Other species: early on measurement by HESS of ***Iron spectrum*** (*Bühler, ICRC 2008; PhysRevD, 75, 4 2007) and VERITAS (last update PhysRevD, 98, 022009, 2018;* and of ***proton spectrum*** (see e.g. *D. Jankowsky's thesis*).

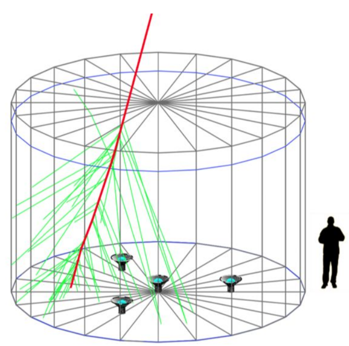
High-Altitude Water Cherenkov Observatory (HAWC)

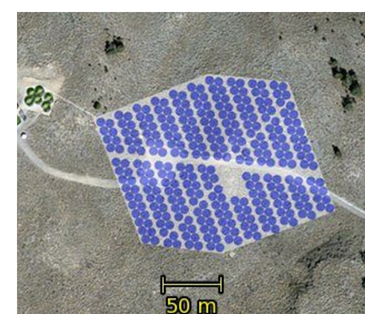
300 water Cherenkov tank, 3 + 1 (central) PMTs each.
~200,000 liters of water each.

Predecesor: Milagro (Los Alamos)
Location: base of Sierra Negra volcano, Mexico.
Collaboration: Mexican-US
Outrigger **upgrade**: August 2018

<u>**Performance:**</u>

- FoV: 15% instantaneous, **⅔** of the sky each day.
- hadron rejection: >99% (> 3TeV)
- 1 year = unbiased survey at 50 mCrab (5σ)
- effective area: ~ $10^{4\text{-}5}$ m^2
- angular resolution: ~ 0.1° (at >10 TeV)
- energy resolution: < 50% (at >10 TeV)





HAWC: results

Surveys:

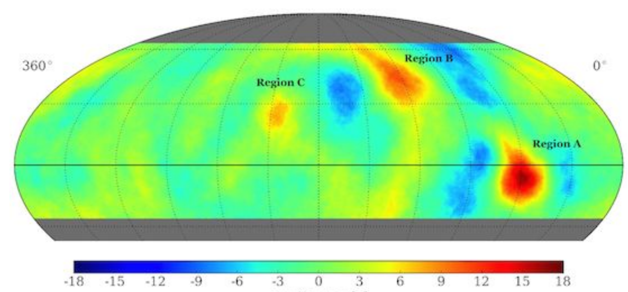
- 3HWC catalog (1523 days, 65 sources, 20 new) ***ApJ,905,76***
- Galactic plane survey (e.g. ***ApJ,917,6)***
- AGN light curves (Mrk 421, Mrk 501) ***ApJ,841,100***

Galactic sources:

- Detected γ rays from the Sun (*PhysRevLett.131.051201*).
- Geminga / Monogem TeV-halos ('older' pulsars) *2017Sci...358..911A*
- Binary systems / microquasars: MGRO J1908+06 (possible pevatron) and SS 433 lobe detection. ***Nature,562, 82–85***

Cosmic rays & fundamental physics:

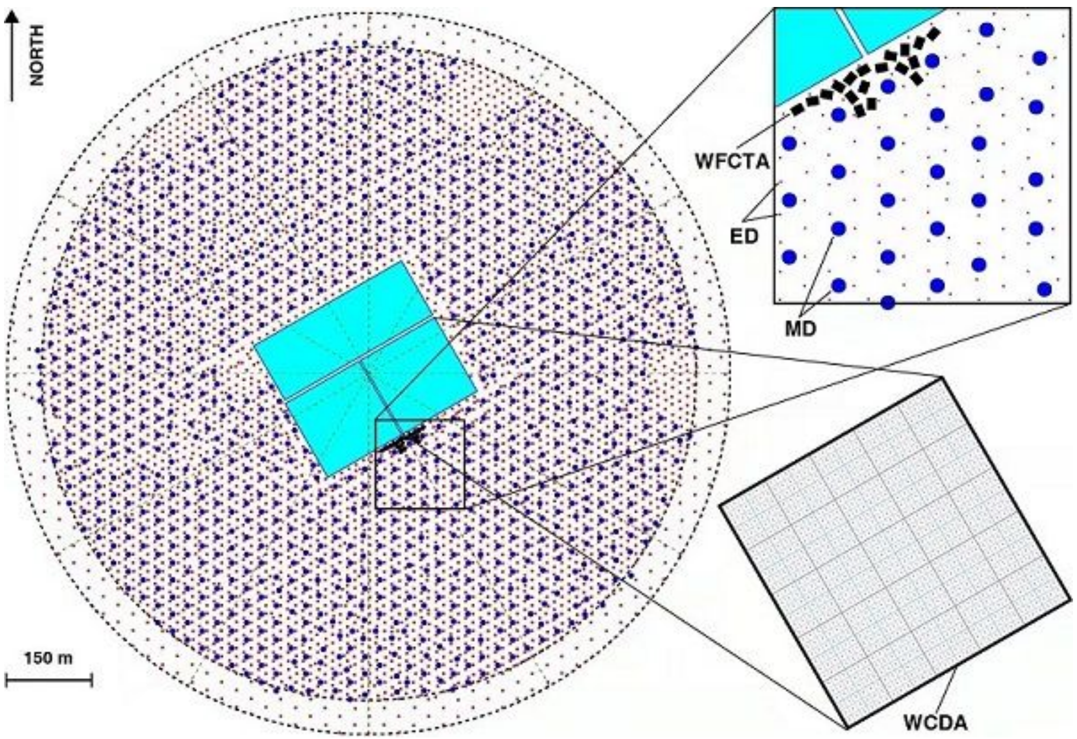
- Neutrino searches from the Volcano. ***APh,137, 102670.***
- Extragalactic Background light limits
- Anisotropies of CRs above 1 TeV. ***ApJ,865,1***
- Dark matter searches (e.g. ***ApJ,945,25)*** & evaporation of primordial black holes (*JCAP,4,26*)
- Positron excess due to pulsars? ***PhysRevD, 96, 10***

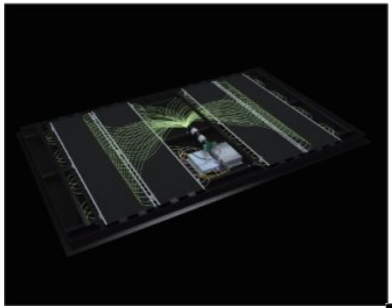


Large High Altitude Air Shower Observatory (LHAASO)

高海拔宇宙线観测站

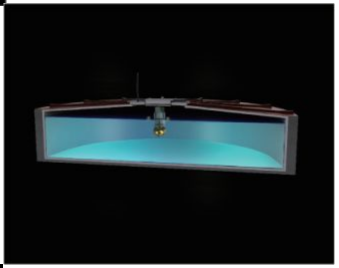
hybrid high-altitude (4410m a.s.l, Sichuan, China) γ–ray observatory of several ***detector arrays*** covering an area of ***1.36 km²***.

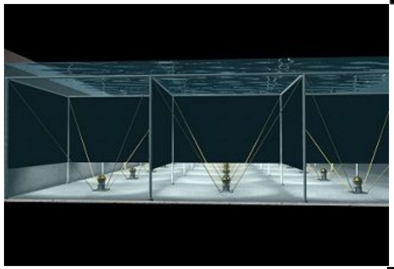




5195 ED (each 1m²)
secondary particles from the EAS, scintillation light

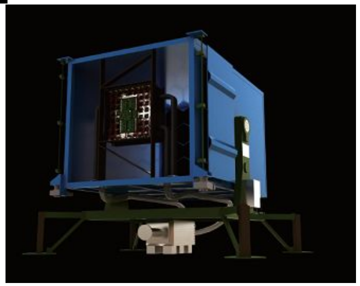
1188 MD:
muon content. Tanks with PMTs measuring water Cherenkov light by muons





WCDA (78000m²):
3 water ponds divided in cells to measure Cherenkov light from charged particles

WFCTA array
telescopes of 5m² mirrors with SiPM (~ 1000 pixels) and a 16°×16° FoV



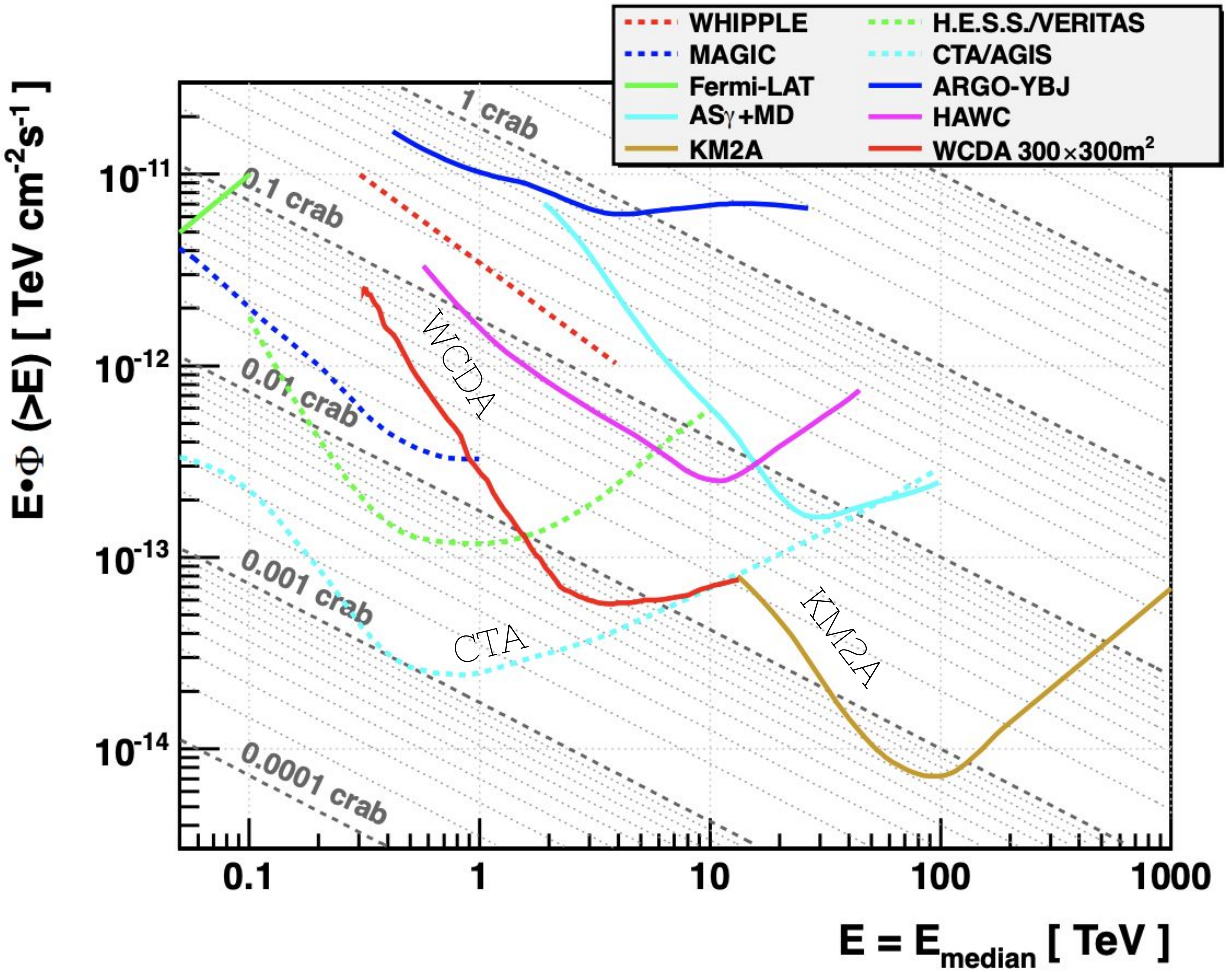
Subarrays:

KM2A (~ 1 km²), WCDA (~10⁵ m²), WFCTA

http://english.ihep.cas.cn

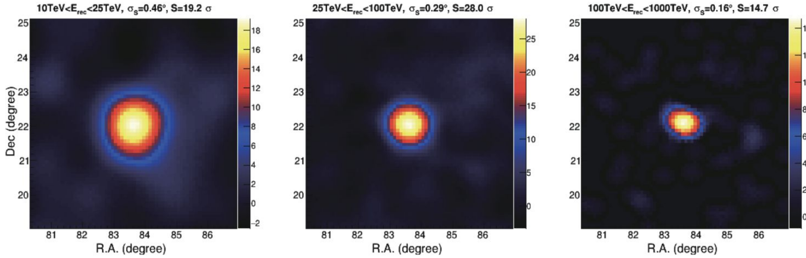
LHAASO: performance

hybrid high-altitude (4410m a.s.l, Sichuan, China) γ-ray observatory of several ***detector arrays*** covering an area of ***1.36 km²***.

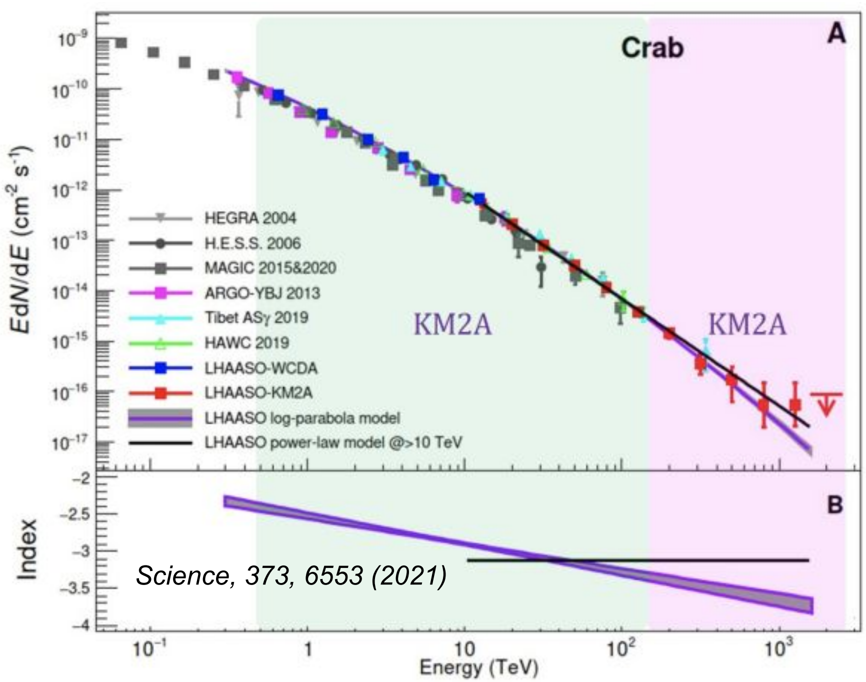


LHAASO: γ–ray astronomy

Crab Nebula



detected up to 3 PeV with KM2A. Electron accelerator up photon energy of E ~ 500 TeV. Proton-component (~ PeV) above that.



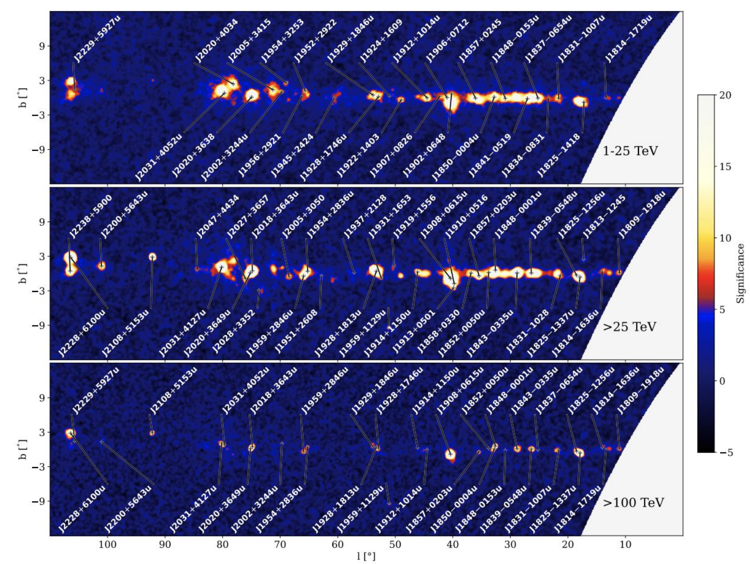
"Other" PeVatrons

Nature, 594, 33–36 (2021)

12 new γ–ray sources discovered in the UHE band → PeV particle accelerators.

- Located in the Galactic plane.
- Discovered with 11-month of 'partially built' KM2A data.
- 11/12 with VHE counterparts.

Catalog of VHE/UHE γ–ray sources (1LHAASO) (https://arxiv.org/abs/2305.17030)

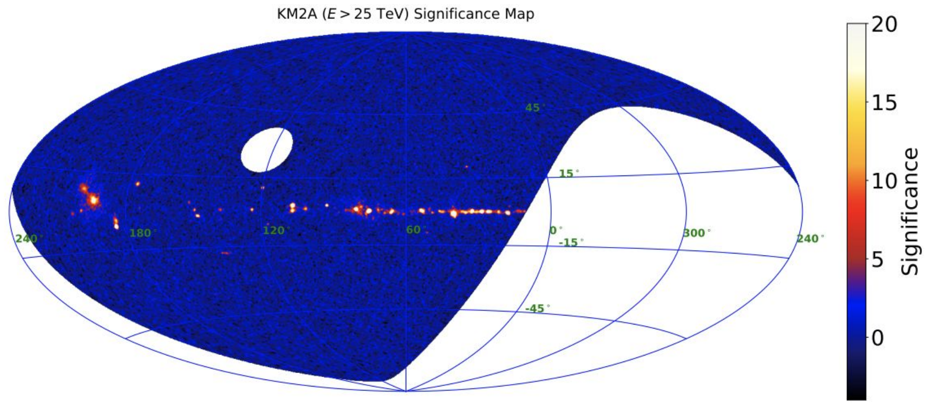


LHAASO: 1LHAASO catalog

- ❏ 508 days of WCDA data.
- ❏ 933 days of KM2A data.
- ❏ $-20 < \delta < 80$ deg

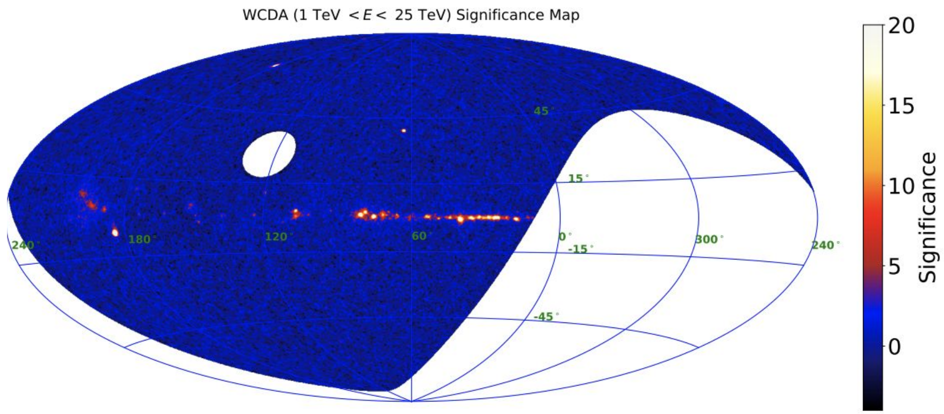
Sources

- ❏ 90 VHE sources, of which ...
  - ❏ 32 are new.
  - ❏ 65 are extended
  - ❏ 7 do not have GeV counterparts.
- ❏ 43 sources in the UHE band (E>100 TeV) at $>4\sigma$. 8 not detected < 25 TeV.
- ❏ 35 associated with pulsars (PWNe or TeV halos).



Data products

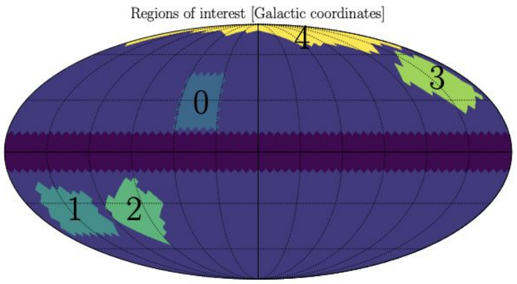
- Association (GeV and TeV)
- Source extension (UHE)
- Source spectra

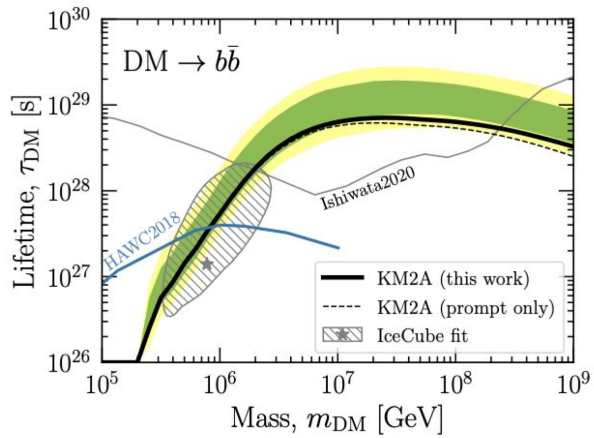


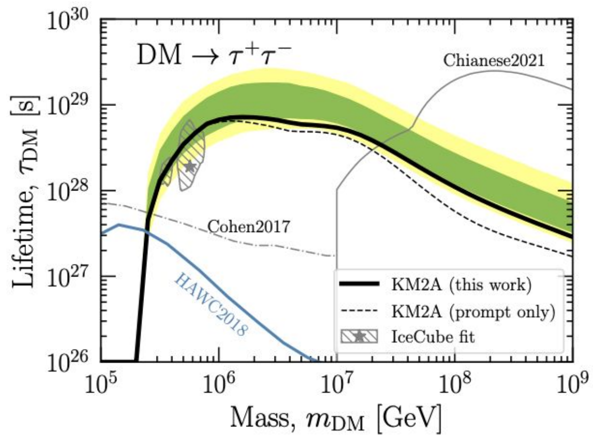
LHAASO: DM, CRs and diffuse γ rays

Dark matter constraints (*Phys. Rev. Lett. 129, 261103*)

- Region 0: close to GC
- Regions 1-4: CRs /control







Diffuse γ-ray emission from the Galactic plane

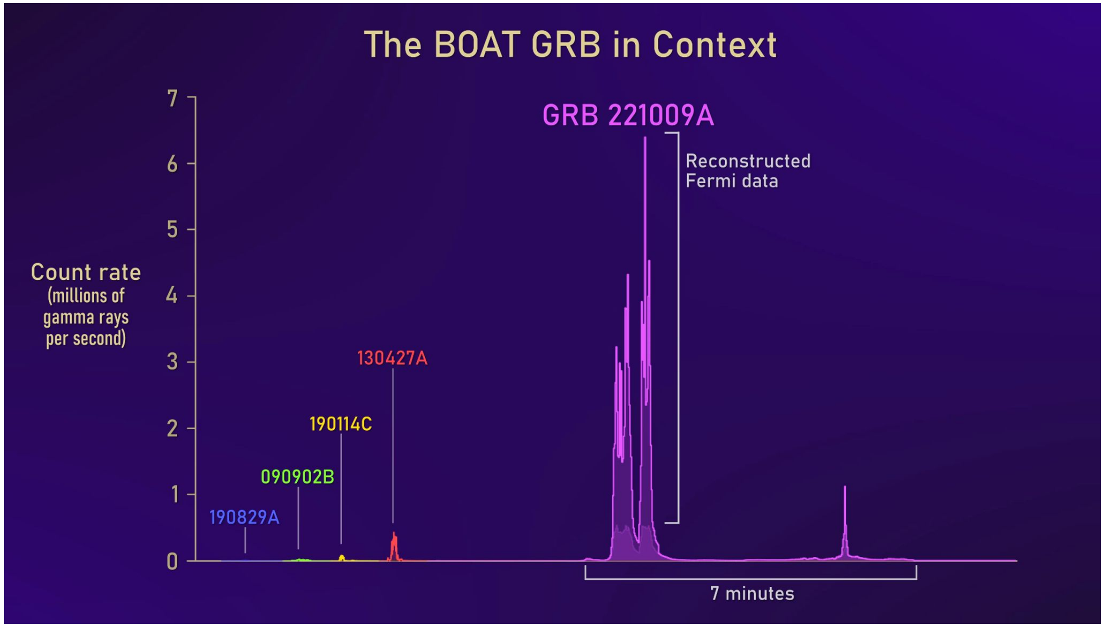
arXiv/2305.05372, accepted in PhysRevL

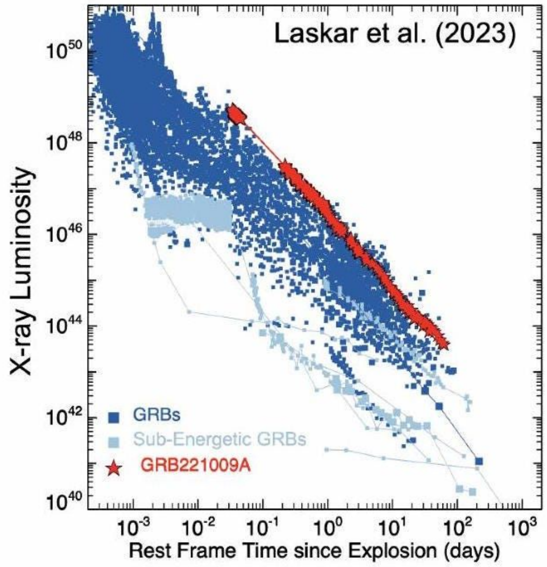
Cosmic rays

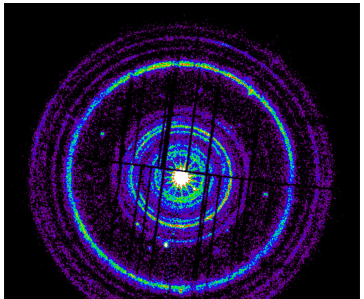
One of the main goals of LHAASO is to measure CR composition and spectra for different group masses.

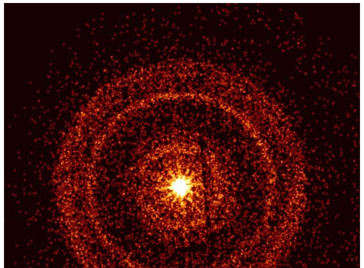
The BOAT: GRB 221009A

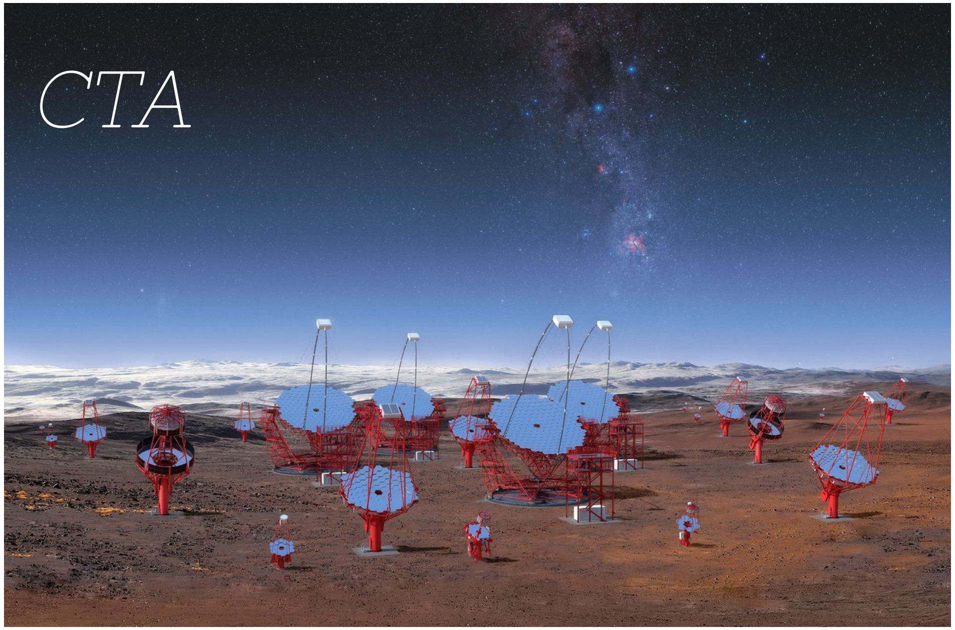
- **B**rightest **O**f **A**ll **T**imes. The highest isotropic energy, highest fluence, highest peak flux, 3rd highest isotropic luminosity.
- z = 0.151.
- **7 minutes** duration (*short bursts < 2s, long bursts >2s*)
- afterglow: No polarization in X-rays (IXPE)
- elusive supernova signal following GRB
- detection by IACTs not claimed yet (strong Moon) ***but detected by LHAASO***: 18 TeV, ***100 sigma***, 5000 photons !!

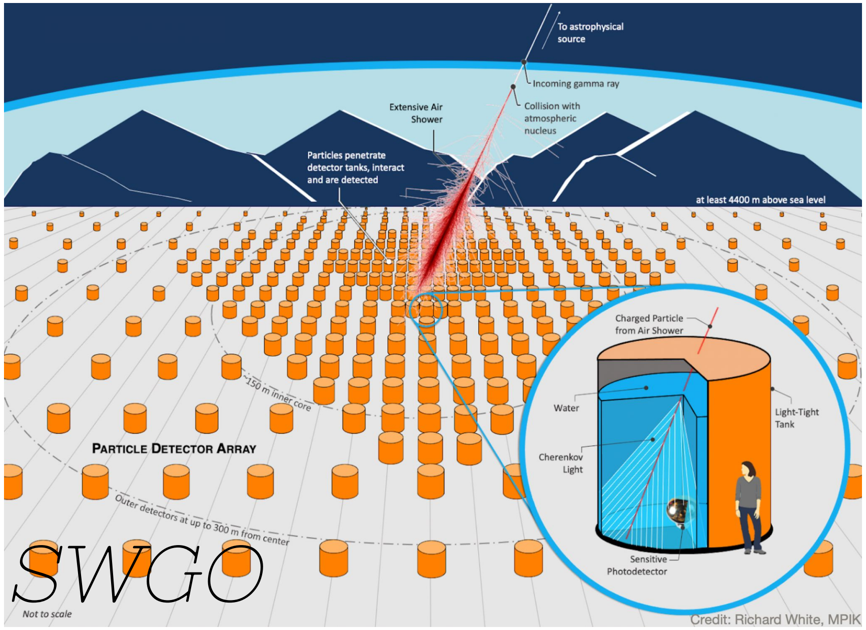





ESA/XMM-Newton/M. Rigoselli (INAF)


SWIFT/NASA, A. BEARDMORE/UNIV. OF LEICESTER





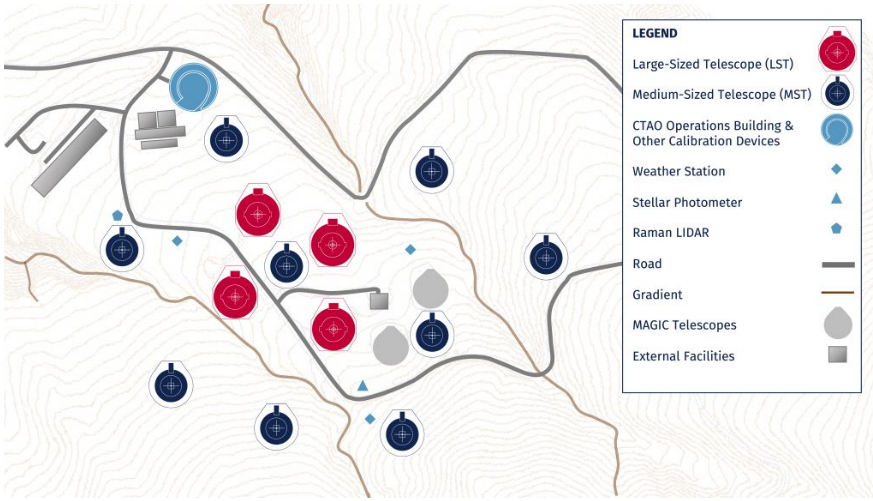
Future γ **ray instruments**

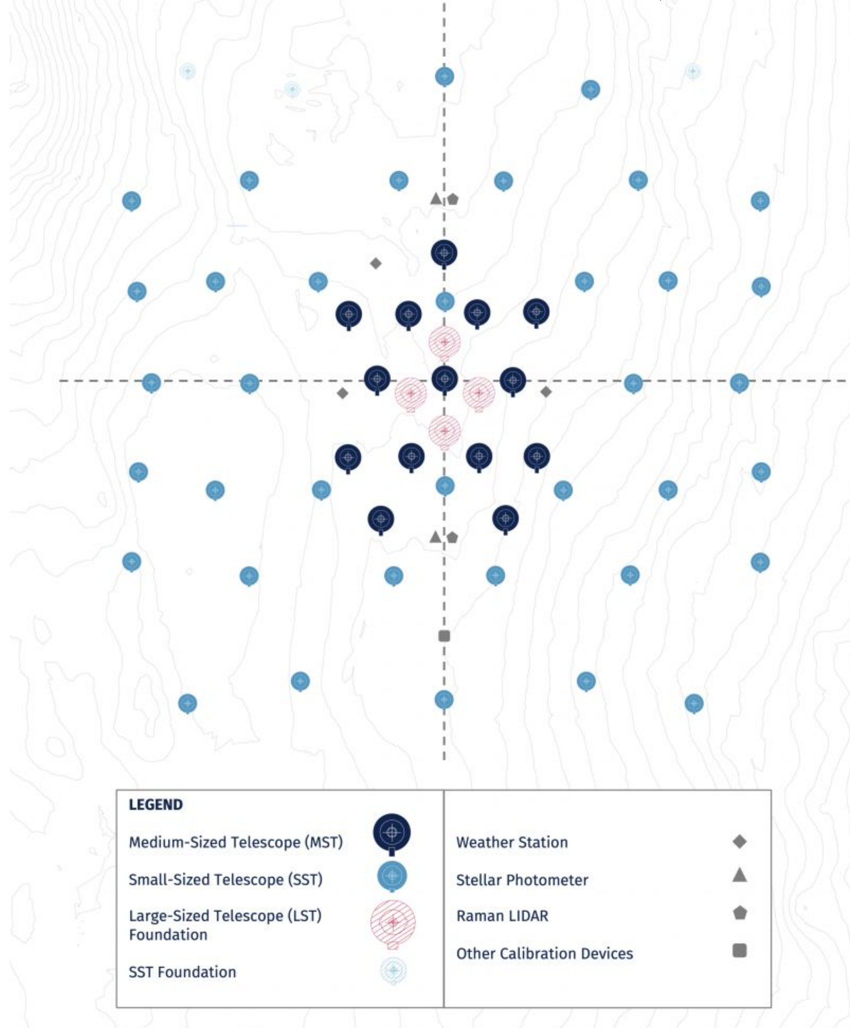
Cherenkov Telescope Array (CTA)

cherenkov telescope array

Two sites → full-sky coverage

Science with CTA book: arXiv:1709.07997
operations begin on: ~~2025?~~ 2027?
constr. costs: >300M EUR (2✕ LHAASO)





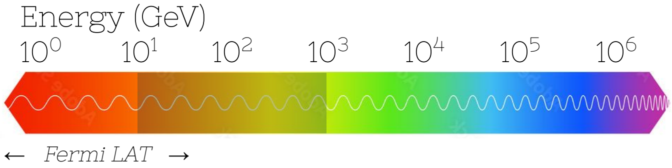
- <u>CTA-N:</u> 4 LST + 9 MST. ***Focus***: extragalactic science.
- <u>CTA-S:</u> *up to 4 LST* + 14 MST + 37 SST (Alpha Conf.). ***Focus***: Galactic science

3 telescope sizes → wide energy range

- Large-Sized Telescope (**LST**): 23-m
- Medium-Sized Telescopes (**MST**): 12-m
- Small-Sized Telescopes (**SST**): 4-m

Open observatory and data (~ 50% time)

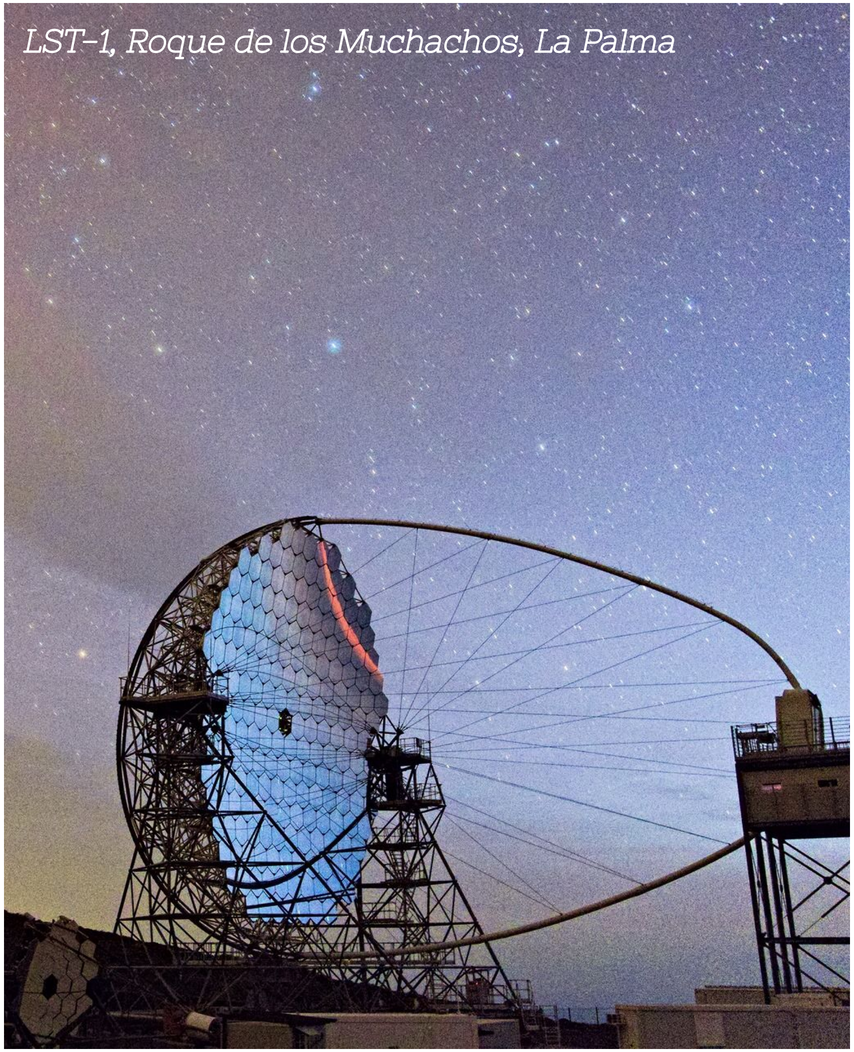
CTA: Large-Sized Telescope (LST)



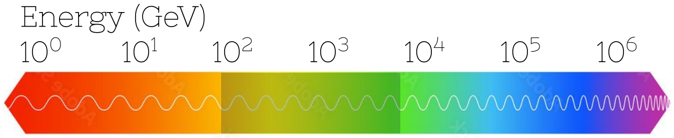
- ❏ 4 × 23-m LST in the North, up to 4 LST in the south.
- ❏ Focus: lowest energies (10 GeV – 1 TeV)
- ❏ First telescope (LST-1, ORM) since 2019.
- ❏ Construction of LST 2-4 ongoing.

<u>Many scientific results:</u>

- Performance study (LST): *accepted in ApJ.* Performance study of joint LST+MAGIC underway.
- Detection of the ***Crab and Geminga pulsars***.
- Constraints on the VHE emission from the ***PeVatron candidate LHAASO J2108+5157*** [*A&A 673, A75 (2023)*]
- ***Detection of the nova RS Ophiuchi***
- ***Detection of several AGNs down to 10 GeV***: Mrk 421, Mrk 501, PG 1553+113, 1ES 1959+650, 1ES 0647+250, BL Lacertae, NGC 1275 ...



CTA: Medium-Sized Telescope (MST)



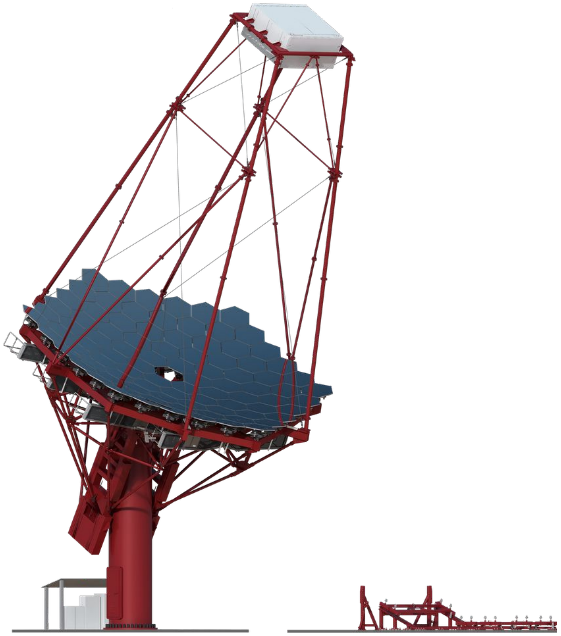
Single-mirror design

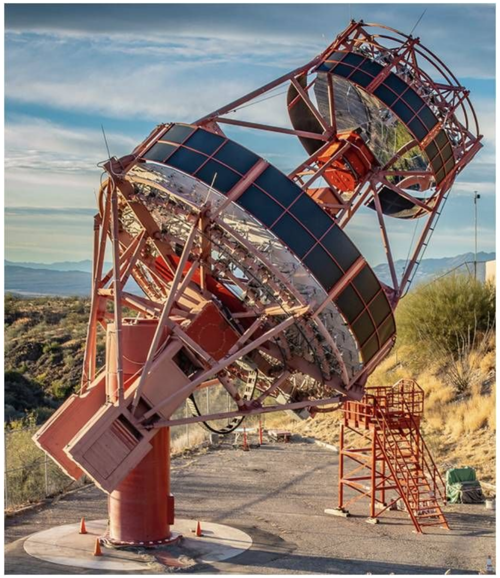
- ❑ CTA workhorses.
- ❑ 9 × 12-m MST in the North, 14 in the South
- ❑ Focus: core energies (150 GeV to 5 TeV)

Two camera designs (both using PMTs):

- ❖ *NectarCAM*: 'analog trigger', similar to LST.
- ❖ *FlashCAM*: 'digital trigger', similar to H.E.S.S. cameras.

MST Prototype: Validation phase (Berlin) from 2012 to 2020 to NectarCAM and FlashCAM tested.





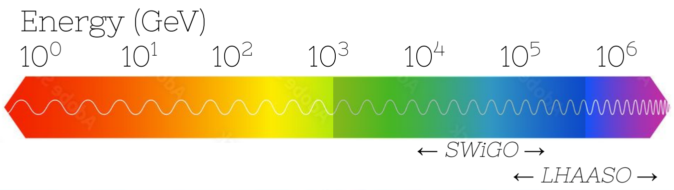
pSCT (FLWO basecamp, Arizona)

Schwazschild-Couder Telescope (SCT)

- **Mechanical structure (mount) similar to MST.**
- **SiPM instead of PMTs.**
- **10-m** primary mirror, 5.4-m secondary.
- 11328 **pixels** (vs ~ 1700-1800 in MST)
- **FoV:** 7.6° (similar to MST)
- **Focus:** smaller PSF, improved off-axis performance, deep learning based analyses.

SCT prototype (pSCT): In Tucson (Arizona, US) since Jan 2019.

CTA: Small-Sized Telescope (SST)



- Modified Schwarzschild-Couder (dual-mirror)
- 37 × 4.3-m SST in the South
- **Focus:** highest energies (5 – 300 TeV)
- **Pixels:** 2048, **SiPM.**
- **FoV:** 8.8°

<u>Prototypes and validation:</u>

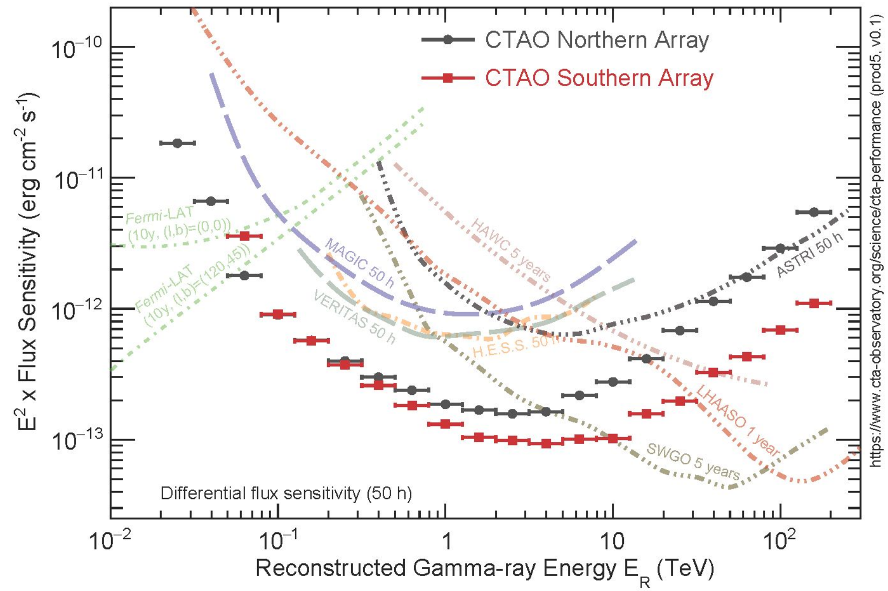
- **Structure**: based on ASTRI-Horn with modifications. Tested within the ***ASTRI-mini array***. First telescope in Tenerife, 8 more to come. In commissioning by end 2023.
- **Camera: SST-CAM,** based on CHEC-S (instead of ASTRI-camera)

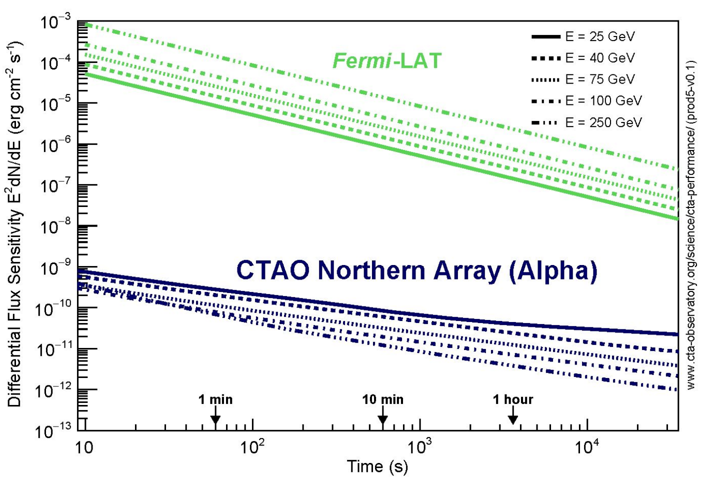
ASTRI Mini-Array: 9 SST-like telescopes in Tenerife. Completement to CTA-N and LHAASO for > 5 TeV γ

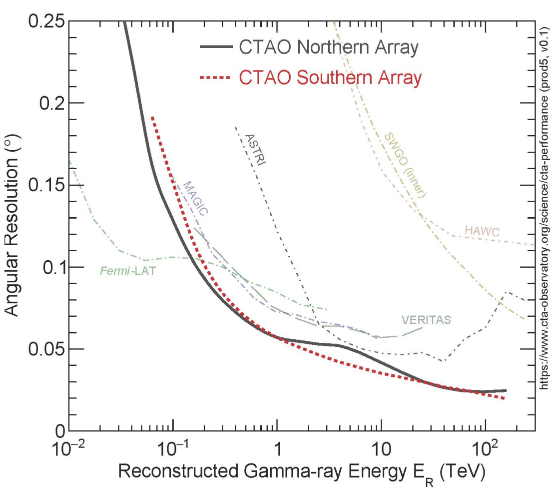
First ASTRI telescope (Izaña Tenerife)

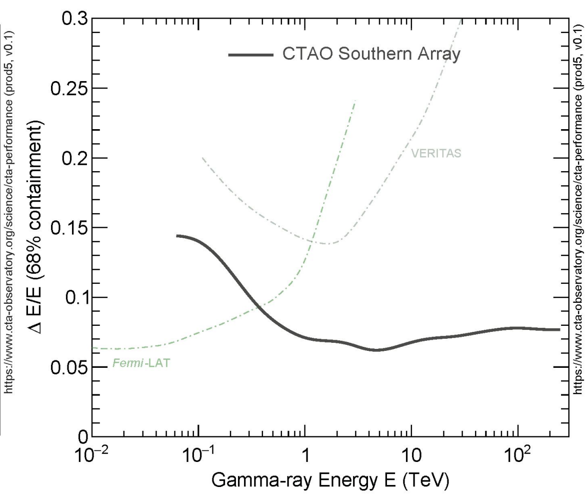
CTA: performance

- **Sensitivity:** ~ 10× better than current instruments, over 4 decades of energy
- **Sensitivity vs time:** 3–5 orders of magnitude better than LAT (for 25–250 GeV) + fast repositioning (~ 20s for LST).
- **Angular resolution (68%):** better than current IACTs. < 0.05° at E > 1 TeV (vs ~ 0.1° MAGIC, VERITAS, HESS)
- **Energy resolution (ΔE/E):** ~ 5% at E > 1 TeV. Better than current IACTs (~ 15%).
- **FoV:** ~8–10° (MST & SST) vs 3–5° (current IACTs)









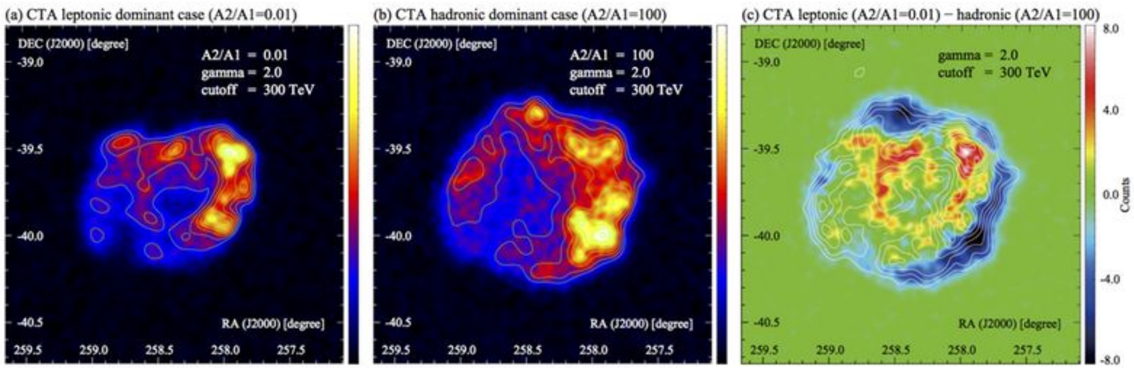
CTA: science and key targets

cherenkov telescope array

Study themes

- Understanding the ***origin and role of relativistic cosmic particles*** (acceleration sites, mechanisms, feedback on star formation and galaxy evolution)
- ***Probing extreme environments*** (neutron stars, black holes, jets, winds, explosions, cosmic voids)
- Exploring ***frontiers in physics*** (dark matter, quantum gravitational effects on photon propagation, axion-like particles)

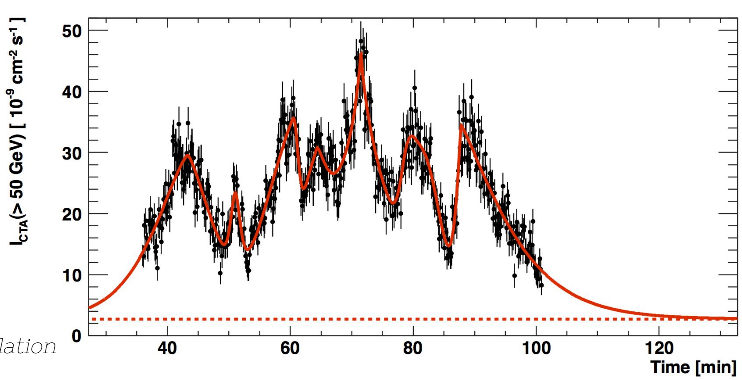
RX J1713-3946 simulation for protons and electrons(TeV-bright SNR)



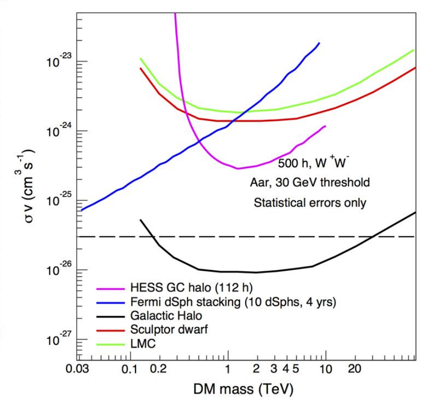
Key targets

- Galactic Center
- Large Magellanic Cloud
- Galactic Plane
- Galaxy Clusters
- Cosmic Ray PeVatrons
- Star Forming Systems
- Active Galactic Nuclei
- Transient Phenomena

https://www.cta-observatory.org/science/study-topics/



PKS 2155-304: 2006 flare simulation

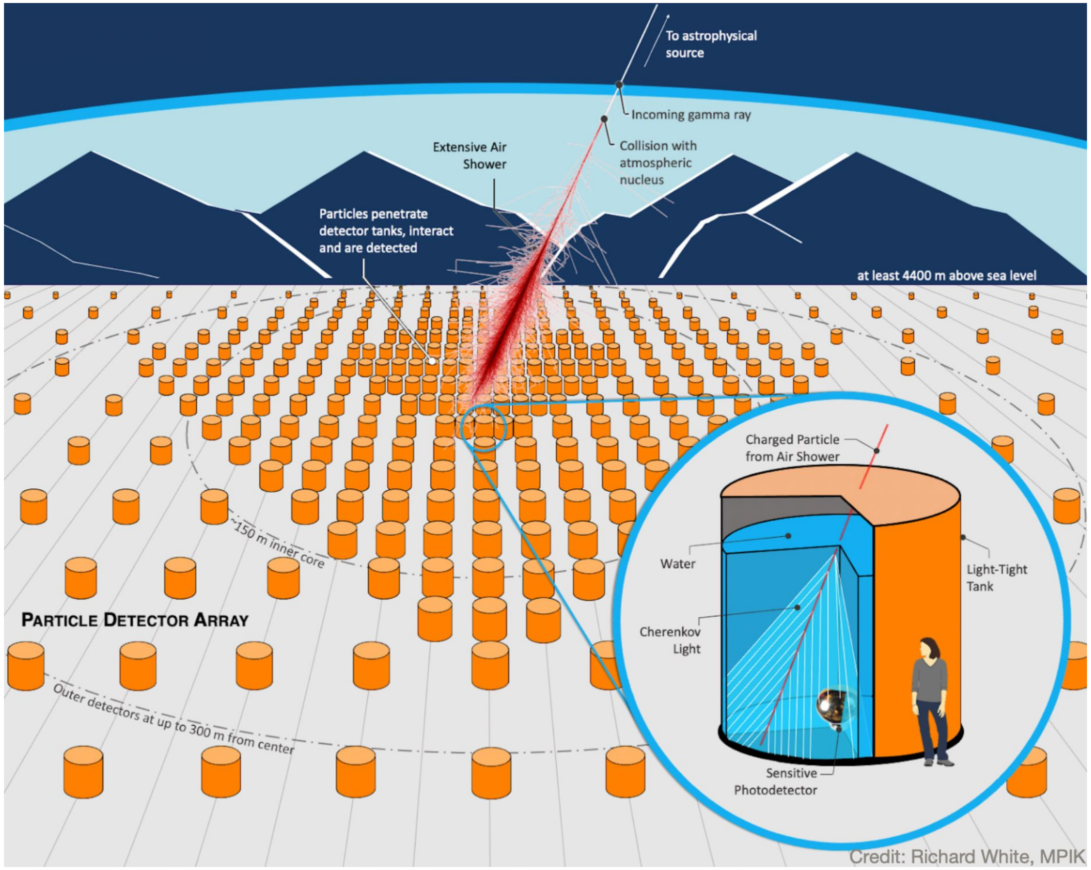


Sensitivity to WIMPs

Southern Wide-field Gamma-ray (SWGO)

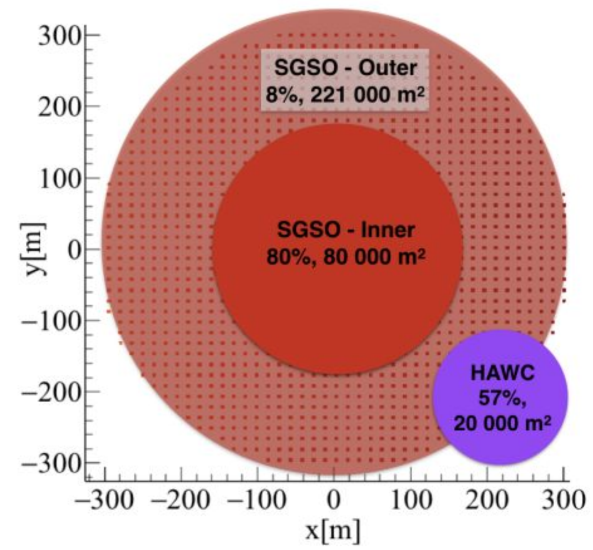
- ❑ high-altitude γ-ray observatory consisting of ***water Cherenkov*** units.
- ❑ first ***wide-field*** instrument in the south (Milagro, HAWC and LHAASO in the North).

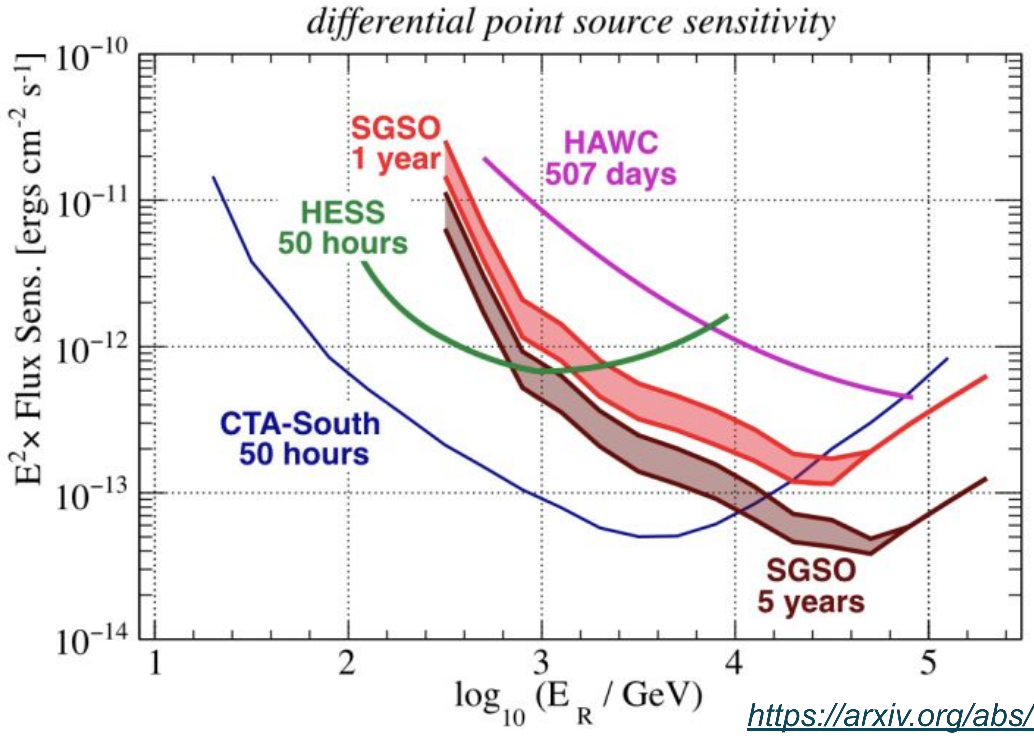
original plans
beginning of operations: 2026 ?
construction: 54M USD ?
operation: 7.5M USD / 5y ?

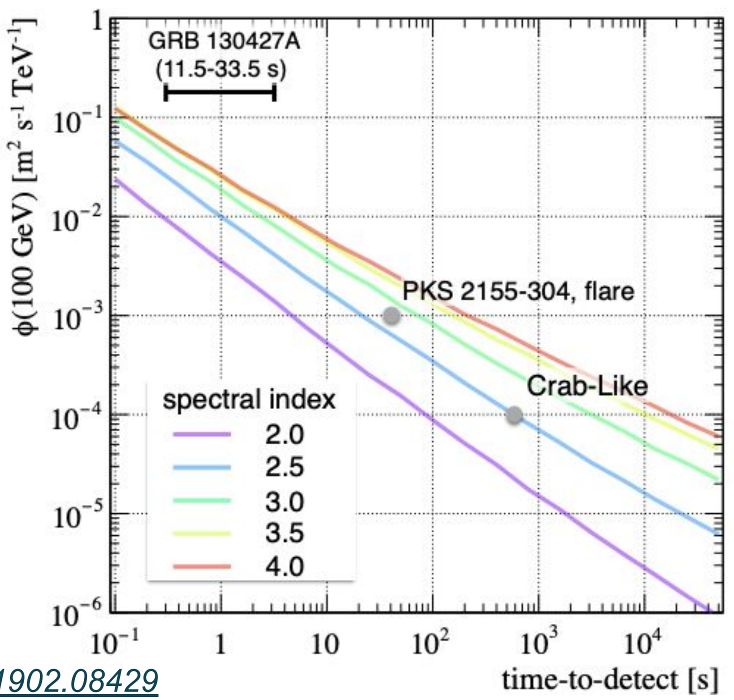


SWGO: performance ("Strawman layout")

- *near 100% duty-cycle* (like HAWC, vs 10–30% for IACTs)
- instrumented area ***~ 3 × 10⁵ km²*** (~15× HAWC).
- Angular resolution: 0.1–0.3°
- Energy resolution: 10–20 %



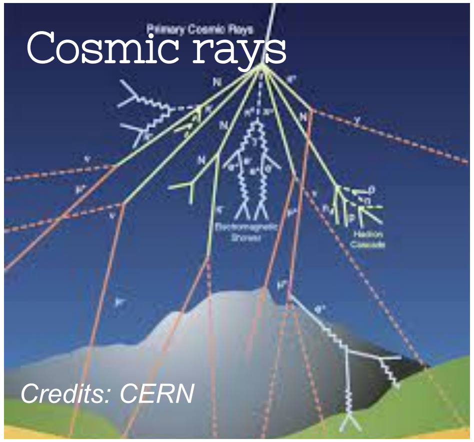


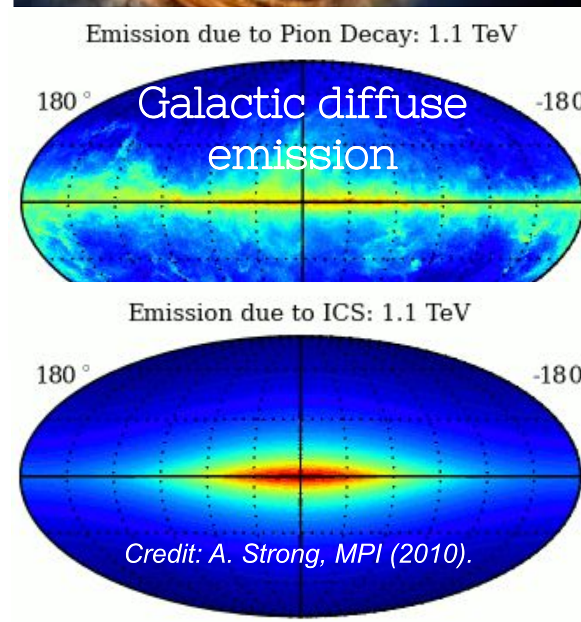


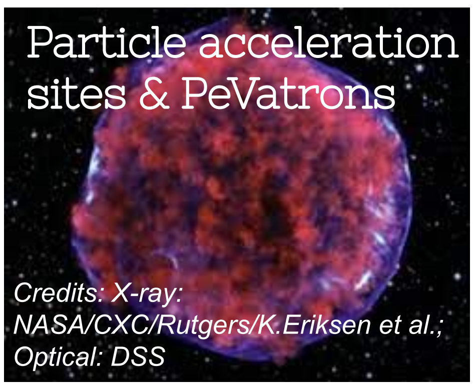
https://arxiv.org/abs/1902.08429

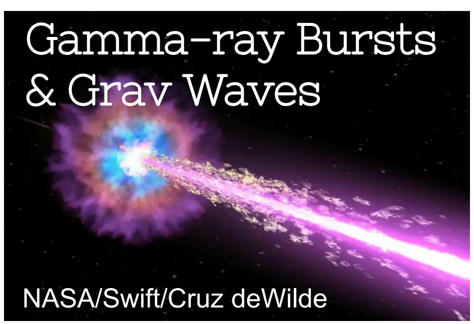
SWGO: science cases

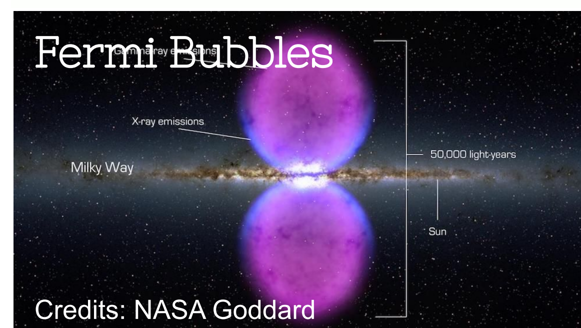
https://arxiv.org/abs/1902.08429









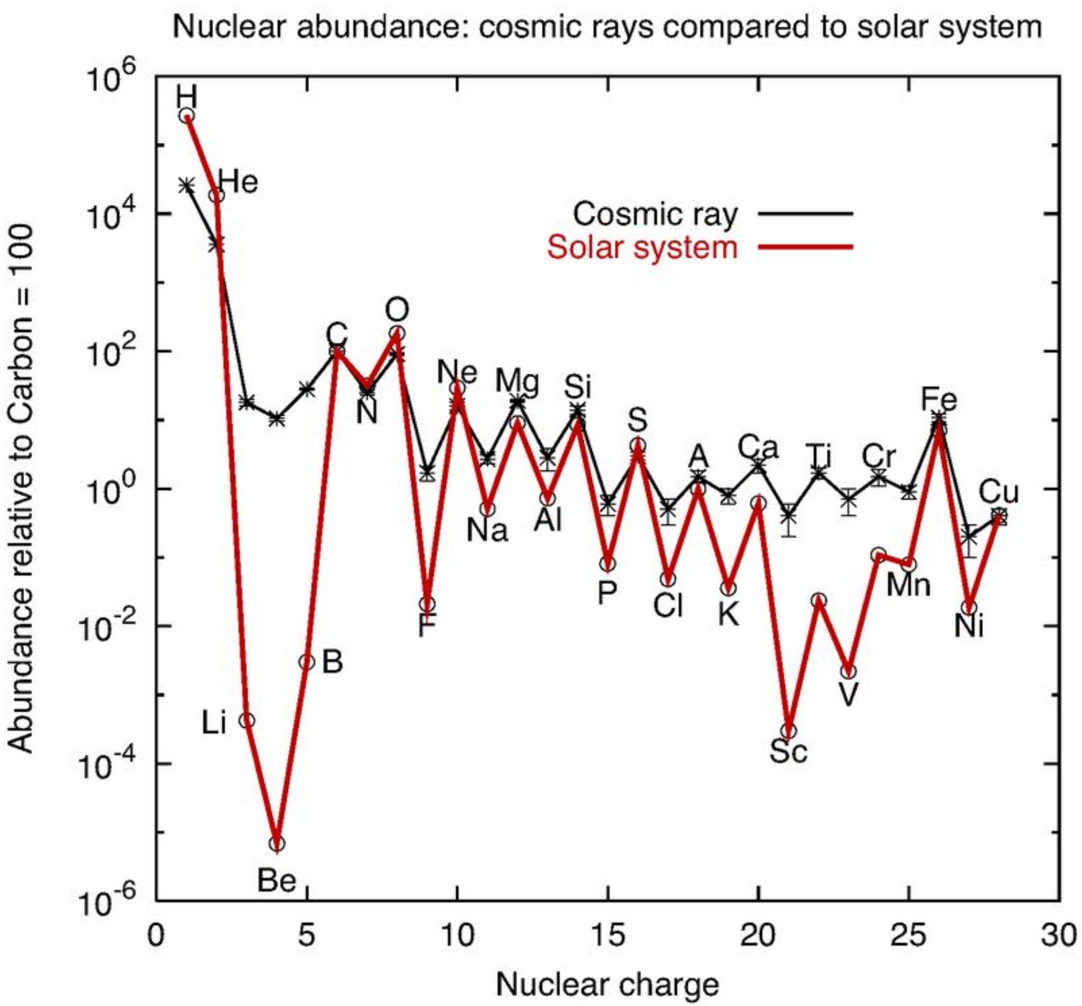


Conclusions

- ★ Universe as a huge cosmic accelerator: ***complement*** to (ground) ***particle experiments***.
- ★ Continues surprises (e.g. *The BOAT*) leading to worldwide collaborative networks to *never miss a thing*.
- ★ ***Astroparticle physics*** getting richer:
  - More ***frequencies*** (HE, VHE, UHE γ rays)
  - More ***messengers*** (γ, ν, GW)
  - More ***phenomena*** (explosions, mergers, interactions, accretion)
  - More ***sources*** (GRBs, FRBs, PeVatrons, diffuse fields).
- ★ Astroparticle experiments getting larger, more complex, more mature, combining technologies:
  - LHAASO
  - CTA
  - SWGO
- ★ Race for ***DM detection*** continues: who will come first?

Backup

Cosmic rays: composition



98% hadronic

- 87 % protons
- 12 % helium
- 1% other nuclei

2% electrons

< 1% other species

- antiparticles
- neutrinos
- gamma rays

Cosmic rays: (energy) spectrum

The origin of galactic cosmic rays
Astron.Astrophys.Rev, 21, 70 (2013)

cosmic rays energies extend beyond the maximum covered by particle colliders:

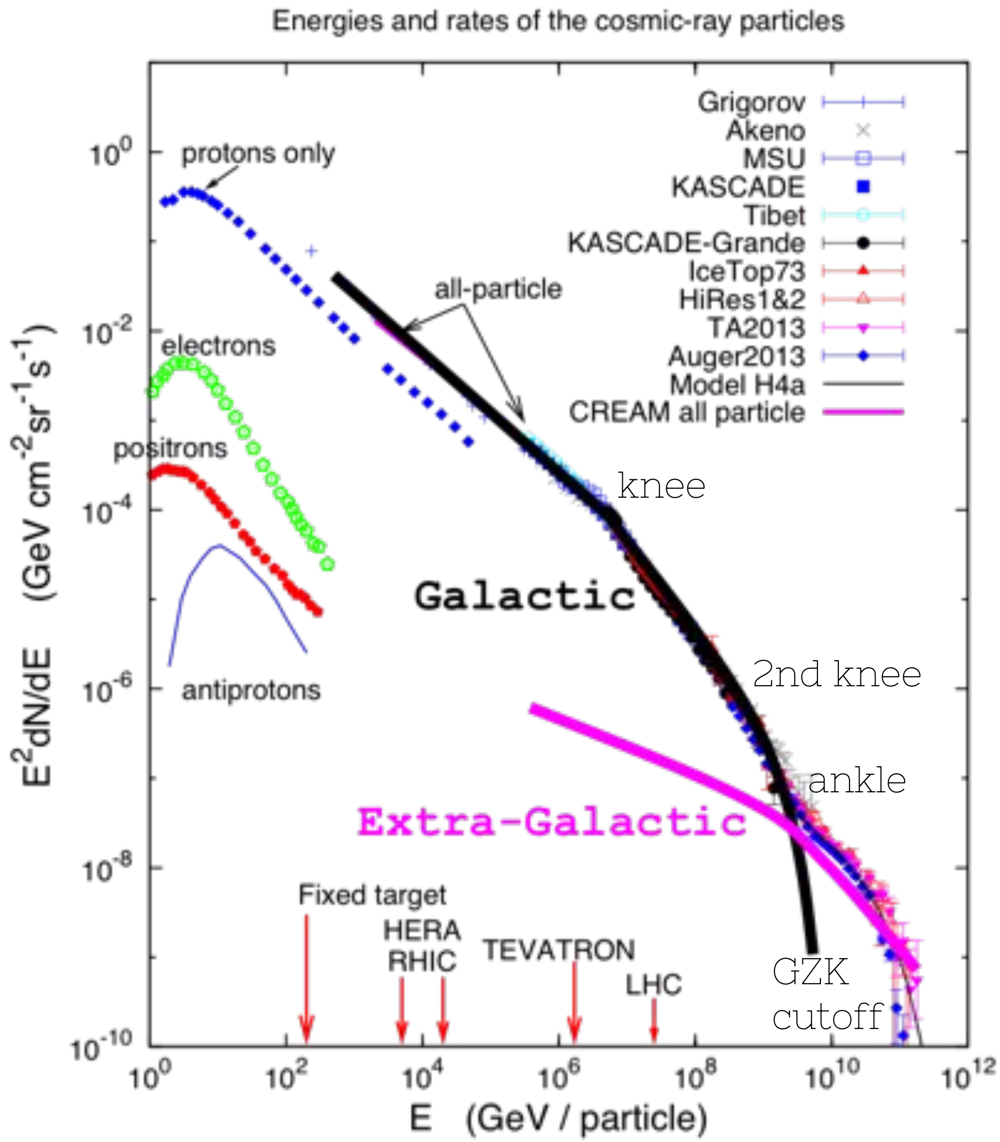
Cosmic particle accelerator(s)

- Charged particles (p,$e^{\pm}$, nuclei) deflected by intergalactic / interstellar magnetic fields
- Neutral particles (γ,ν,g) not affected. Point back to sources.

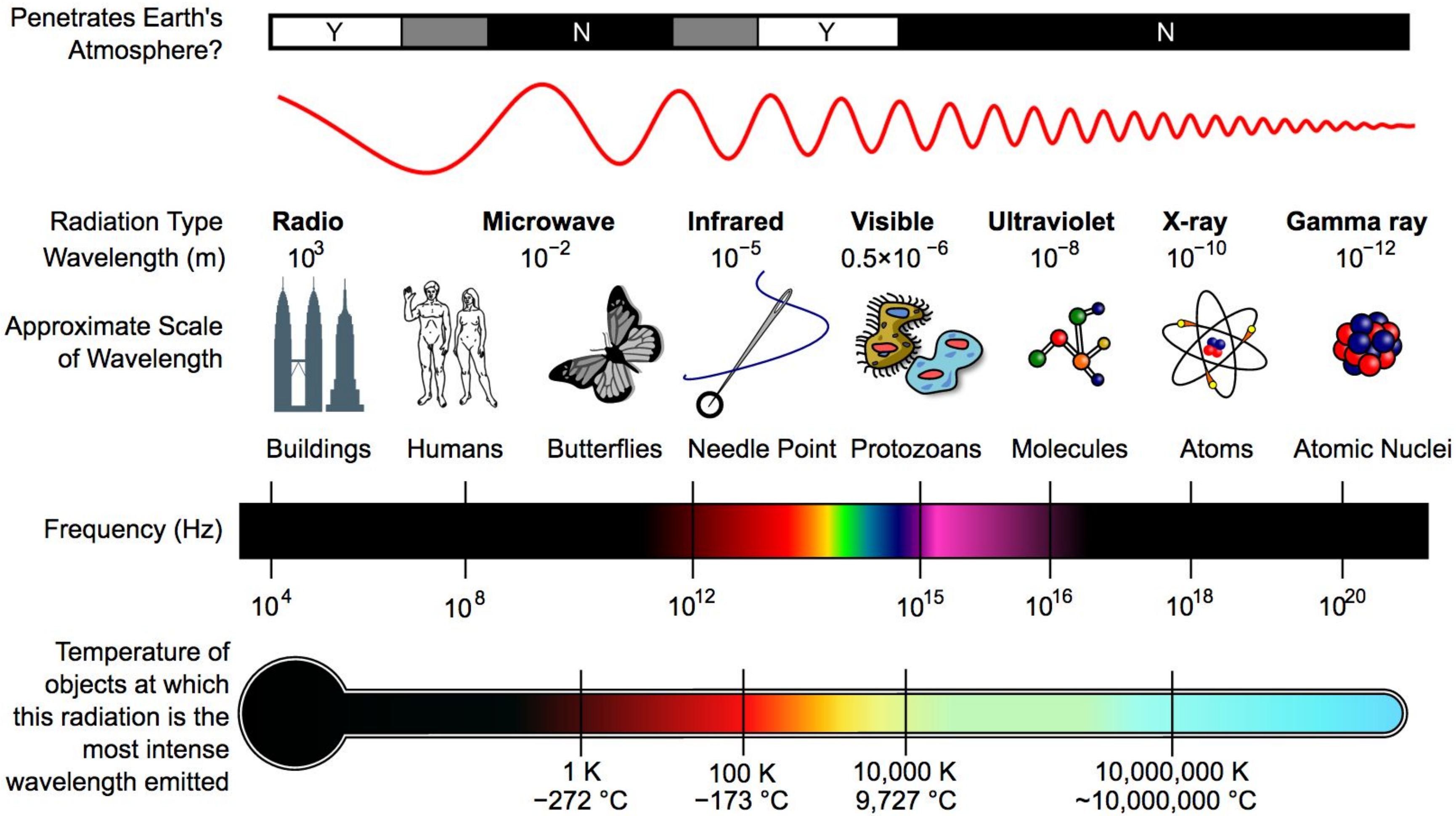
Spectral components:

- below the knee: solar CRs
- knee to ankle: galactic CRs.
- above ankle: extragalactic CRs.
- above GZK: CMB interaction.

Gamma rays: ***astronomy*** of the most violent phenomena in the Universe

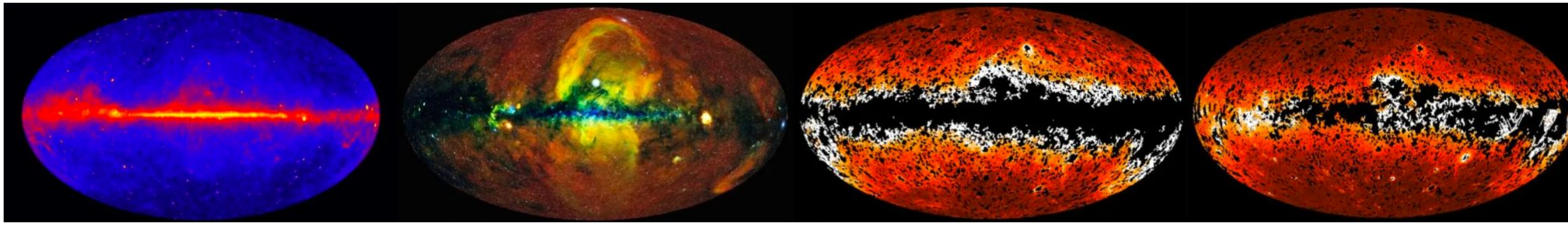


Atmospheric windows: The electromagnetic spectrum

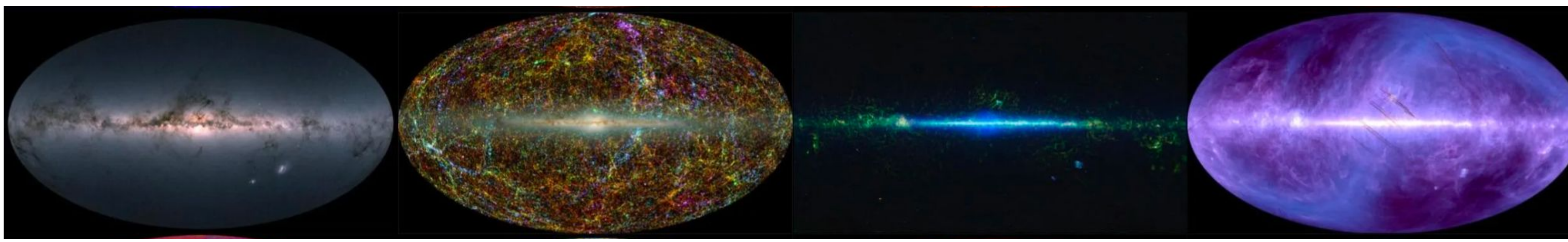


Credits: Wikimedia Commons user Inductiveload, NASA

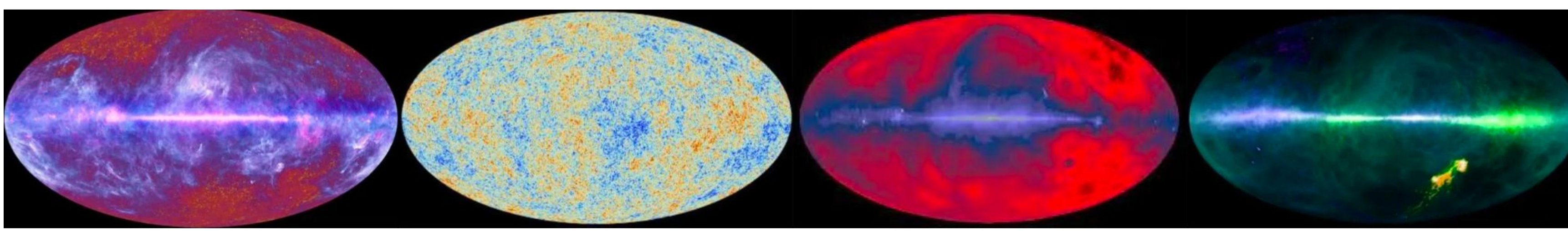
Atmospheric windows:
The electromagnetic spectrum



γ rays (LAT) | X-rays (eROSITA) | FUV (GALEX) | NUV (GALEX)



Optical (Gaia) | Near IR (2MASS) | Infrared (WISE) | Far IR (AKARI)



submm/857 GHz (Planck) | CMB (Plank) | Radio / 408 MHz Jodrell Bank, Effelsberg, Parkes | Hydrogen – 21cm Effelsberg, Parkes

High Energy (HE) gamma-rays, E > 100 MeV

DAMPE (HE γ rays, e−, ~ TeV CRs). CAS, **since** Dec. 2015

Results:

- **Direct detection of a break in cosmic e±** (*Nature, 552, 7683*)
- CR proton spectrum from 40 GeV to 100 TeV (*Science Advances, vol. 5, issue 9*)

CALET (onboard the ISS), JAXA. **since** Aug. 2015

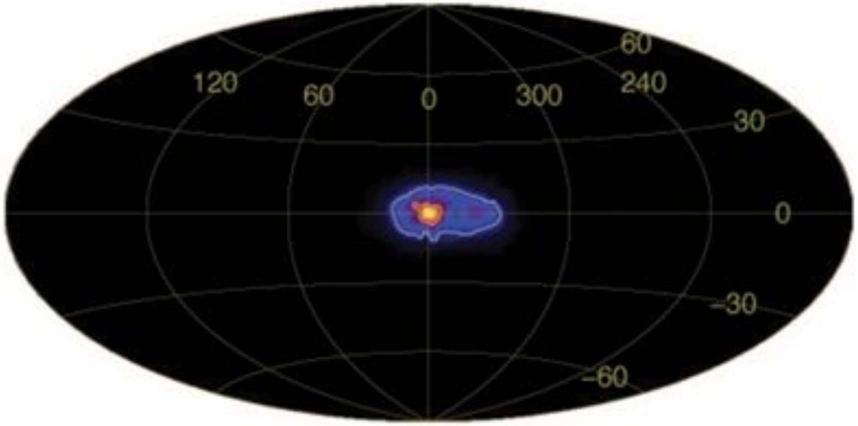
Recent results & developments:

- CR e± spectrum (100 GeV to 4.8 TeV, *PhysRevLet 120, 261102*)
- Improved gamma reconstruction (presented at ICRC '23)

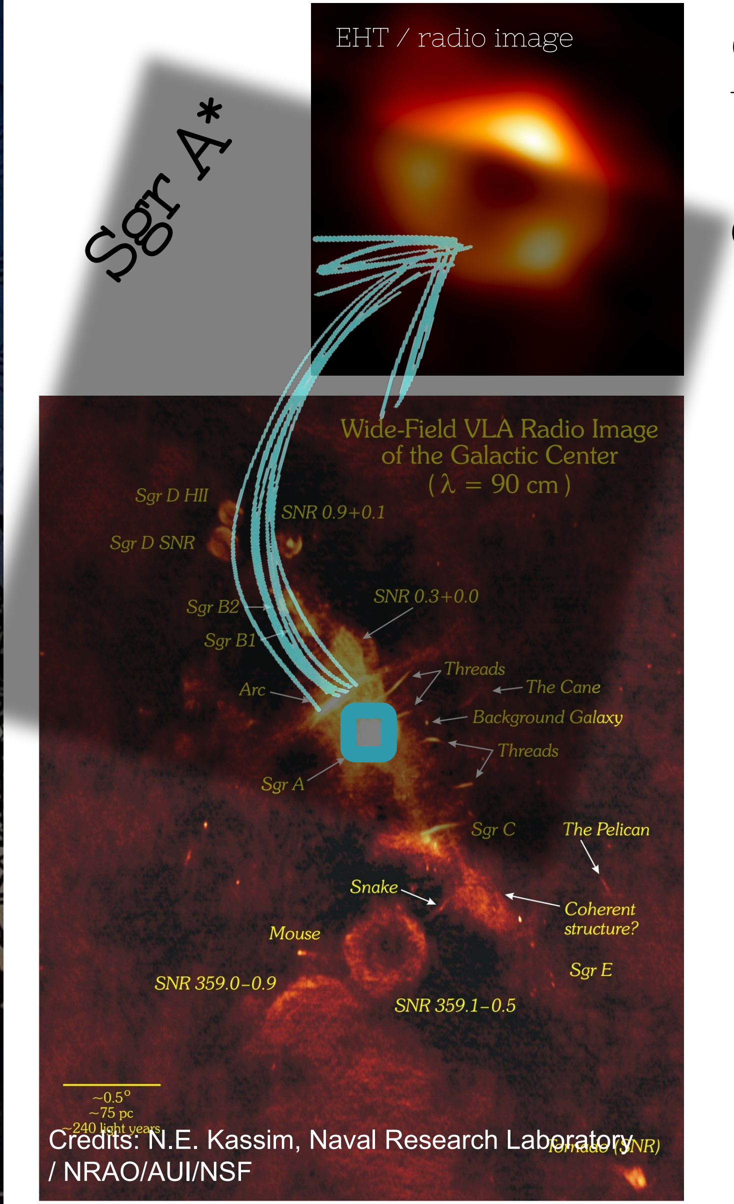
INTEGRAL (low-energy γ rays + X-rays + optical monitor). ESA. **since** 2002 !!

Some results:

- 700 new hard X-rays.
- 511 keV large-scale sky map annihilation) with Galaxy center.



Many discoveries



Credits: N.E. Kassim, Naval Research Laboratory / NRAO/AUI/NSF

CRs up to the knee from Galactic origin, but … which sources?

Candidates (emission beyond ~100 TeV):

- **Galactic center / Sgr A*** (*JCAP 4, 37; Nature 531, 476–479*)
  - Emission up to 50 TeV
  - parent protons with energies ~ 1 PeV (if produced by CRs diffusing away and emitting through π^0 – decay from pp interactions),
  - rate not enough to explain the rate of observed galactic CRs,

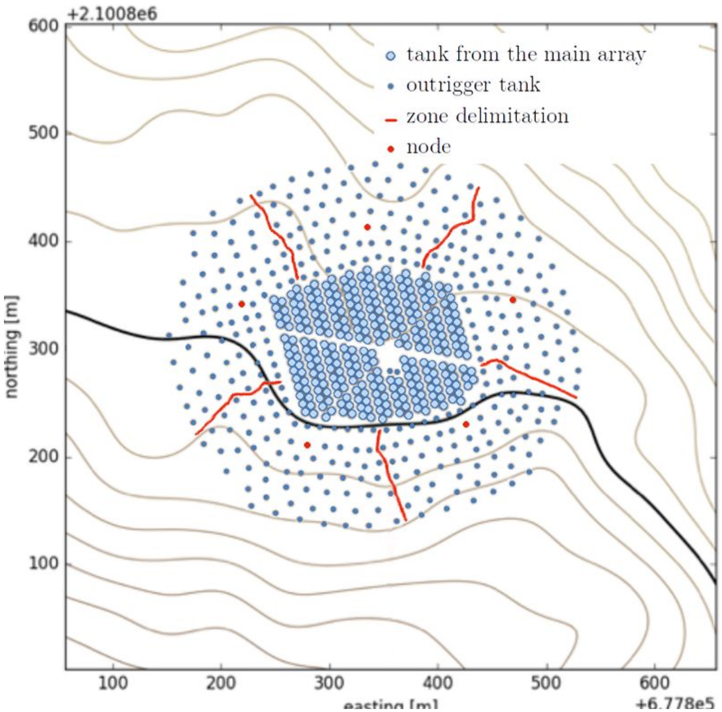
HAWC: upgrade

Upgrade

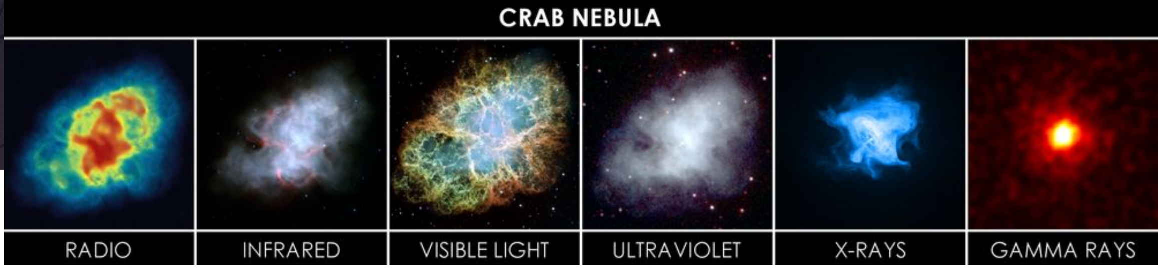
The problem: many events above 10 TeV (effective area 10^5 m^2) with cores outside the array → large leakage → bad reconstruction.

The solution: Sparse Outrigger Array. ~200 small water Cherenkov detectors (2.5 m^3 vs 180 m^3) over 4 × ~20,000 m^2. Finished in August 2018.

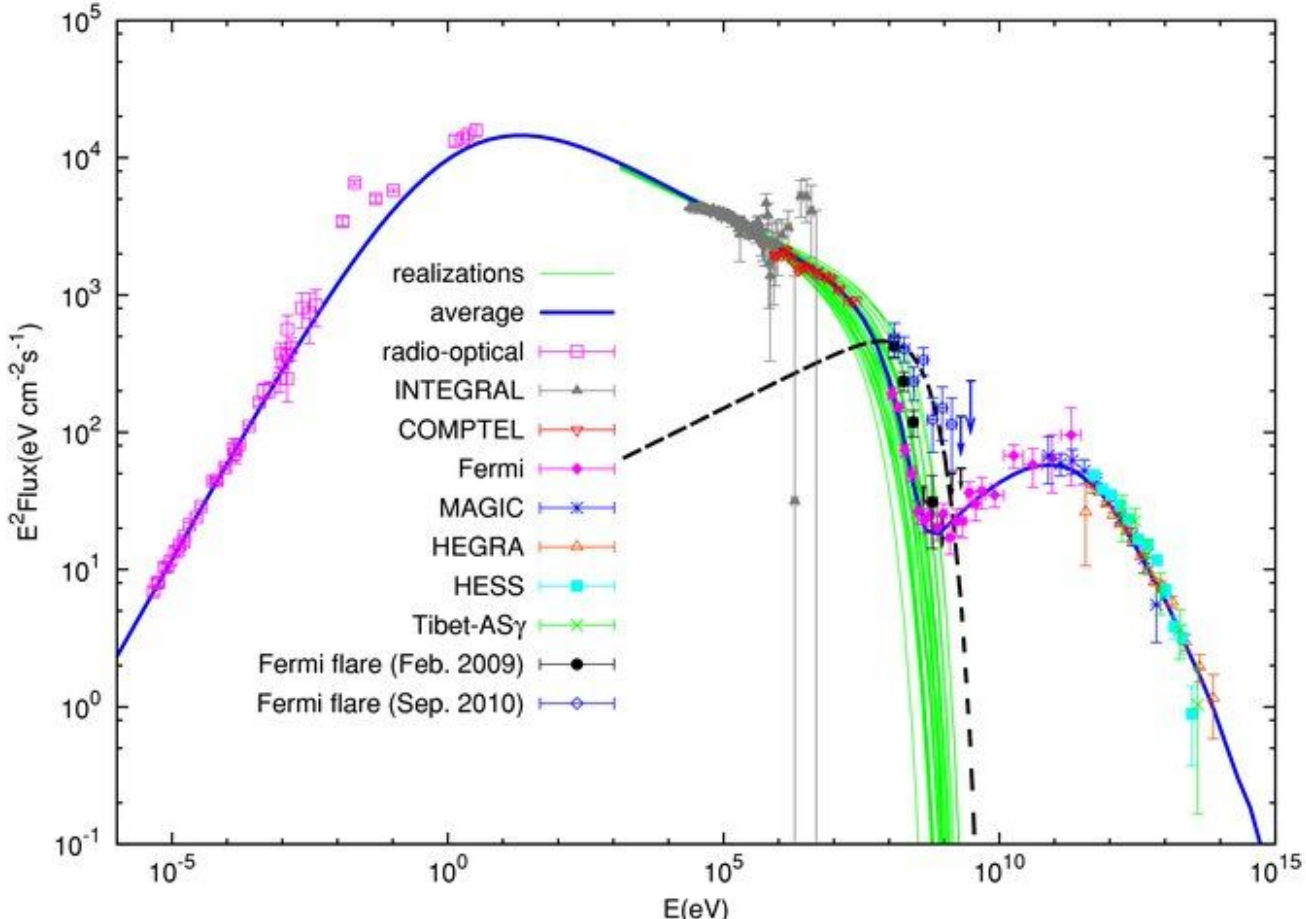
Improvement: Increase a factor 3-4 the high energy showers contained in the 'extended' array.



Crab Nebula



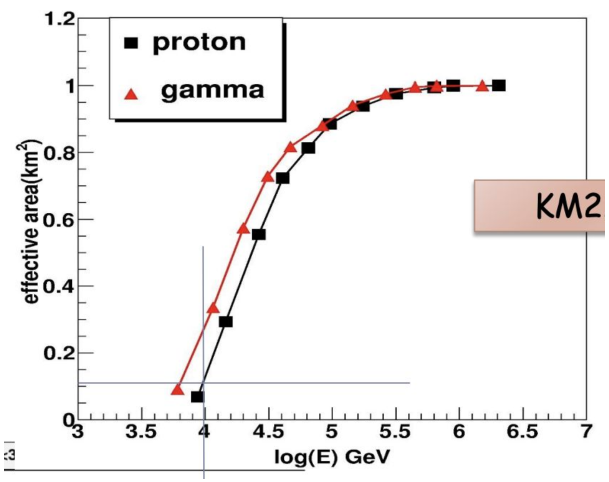
'Standard candle'. Stable, except when it flares

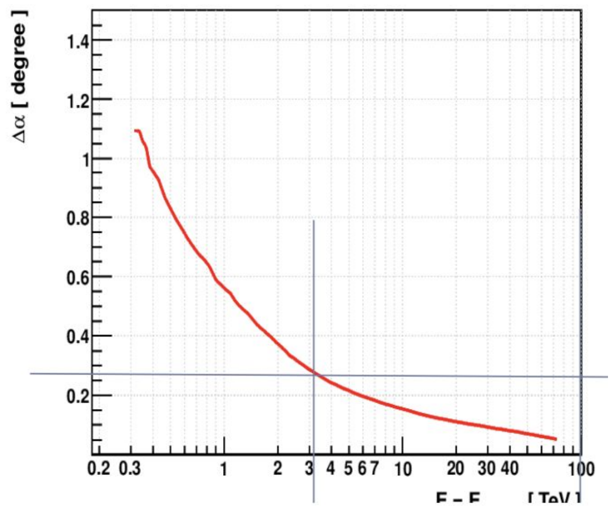


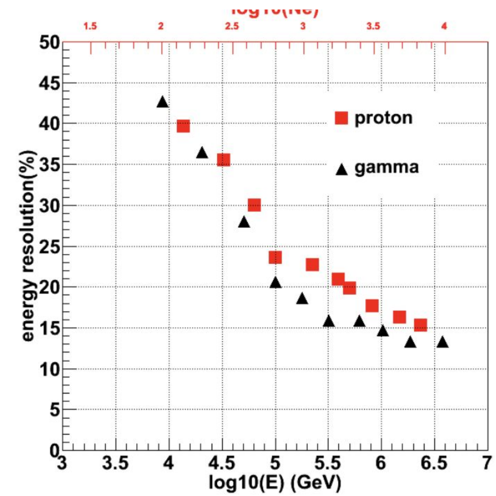
Q. Yuan et al. ApJL 730 (2): L15

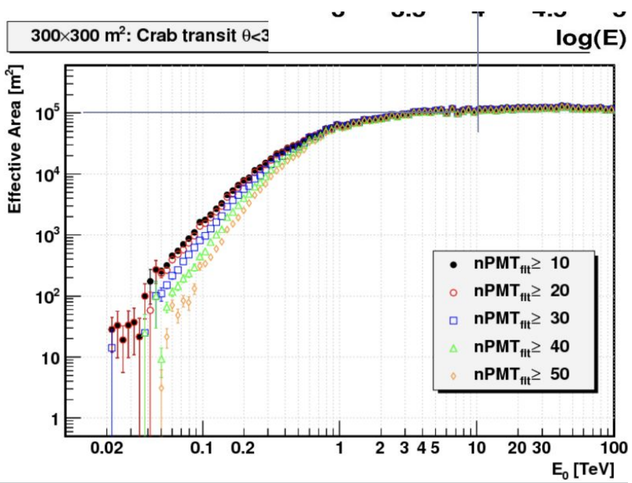
LHAASO: performance

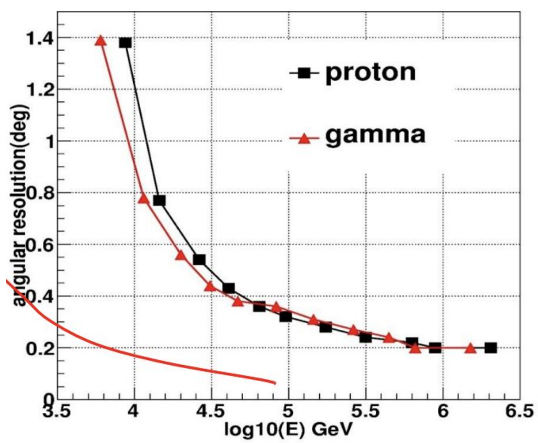
hybrid high-altitude (4410m a.s.l, Sichuan, China) γ-ray observatory of several ***detector arrays*** covering an area of ***1.36 km²***.

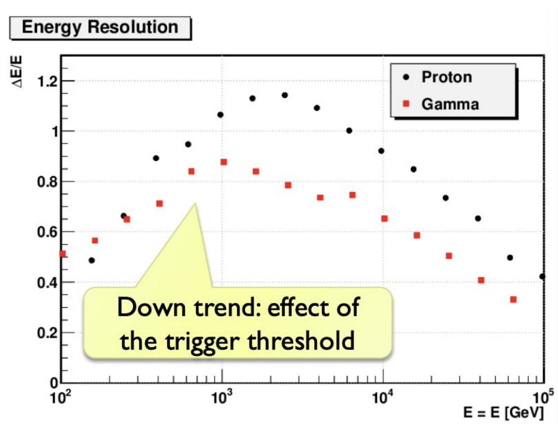








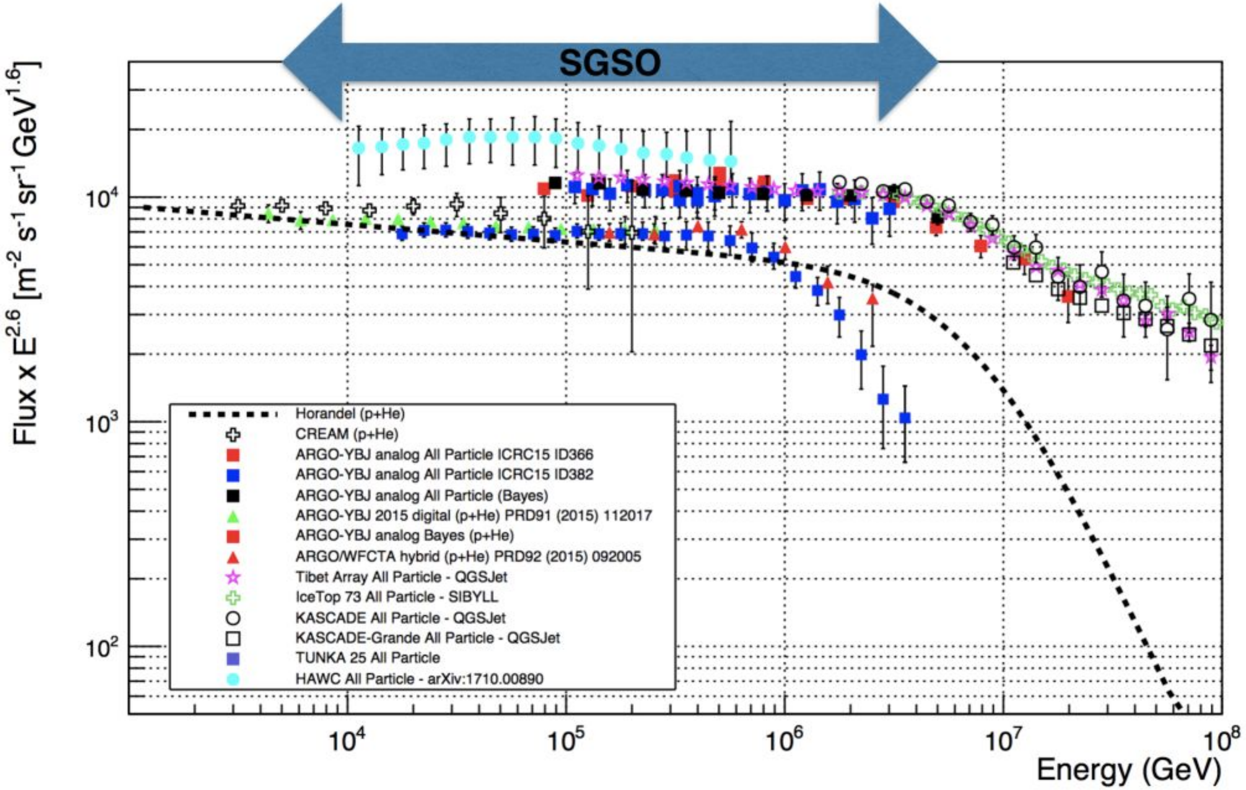




SWGO: science cases

Cosmic rays:

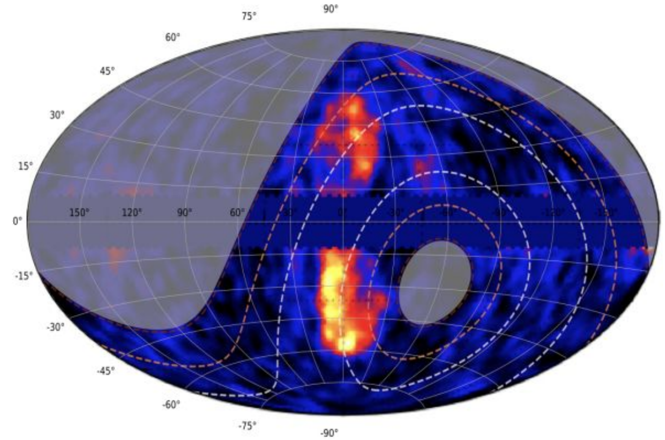
- *Spectrum and composition:* 5 mass groups (p, He, CNO, MgSi, Fe) up to 10^{17} eV.
- *Anisotropy*: first 10 TeV skymap of cosmic ray anisotropy produced with IceCube + HAWC.
- *Electron spectrum and anisotropy*
- *Space weather* / heliospheric physics

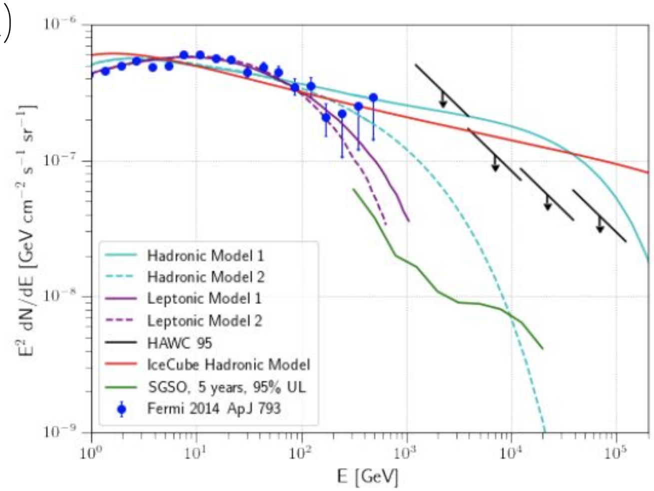


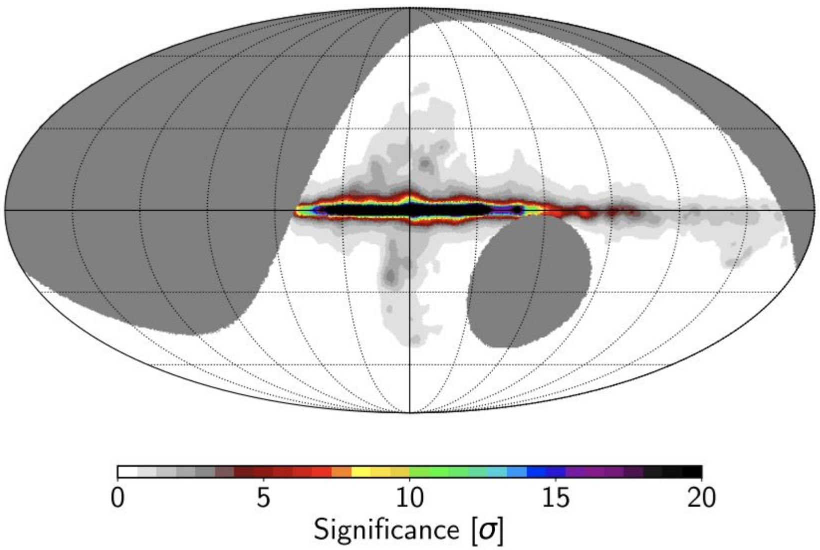
SWGO: science cases

Particle accelerators:

- *Pulsar emission / halos:* (Geminga-like) origin of positron excess seen by PAMELA & AMS ?
- *Fermi bubbles*: if extending up to ~ TeV.
- *Pevatrons, SNRs:* SNRs still main candidates for CRs up to the knee (Energy budget and spectrum).
- Unbiased survey of the *Galactic Plane*
- The *Galactic Center*
- Star-forming regions (only a few in the TeV band)
- *Galactic diffuse emission* (needs large FoV and careful background modelling)



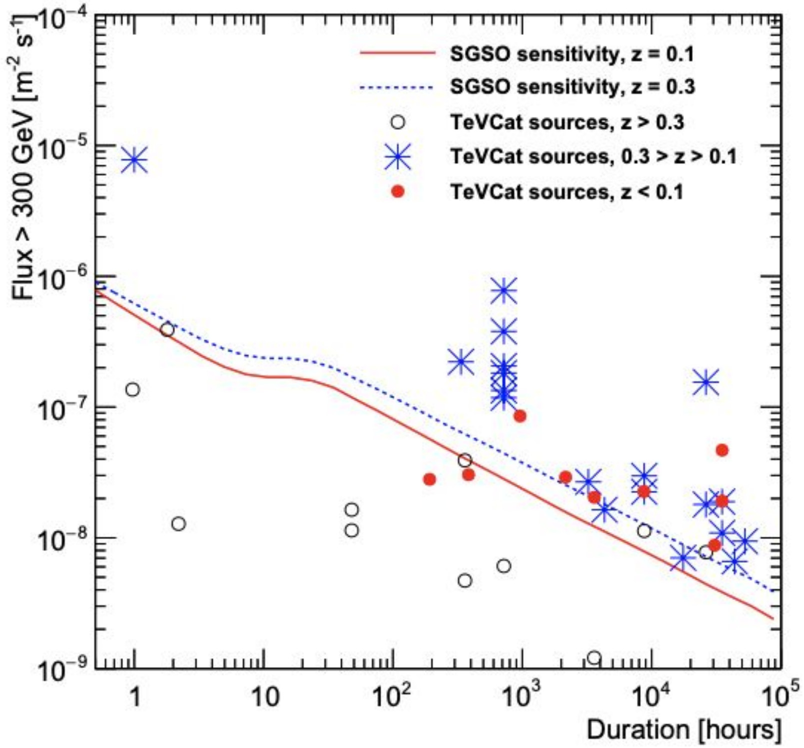


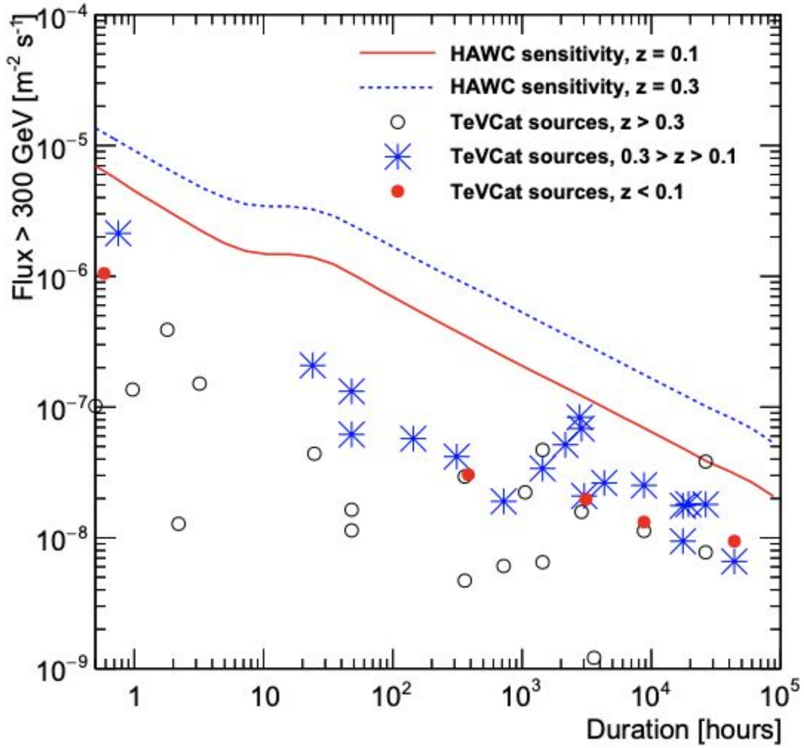


SWGO: science cases

Transients:

- Active Galactic Nuclei: (extreme) blazars, variability and periodicity (duty cycle).
- Cosmic voids and Intergalactic Magnetic Field (IGMF).

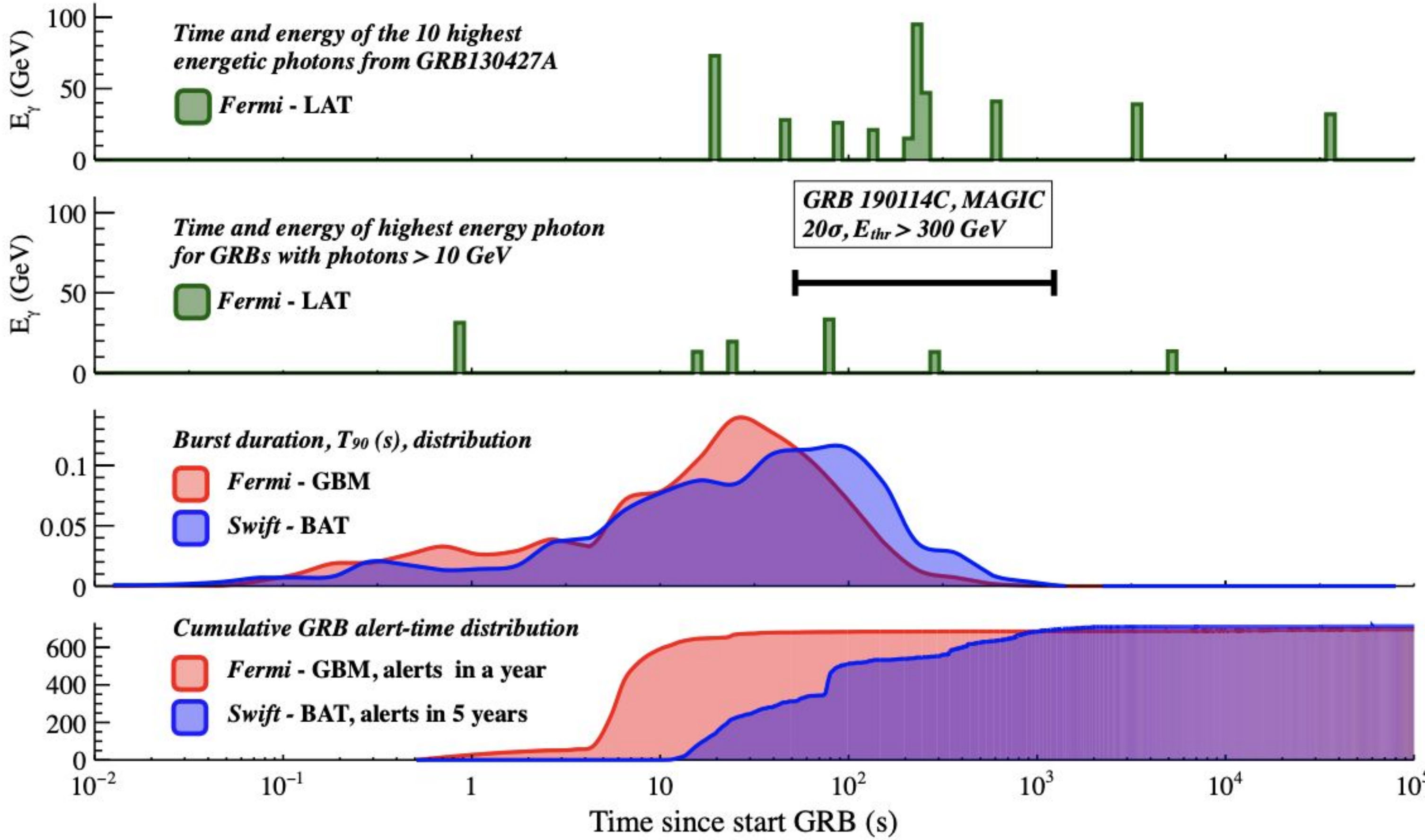




SWGO: science cases

Gamma-Ray Bursts & GW

- The BOAT missed (in IACTs) because of the Moon. Many other GRBs missed because daytime or weather conditions.
- GW from neutron star mergers to provide additional targets.



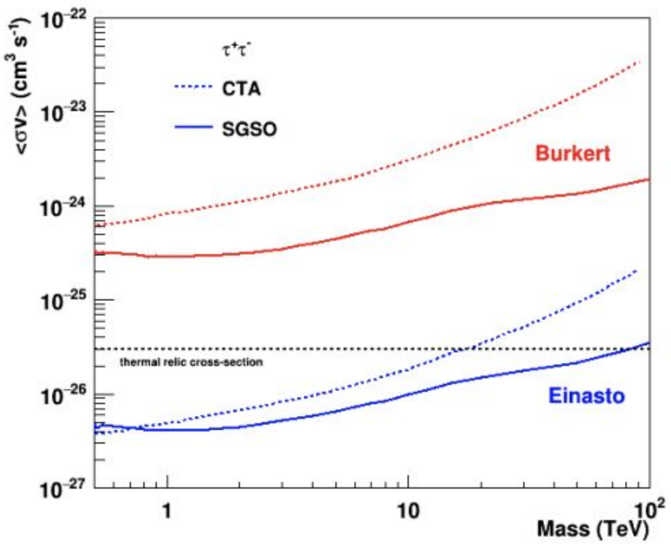
SWGO: science cases

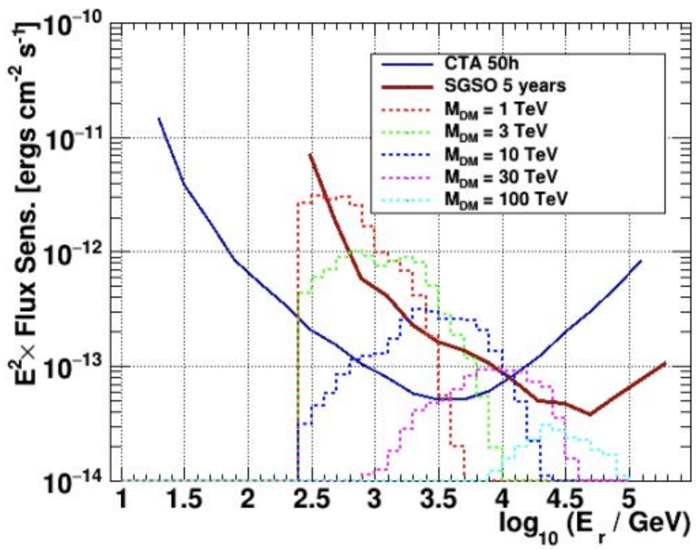
Dark matter & primordial black hole searches

- Galactic halo
- Dwarf spheroidal (satellite) galaxies
- PBH may evaporate producing high-energy gamma-ray bursts.
- Axion-like particles (ALPs) through the study of the EBL.

Lorentz invariance violation

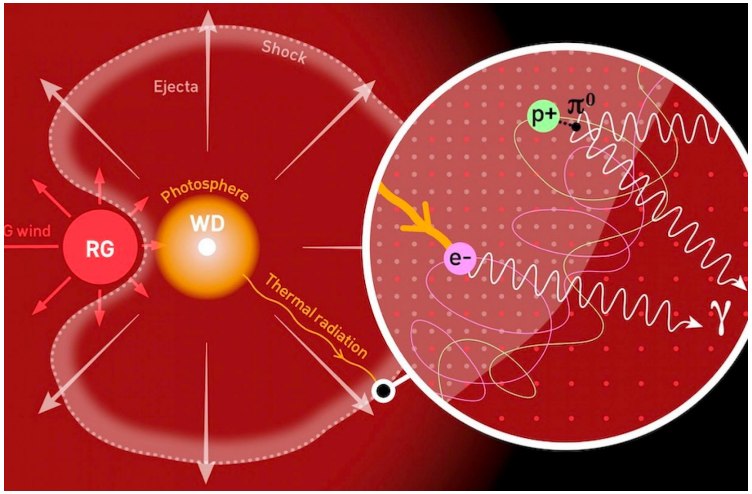
- From spectral features
- From variability





IACTs: results / Galactic

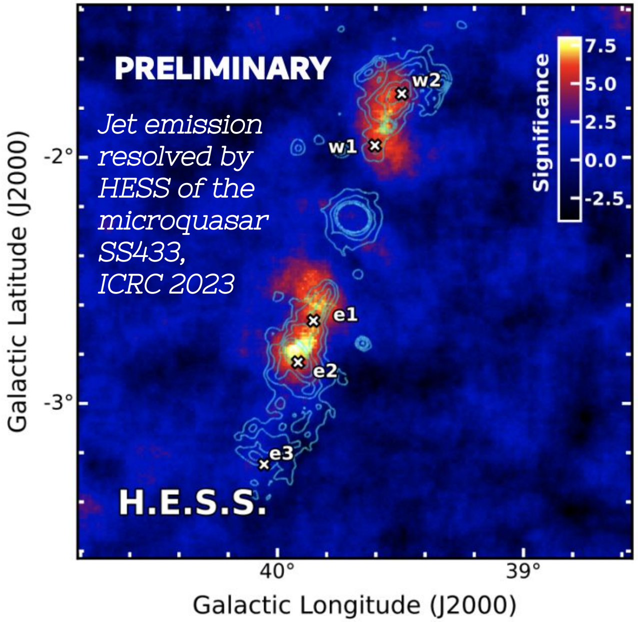
Hadronic emission from RS Oph novae, MAGIC (NatAst, 6, 689-697, 2021)



Pulsars:
- ❑ Crab (up to 2 TeV). Vela (HESS), Geminga (MAGIC, LST-1). Cutoff + PWL extension to VHE.

Binaries:
- ❑ SS 433: spectral modelling, morphology.
- ❑ PSR B1259-63 (binary pulsar)

Galactic center:
Dark matter origin? PeVatron?



Novae:
- ❑ **RS Ophiuchi**: symbiotic nova detected in 2021 by HESS, MAGIC, LST-1. Proton acceleration. *Sci 376, 6588; NatAst, 6, 689-697*)

Other transients:
- ❑ FRBs, SNe, etc.

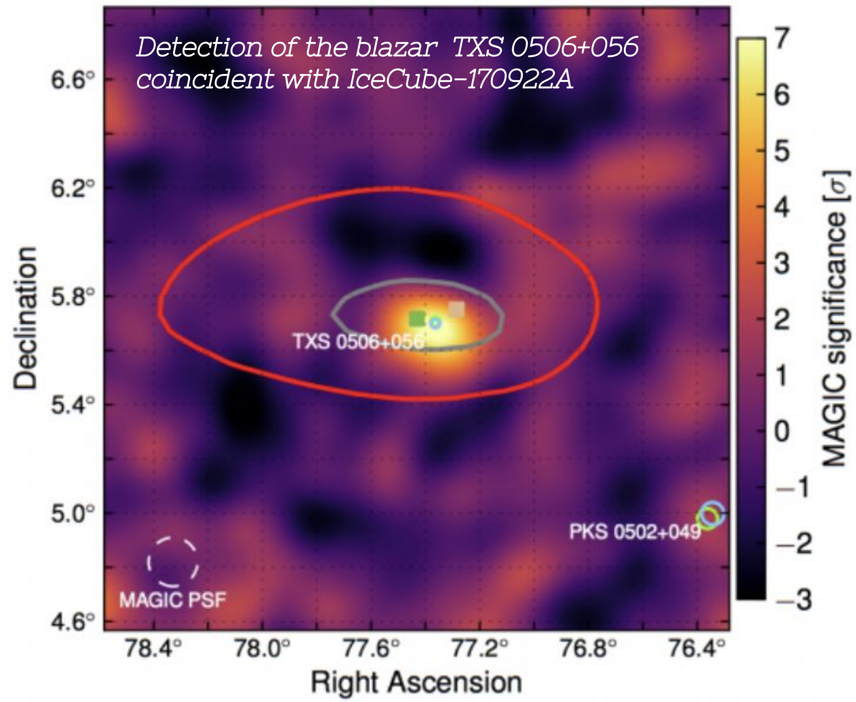
Extended sources:
- ❑ MGRO J1908+06 (VERITAS)

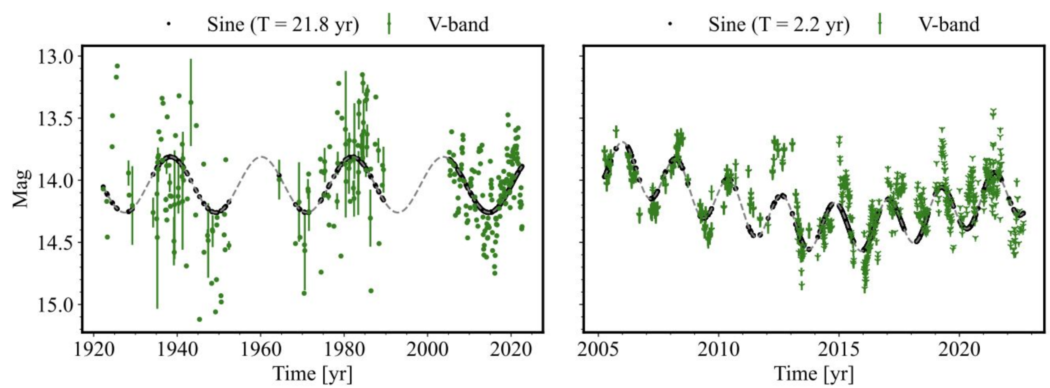
IACTs: results / Extragalactic

Blazars

Too many new advances to list here

- **Theory**: more detailed models and simulations of structured jets, lepto-hacronic, multi-zone and jet-ISM interactions.
- **~ 85 blazars** detected in VHE. Most are BL Lacs, a few FSRQs.
- **Hot topics:** extreme blazars, binary systems (e.g. PG 1553+113), etc.
- **Multi-wavelength** observations in most new results.
- **Multi-messenger** (synergies with IceCube) is a hot topic: TXS 0506+056 / IceCube-170922A ***Science, 361, 6398***



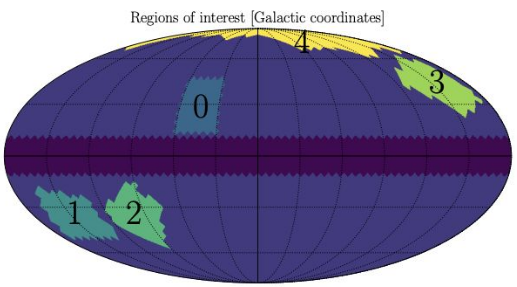


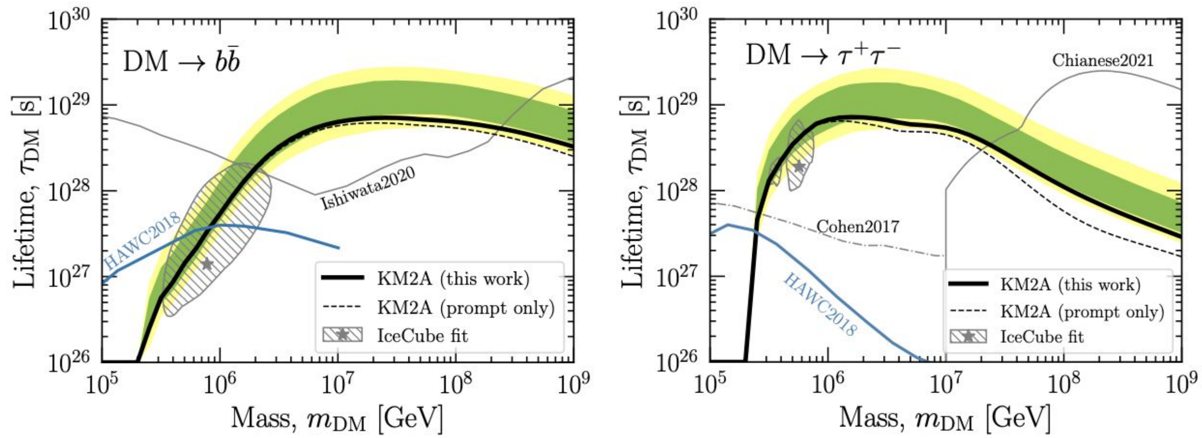
pseudo-periodicity of the (binary BH?) blazar PG 1553+113

LHAASO: DM, CRs and diffuse γ rays

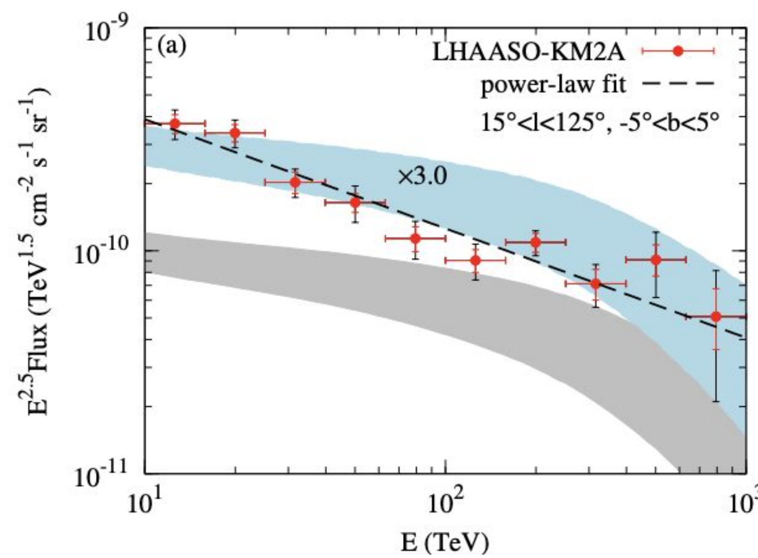
Dark matter constraints (*Phys. Rev. Lett. 129, 261103*)

- Region 0: close to GC
- Regions 1-4: CRs /control





Diffuse γ-ray emission from the Galactic plane (arXiv/2305.05372, accepted in PhysRevL)



Cosmic rays

One of the main goals of LHAASO is to measure CR composition and spectra for different group masses.