Gamma-ray Astronomy from Space & Ground

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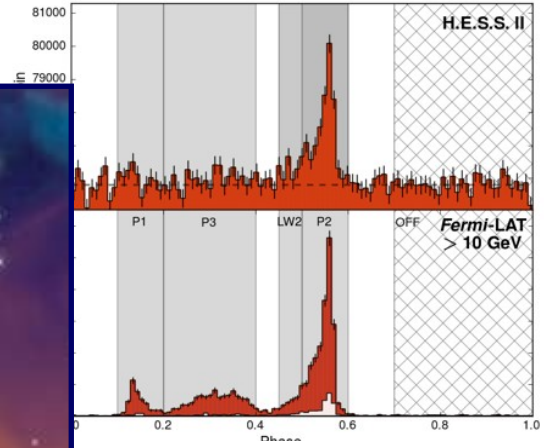
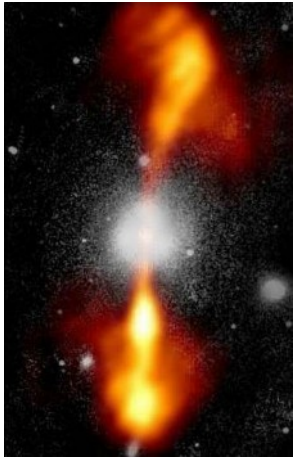
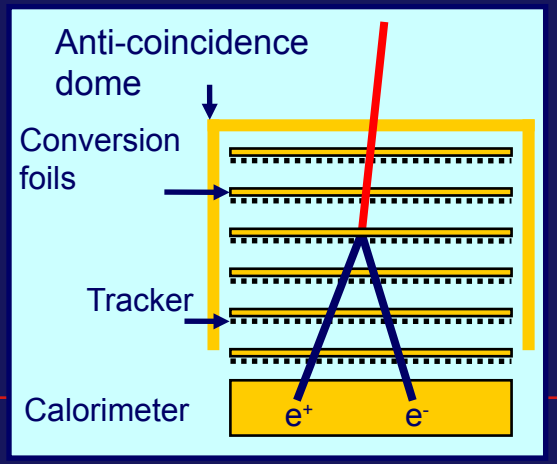
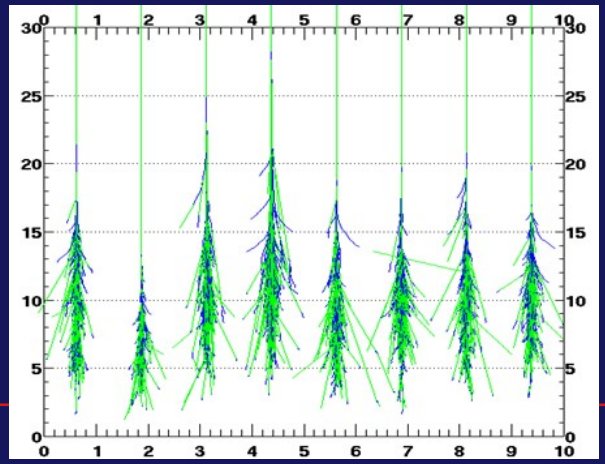


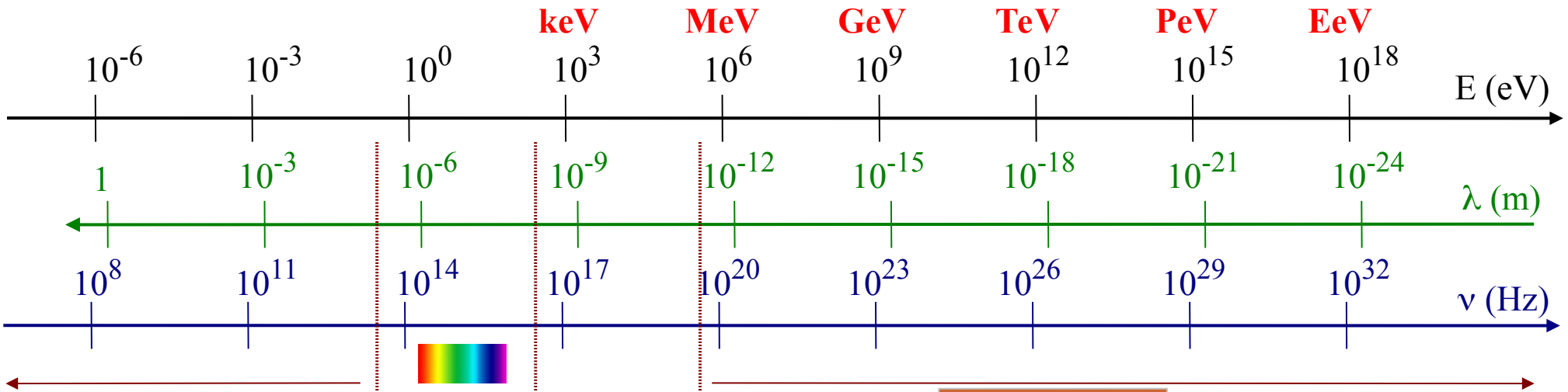


Detection Techniques & Instruments

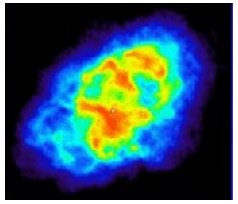




The Electromagnetic spectrum



Radio



Cold objects (10K),
Dust,...
Synchrotron emission of accelerated electrons

IR *Visible* *UV*

Hot objects
(~2000K),
sun, nebula

X rays

Very hot compact objects
(~10^{6}K),
pulsars, black holes...
Size ~km

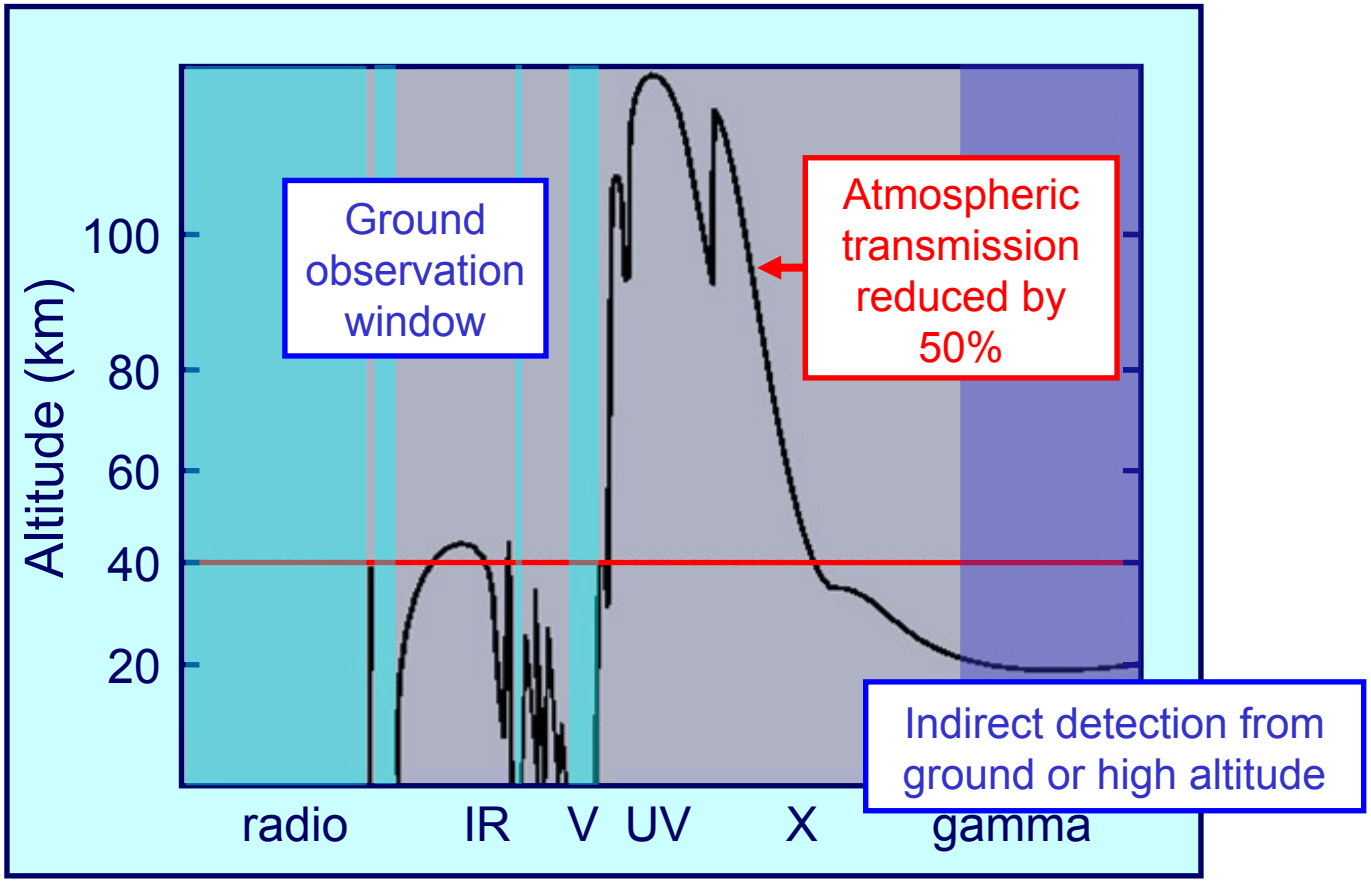
γ rays

VHE
(Very High Energy)

UHE
(Ultra High Energy)

Extreme objects, non-thermal processes
(Particle acceleration in shocks)
Inverse Compton, Bremsstrahlung, Annihilation,
Pion disintegration

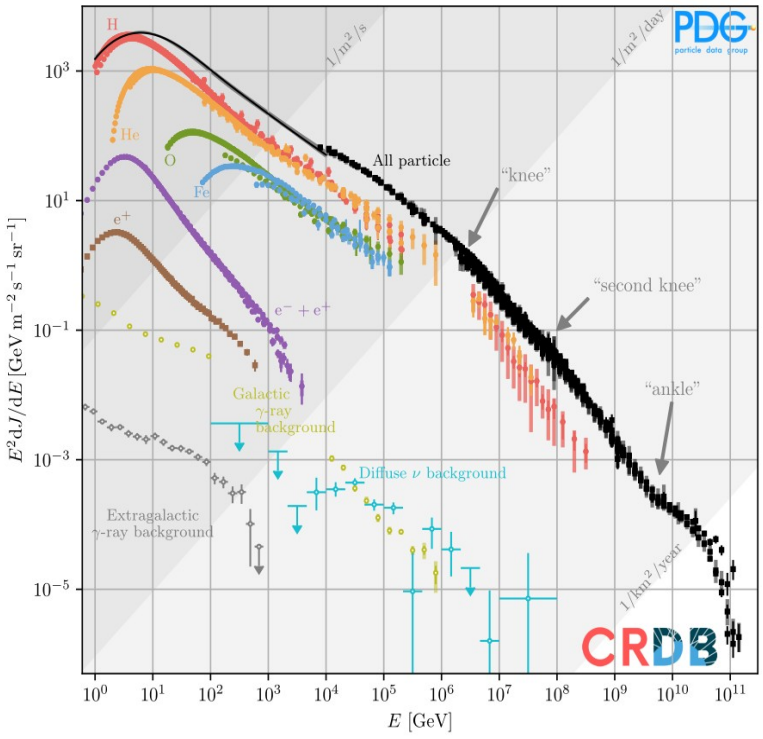
Constrains – Atmospheric transmission



Space or Ground ?

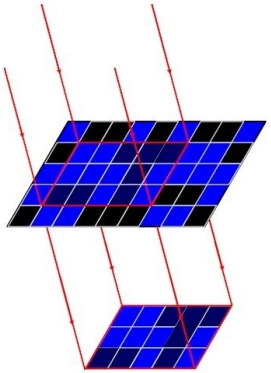
- Flux falling quickly with energy
  ⇒ Need large effective area at high energy
- Atmosphere opaque to γ-rays

- Direct detection from space
  limited to E $\lesssim$ 100 GeV (statistics)
- Indirect detection from ground
  (atmospheric showers)

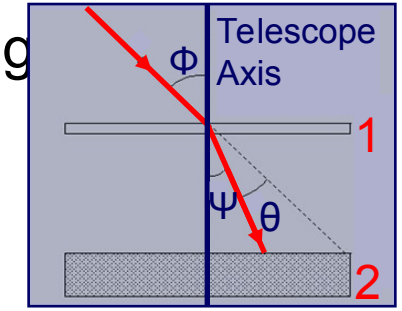


Space Instruments

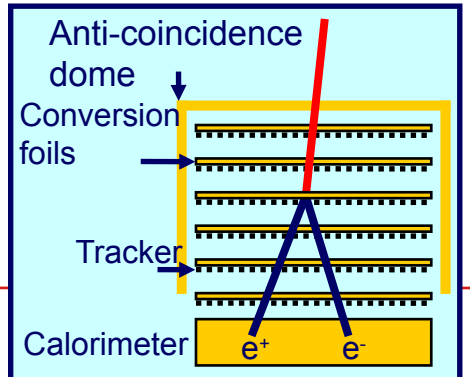
- Low energy (< 1 MeV): photoelectric effect
  ⇒ Coded mask telescope
  (Integral, Swift-BAT)



- Intermediate energy: Compton scattering
  ⇒ Compton telescope (Comptel, …)

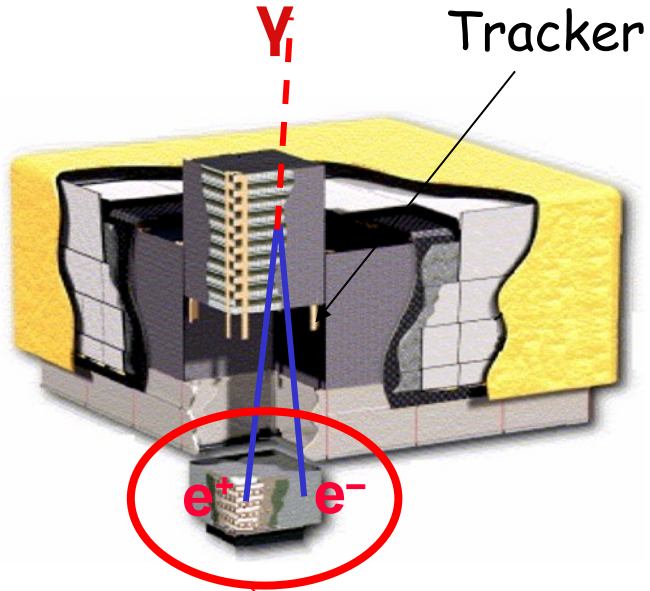


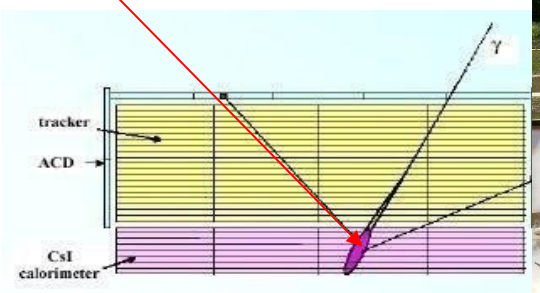
- High energy (> 10 GeV):
  pair creation telescope
  (Agile, Fermi-LAT)



Fermi-LAT

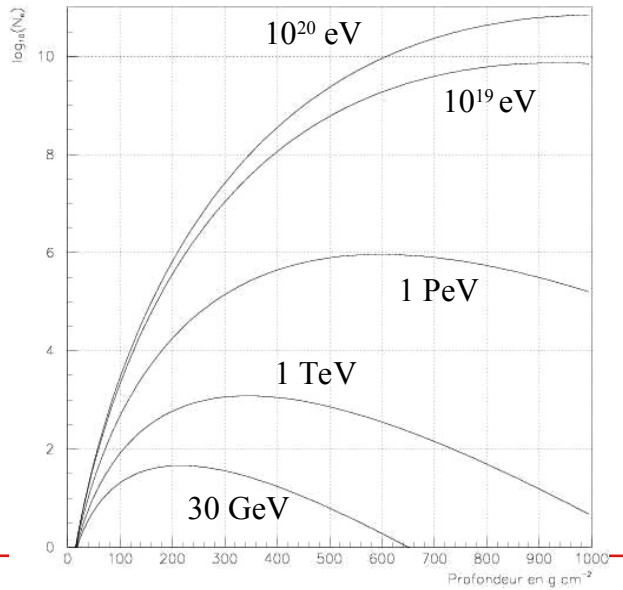
- High precision tracker
  - 18 planes X/Y, Si strips (228 µm)
  - 900 000 channels
  - Angular resolution varying with energy
    4° @ 100 MeV ⇒ 0.1° @ 10 GeV
- Hodoscopic Calorimeter
  - 1536 cristals, CsI(Tl), 8 layers
- Segmented anti-coincidence dome
  - 89 foils of scintillator
- Launched by Delta rocket June 11th 2008
- Still operating
  - one solar array failure in 2018





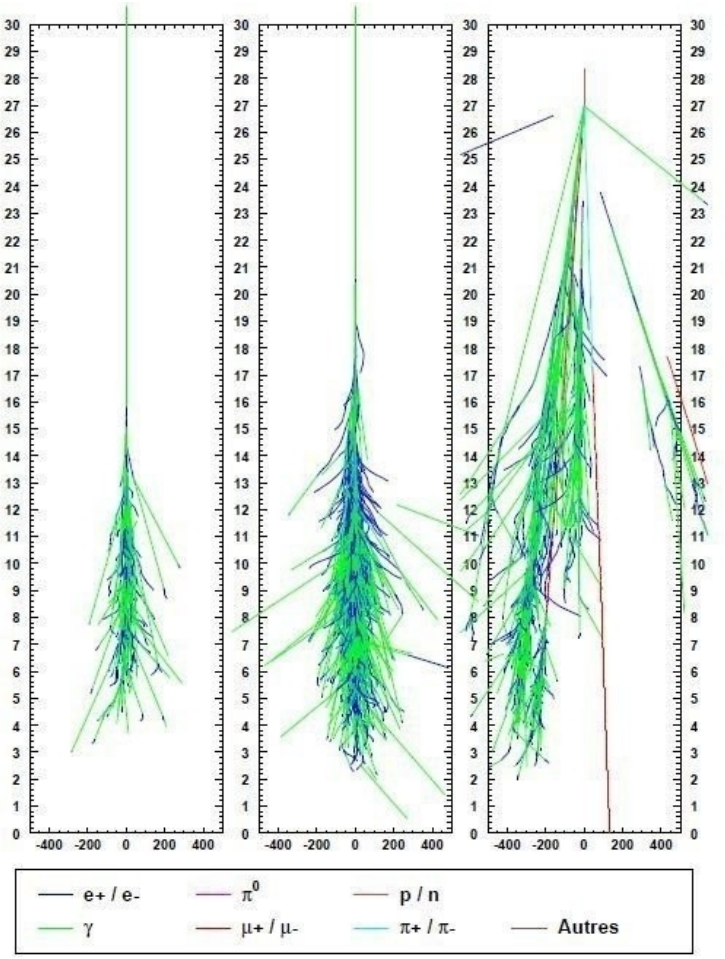
Ground-based Detection - Atmospheric Showers

- Atmosphere acts as inhomogeneous calorimeter
- Pair creation & Bremsstrahlung
  ⇒ extensive, atmospheric showers
- Additional processes in hadronic showers



Depths (g cm^{-2})

E_0	T_{max} (g cm^{-2})	Altitude (m)	N_e (t_{max})
30 GeV	216	12000	50
1 TeV	345	8000	1200
1000 TeV	600	4400	$0{,}9 \times 10^6$
10^{19} eV	936	1200	$7{,}4 \times 10^9$
10^{20} eV	1021	0	$7{,}0 \times 10^{10}$



Ground-based Detection
(E > 10 GeV)

TIBET
LHAASO

Primary (γ,hadron)

Atmospheric
Shower

Scintillator
or water

μ

Primary (γ,hadron)

Atmospheric
Shower

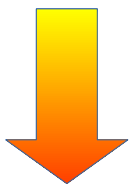
Cherenkov
Emission

Cherenkov
Telescope

Comparison

IACTs

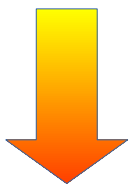
- Good angular & energy resolution
- Good background rejection (image shape)
- Small field of view (a few °)
- Small duty cycle (dark nights)



- Deep analysis of selected targets

Sampling Experiments

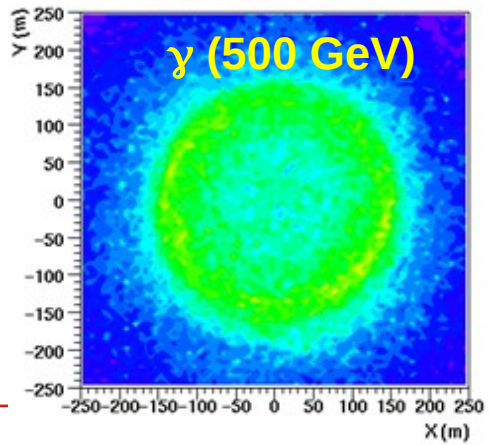
- Large field of view
- Large duty cycle
- Poor resolution
- Poor background rejection

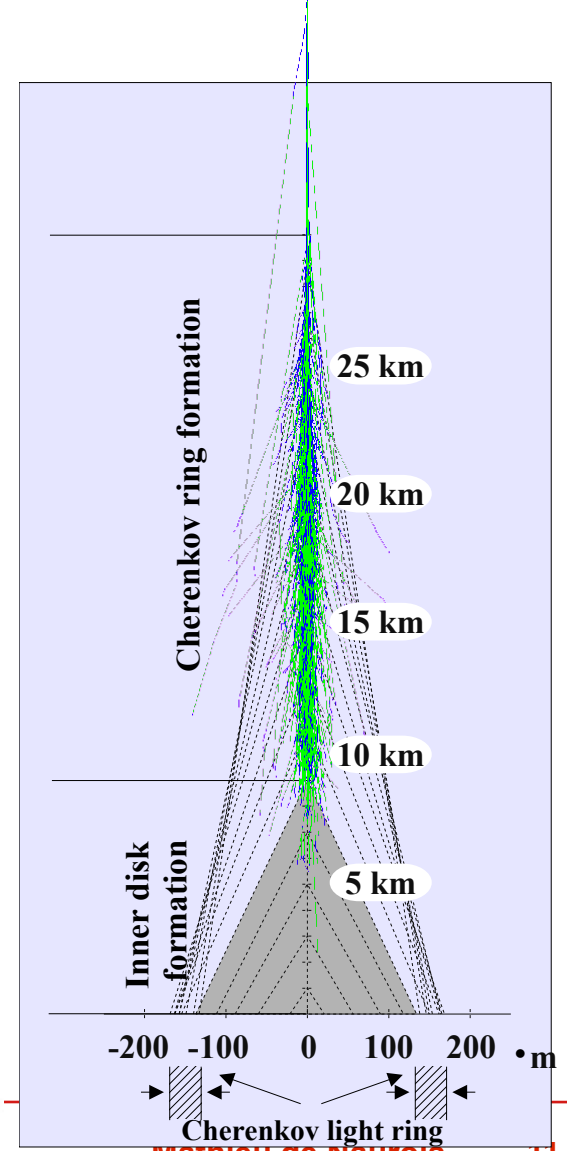


- Large surveys

Cherenkov Emission

- Opening Angle: $\cos\theta = \frac{1}{n}$
- Refractive Index : $n - 1 \propto \rho(z)$
- Density : $\rho(z) \propto \rho_0 \exp\left(-\frac{z}{z_0}\right)$
- Angle varies from ~ 1.4° at see level to 0.30 at 30 km
- Very brief (~ ns) emission, ring-shaped emission





Very High Energy ɣ-ray World

High Energy Stereoscopic System (H.E.S.S.)

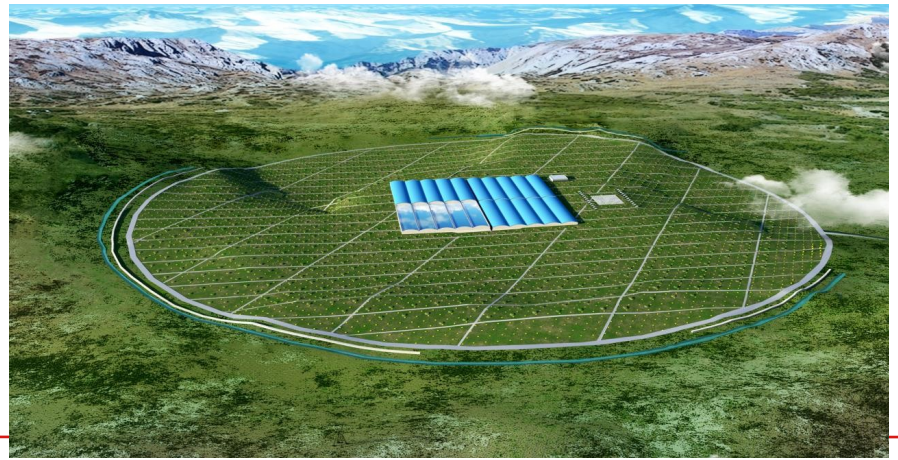
- Array of 4+1 Cherenkov telescopes located on Khomas Highland, Namibia (1800 m)
  - H.E.S.S. phase 1 (09-2002):
  - 4 telescopes: Ø 12 m,107 m^2
  - Stereoscopic reconstruction
  - 960 PMTs/camera, Field of view : 5°
  - Observations : ~1000h/year
  - Source position : ~ 10''
  - H.E.S.S. phase 2 (09-2012):
  - 5^{th} telescope, Ø 28 m, 600 m^2 (largest IACT in the world)
  - 2048 PMTs, Field of view : 3.5°
    → Energy threshold (zenith) ~ 30 GeV

Ask AI

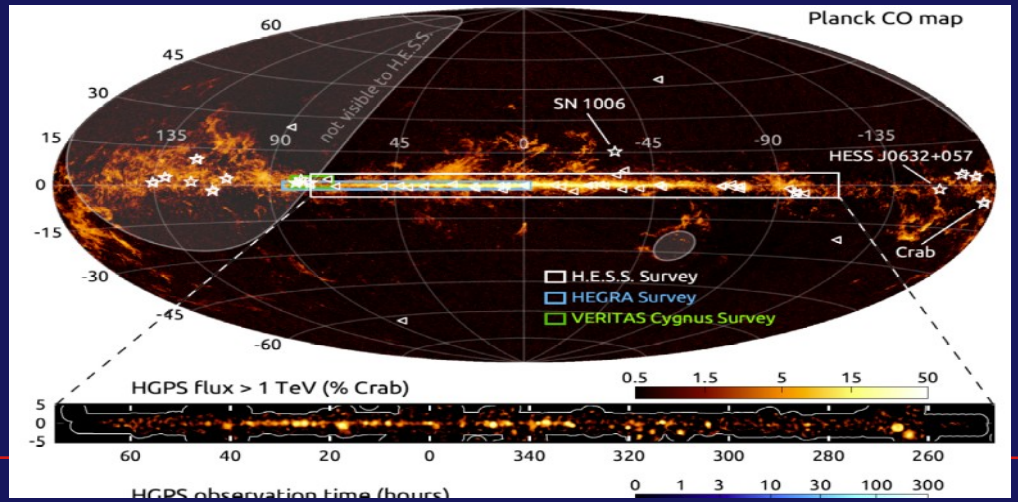
Sampling experiments

- HAWC – High Altitude Water Cherenkov
  - Altitude: 4100m, Mexico
  - 20000 m^2 covered with 300 water Cherenkov detectors equipped with 1200 PMTs
  - Inaugurated in April 2015

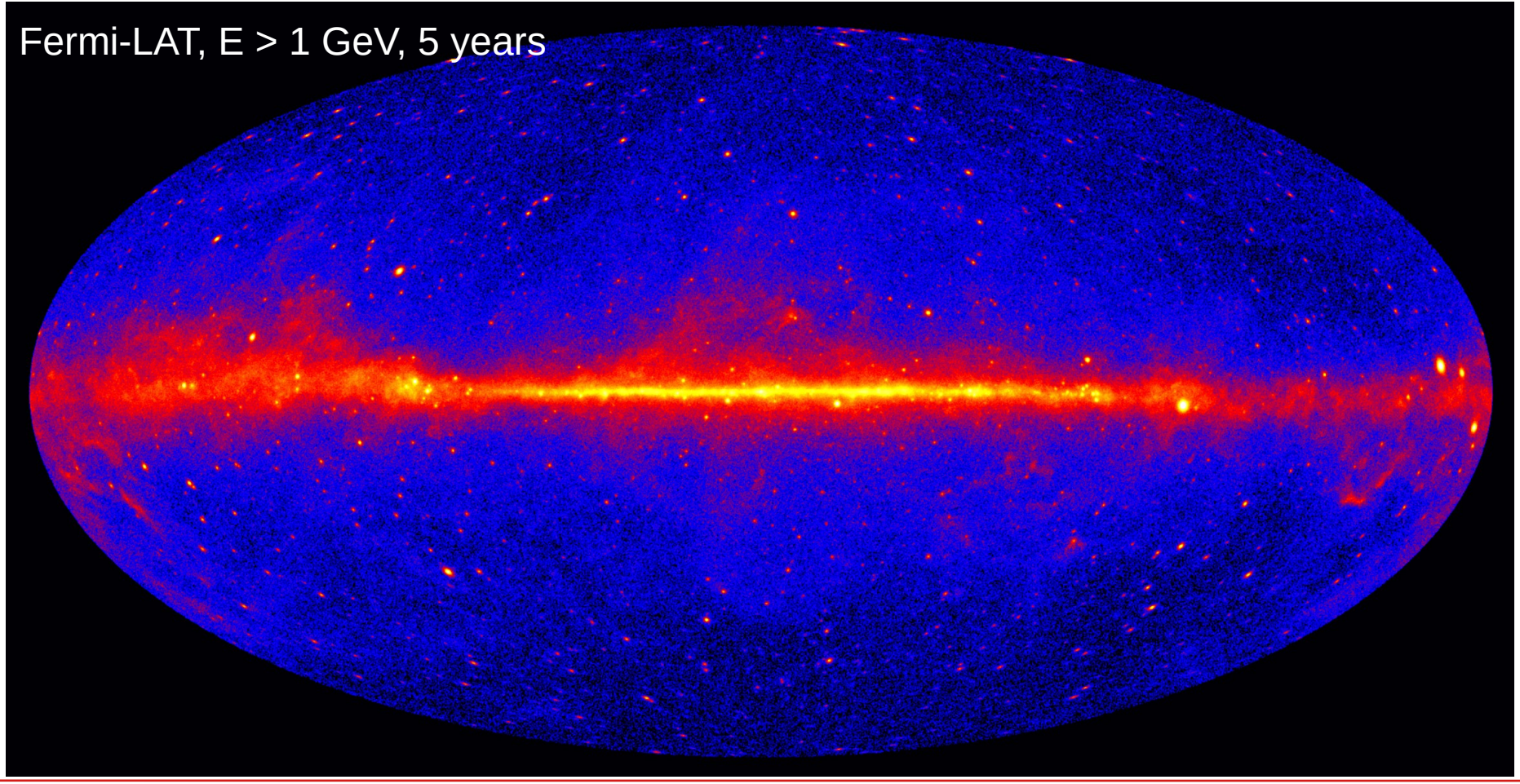
- LHAASO – Large High Altitude Air Shower Observatory
  - Large array (1.3 km^2), several techniques: Scintillators, Water Cherenkov, Muon detectors, Wide Field Air Cherenkov Telescopes
  - Sichuan, China



The Milky Way



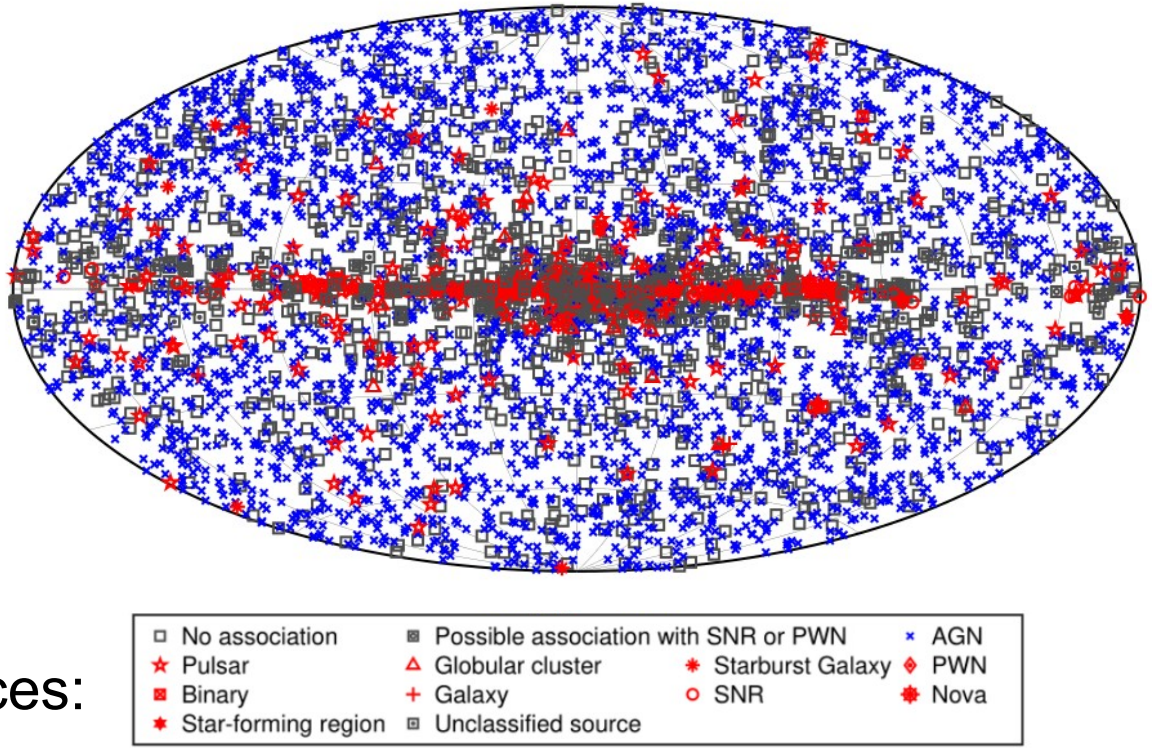
The Milky-Way in Gamma-Rays



4FGL – DR3 Catalogue

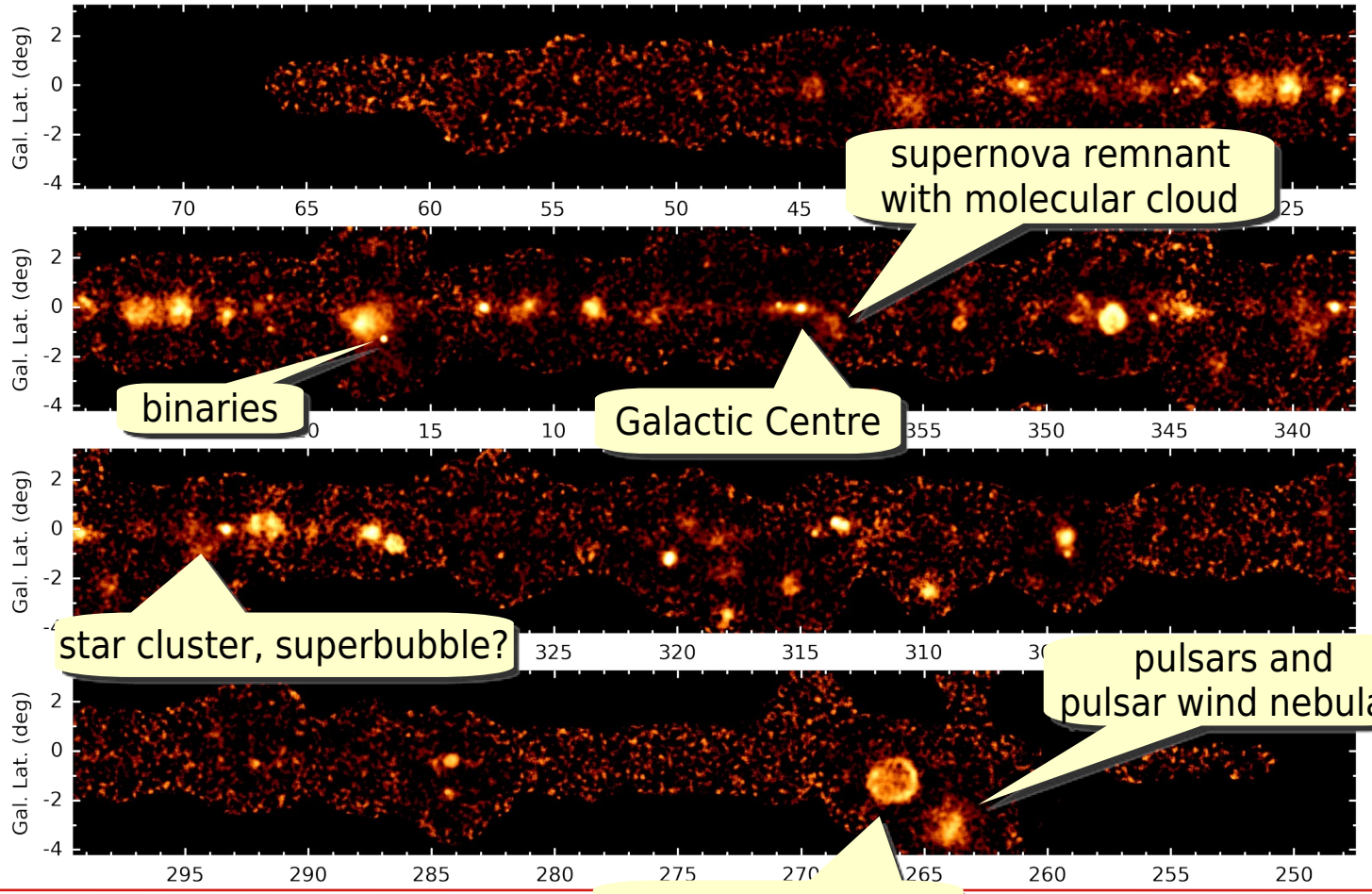
- 6658 sources (June 2022)
- Identified Galactic Sources:
  - 137 Young pulsars
  - 139 Millisecond pulsars
  - 44 Supernova remnants
  - 22 Pulsar wind nebulae
  - 41 Globular clusters
  - 9 Low-mass X-ray binaries
  - 11 High-mass X-ray binaries
  - 6 Star-forming regions
  - 8 Novae
- Identified Extra-galactic Sources:
  - 3932 Blazars
  - 67 Radiogalaxies and other AGNs

https://arxiv.org/abs/2201.11184



VHE View – H.E.S.S Legacy Survey

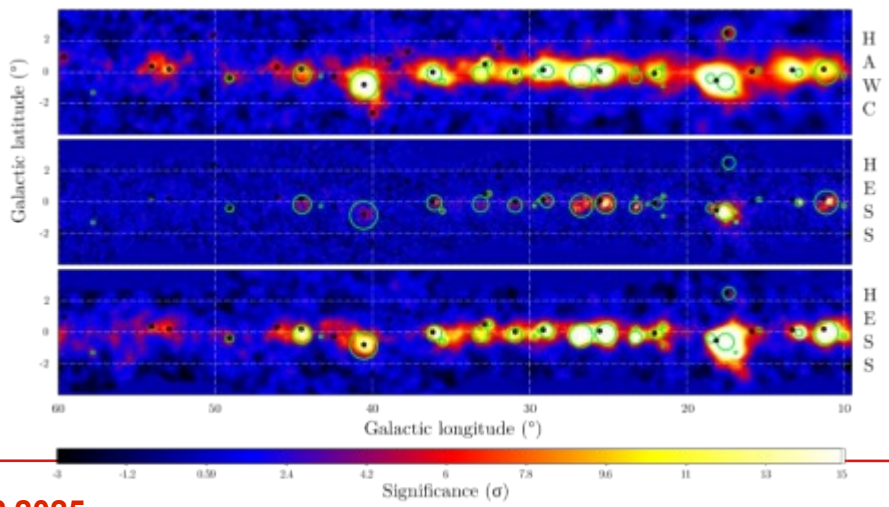
- Major H.E.S.S. project over 10 years (⇒ 2013)
- 78 VHE sources of different types:
  - 12 PWNs
  - 8 SNRs
  - 8 Composites
  - 3 Binaries
  - Sgr A*
  - 11 without counterparts
  - ...



Very – High Energy View – Others

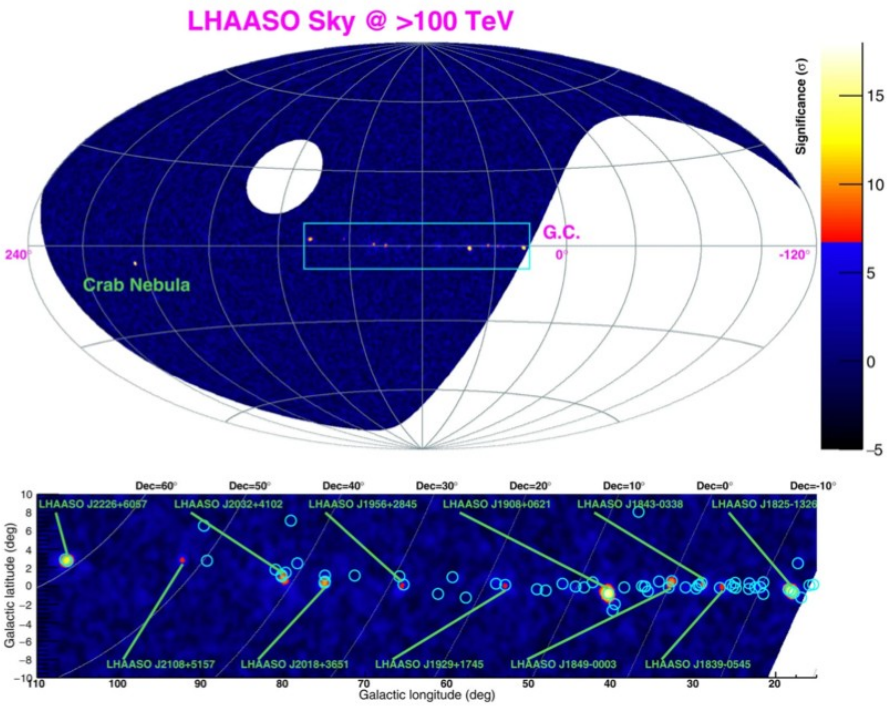
HAWC

- 65 sources $\geq 5\ \sigma$, overlapping each other (poor angular res.)
- Agrees with H.E.S.S. after smoothing (0.5°)



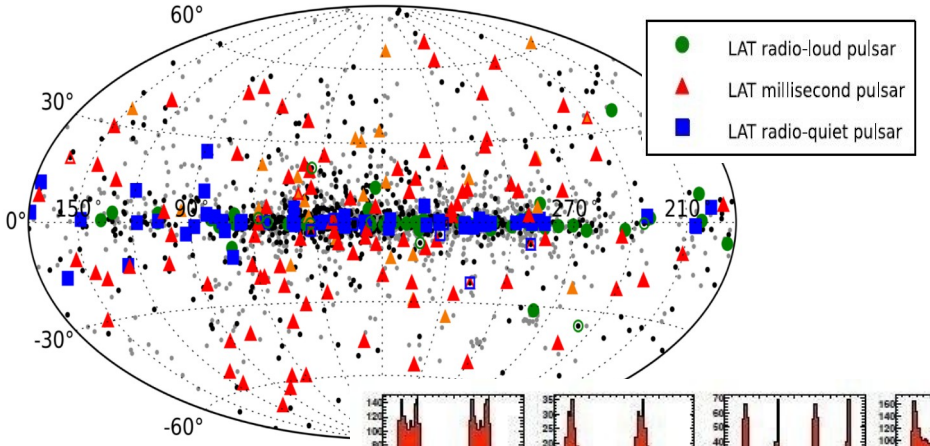
LHAASO

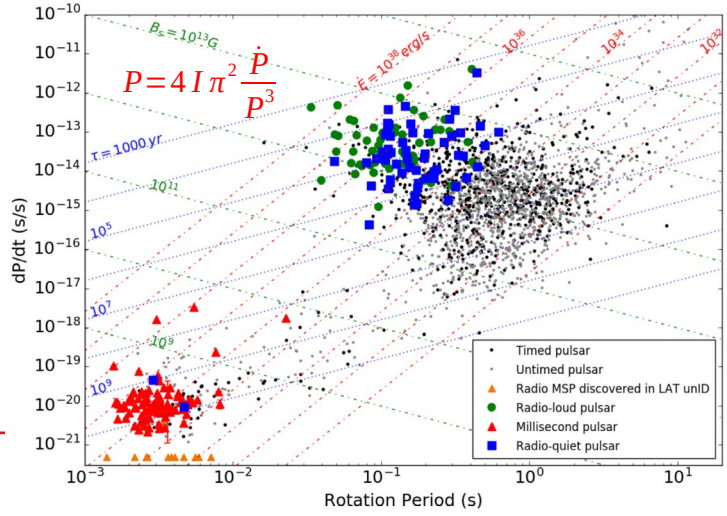
- Ultra high energy photons from 12 galactic sources (>100 TeV)

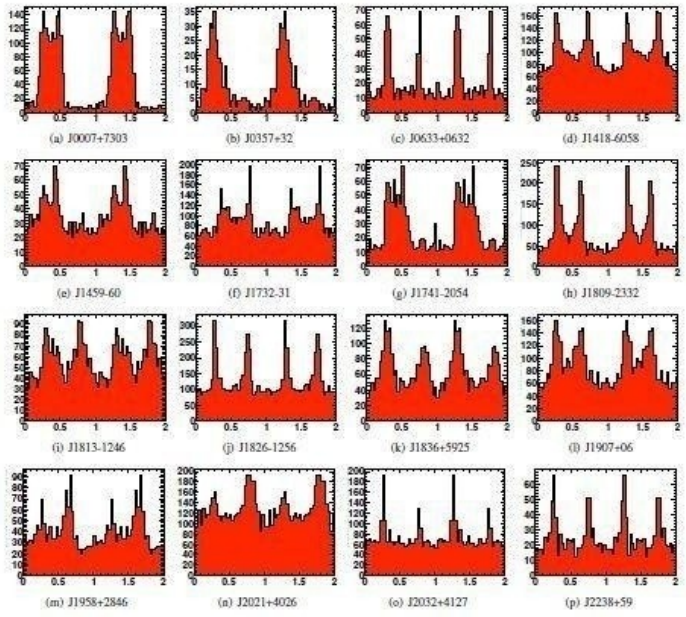


Gamma-ray pulsars

- Fermi: discovery of a full population of pulsars, including many millisecond, recycled pulsars
- Strong constraints on the geometry of emission zone (con opening angle vs energy)

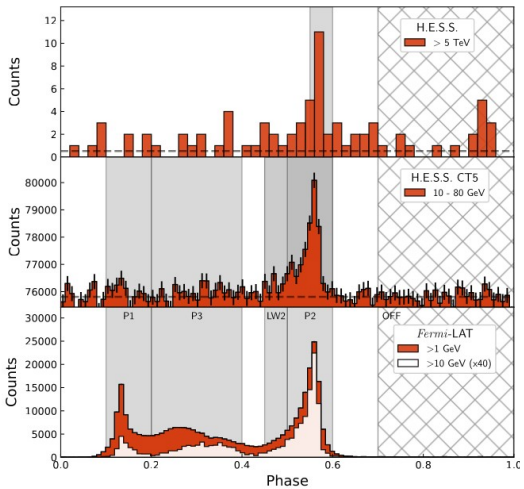


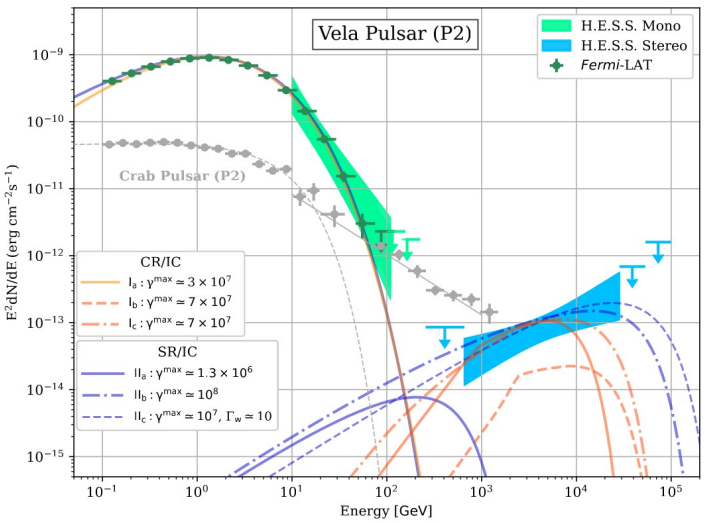


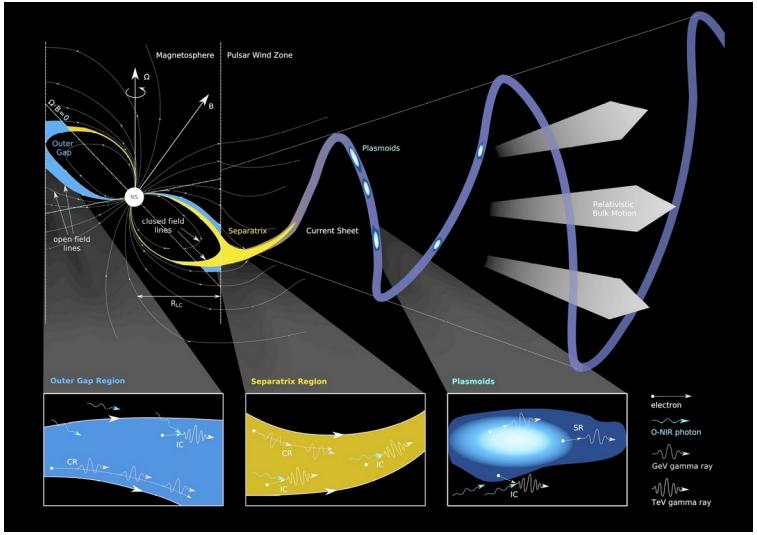


Pulsars from ground

- 3 VHE pulsars observed from ground: Crab, Vela & PSR B1706-44
- Amongst brightest pulsars in Fermi 2PC catalogue
- Very-high energy emission (20 TeV in Vela) from IC component on IR
- Must occur far from light cylinder (otherwise strong sync. cooling)

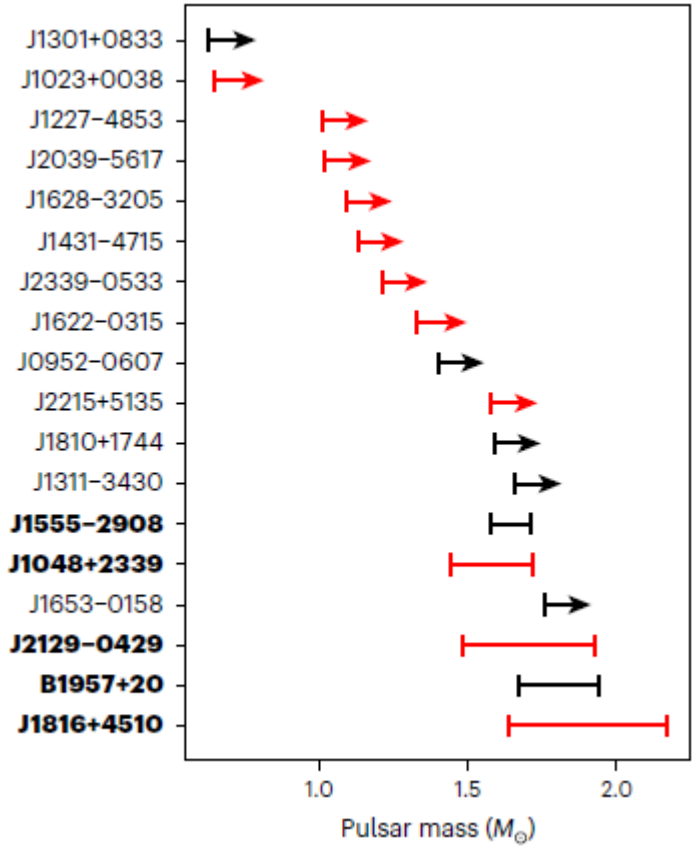






Millisecond pulsars & Neutron Stars

- Millisecond pulsars are **old**, but **re-accelerated** due to interaction in **binary** system.
- Best natural clocks known (no glitches etc)
- "**Black widows**" & "**redback spiders**" eat their mates.
- Those with eclipses can be used to estimate neutron star mass (direct information on system inclination)
- Can also be used to constrain stockastic background of gravitational wave

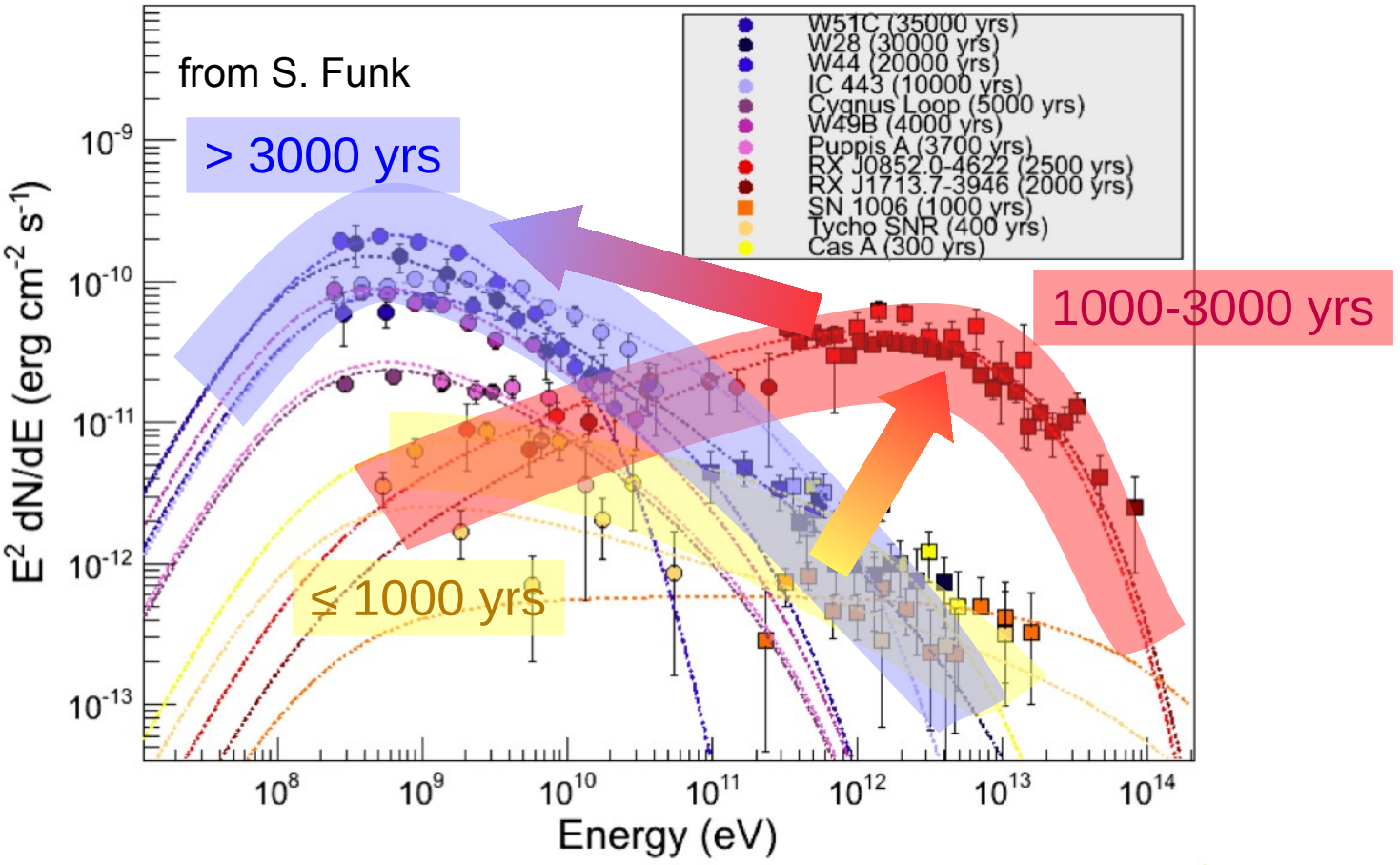


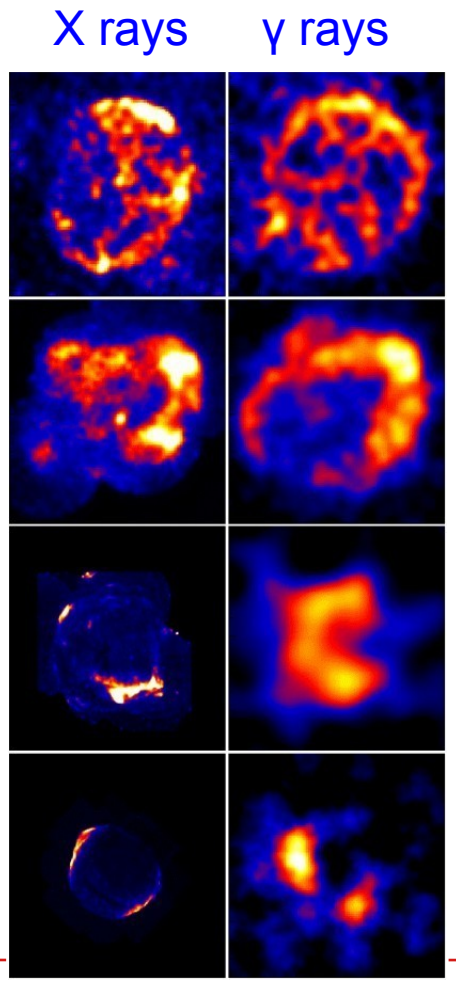
Science

A gamma-ray pulsar timing array constrains the nanohertz gravitational wave background

Nature Astronomy, **7**,451–462 (2023)

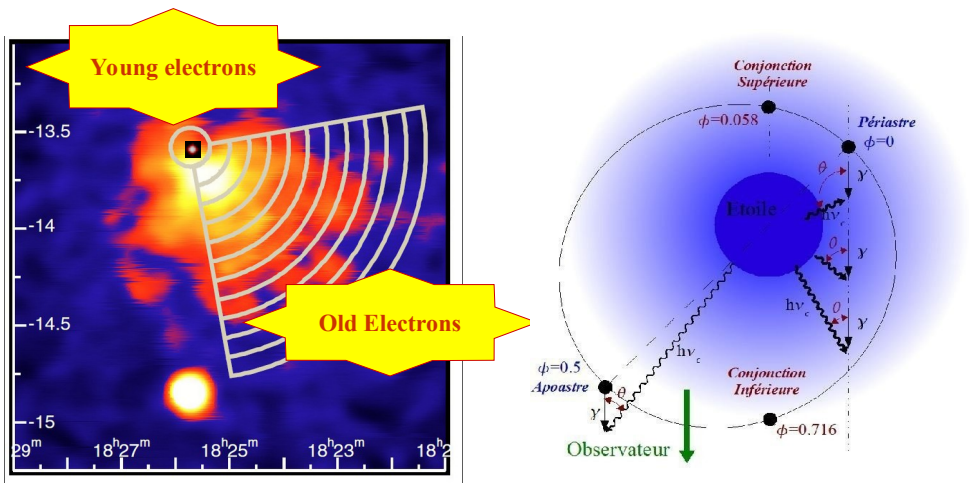
GeV-TeV spectra of supernova remnants

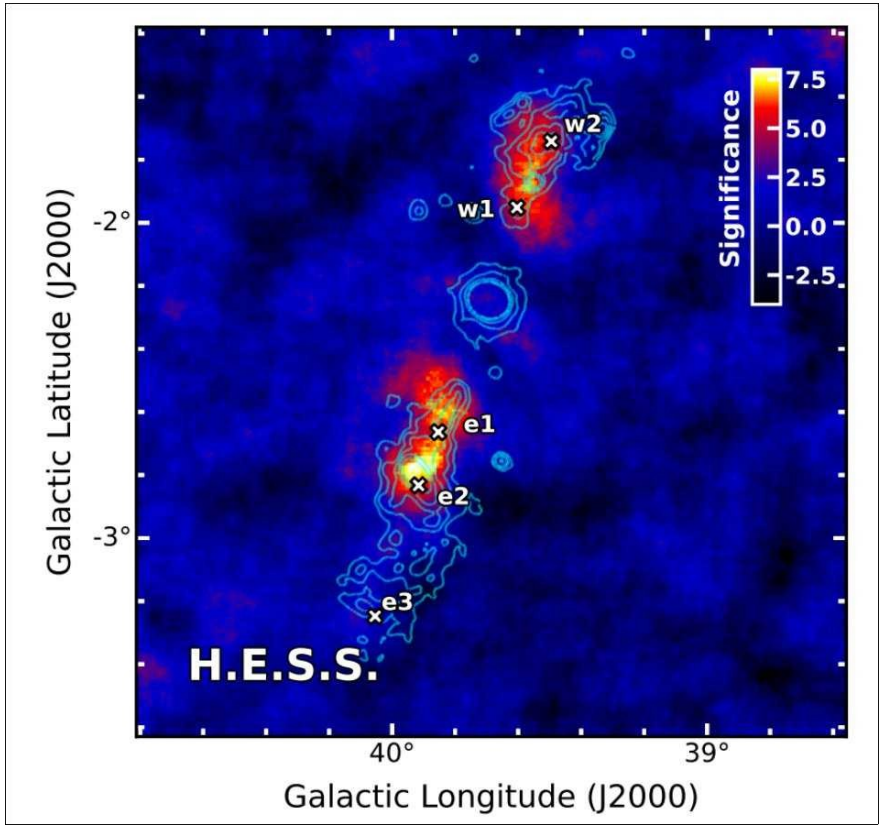




Other sources in the Milky Way

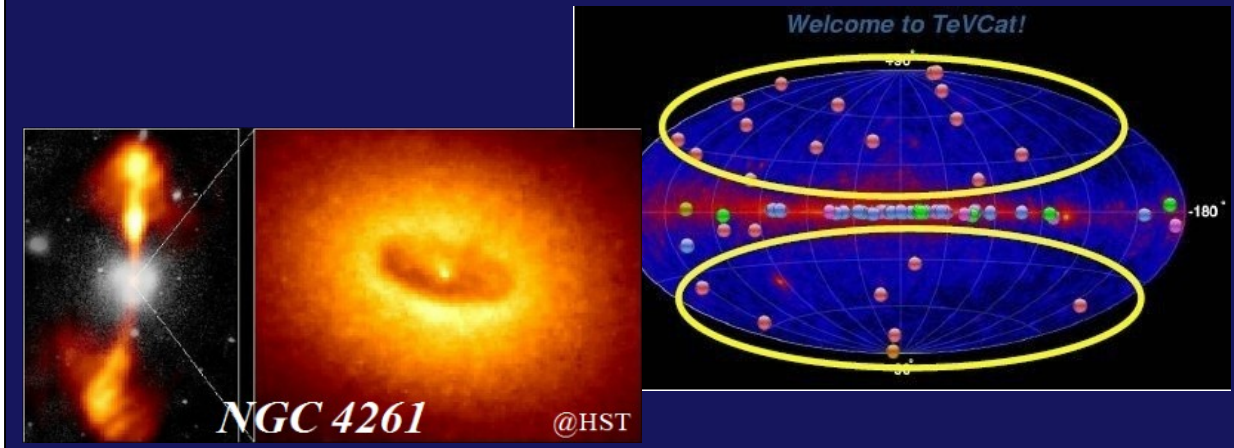
- Pulsar Wind Remnants
- Binary systems & Microquasars
- Novae
- Interacting Stellar Winds
- Galactic Centre (Black Hole)
- ….





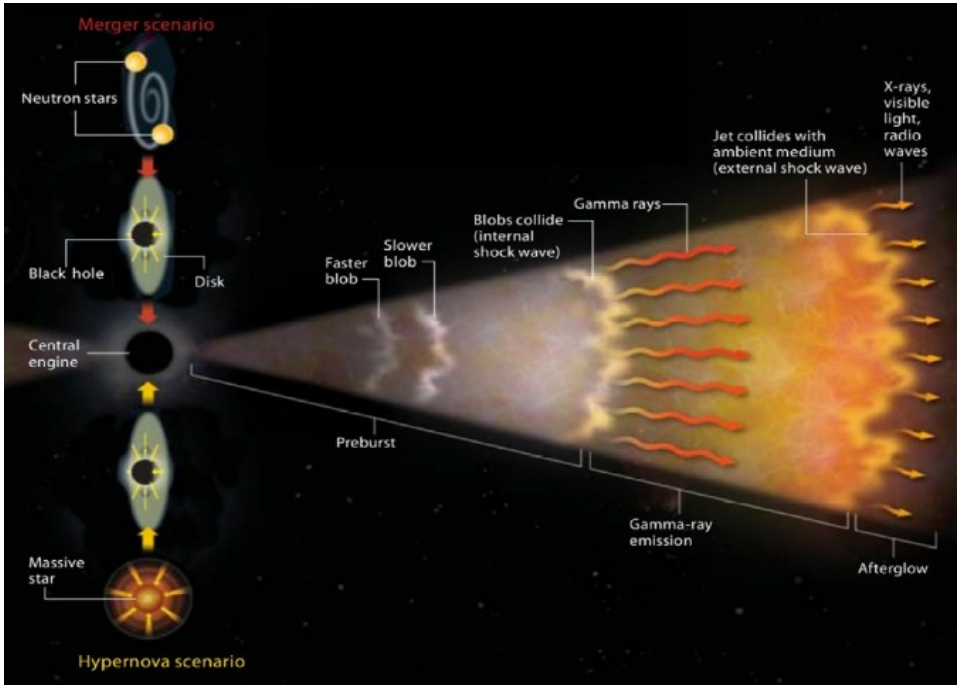
Microquasars – SS 433

Extragalactic Science



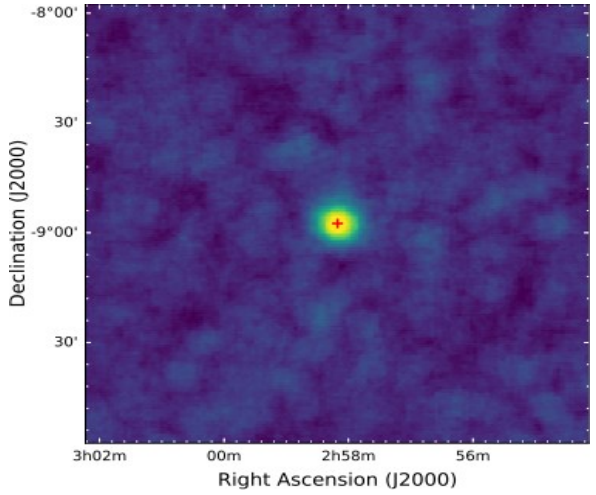
Gamma Ray Bursts up to TeV Scale

- Recent revolution in VHE astronomy
- Two populations
  - Long GRBs: Collapse of massive stars
  - Short GRBs: Neutron star mergers
- Recent detections (Long GRBs):
  - GRB 180720B (HESS)
  - GRB 190114C (MAGIC)
  - GRB 190829A (HESS)
  - GRB 201216C (MAGIC)
  - GRB 221009A aka BOAT (LHAASO)
- Hint from short GRB
  - GRB 160821B (MAGIC, 3 σ)

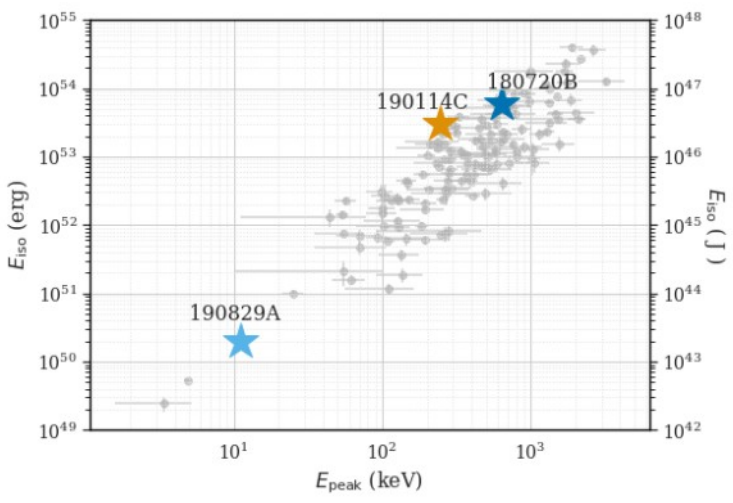


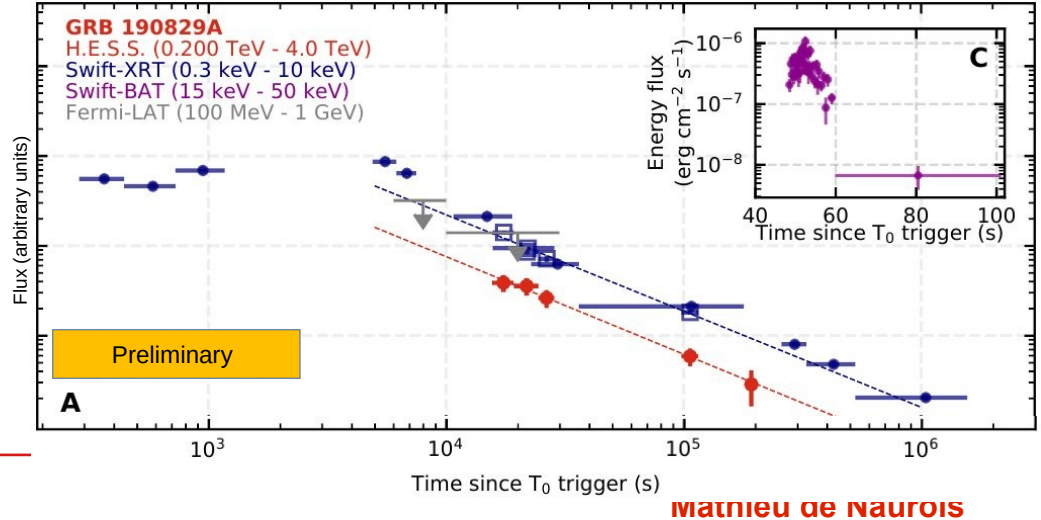
GRB 190829A

- Long GRB (t_{GBM90} ~ 60 s, t_{BAT90} ~ 60 s) @ z = 0.078
- Observation started at t_0 + 4h20 (ATel #13052)
- Followed during 3 nights (22, 6 and 3 σ)!
- Extending up to > 3 TeV
- Modest energy but one of the closest ever



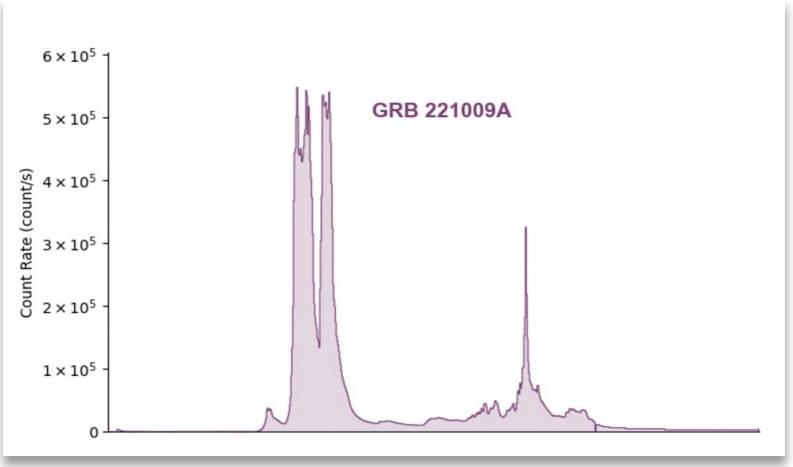
H.E.S.S. Collaboration - Science 372 (2021)

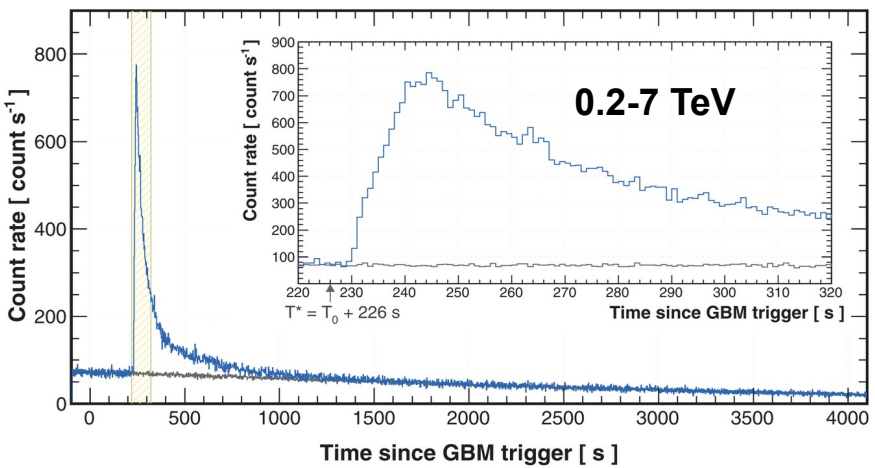




B.O.A.T.: The Brightest Of All Time

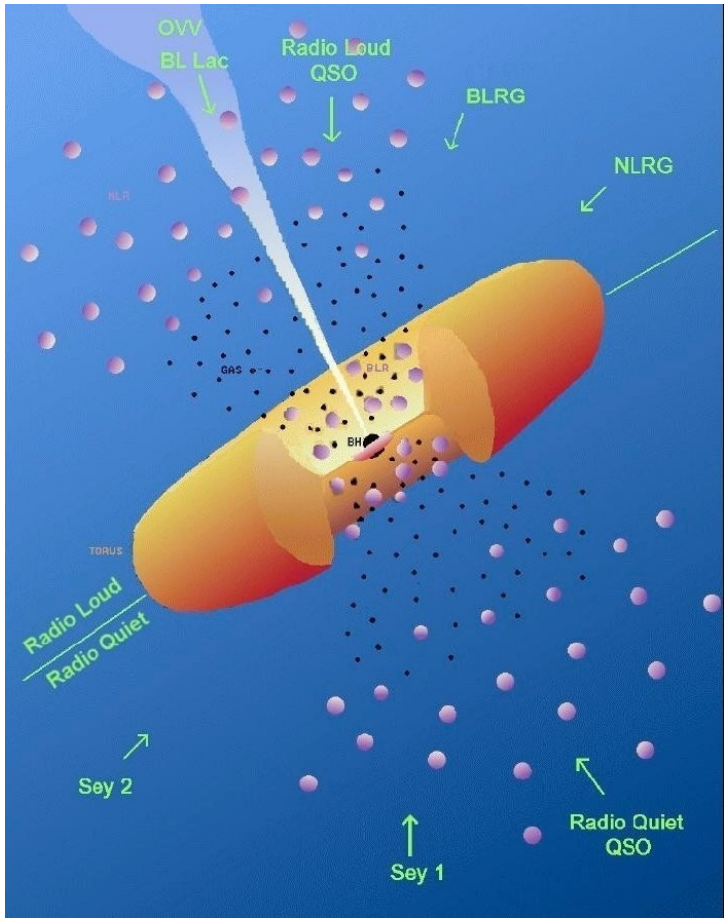
- GRB221009A was an extraordinary event:
  - very energetic (~10^{55} erg) and close to Earth (z=0.151)
  - thought to be a once-in-10,000-year event
- LHAASO detection up to ~ 14 TeV, >60,000 photons above 0.2TeV
  - T_0 ≈ 225–228 s
  - Estimated Lorentz Factor of the Jet ~ 440





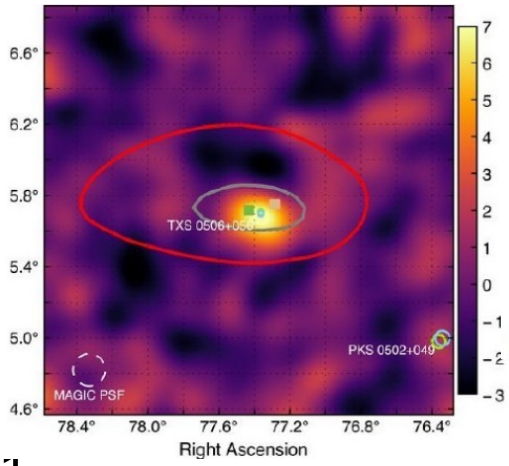
Active Galactic Nuclei

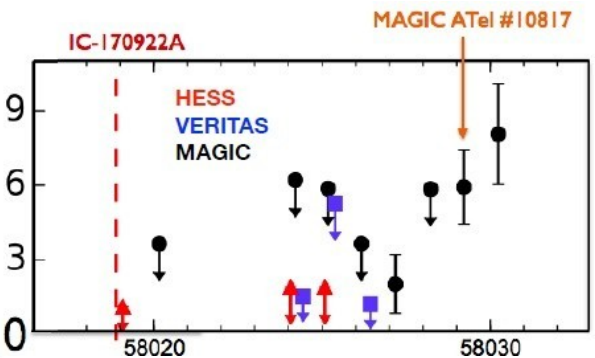
- Most numerous class of extragalactic sources
  - Supermassive black hole surrounded by an accretion disk
  - Some have ultrarelativistic jets, some not
  - “Blazars” have jets pointing towards the earth and show highly variable TeV emission
- Physics:
  - Mechanisms of relativistic jet production (acceleration & ejection)
  - Probes of the extragalactic background light (EBL) through pair absorption
  - Tests of Lorentz Invariance
  - ...

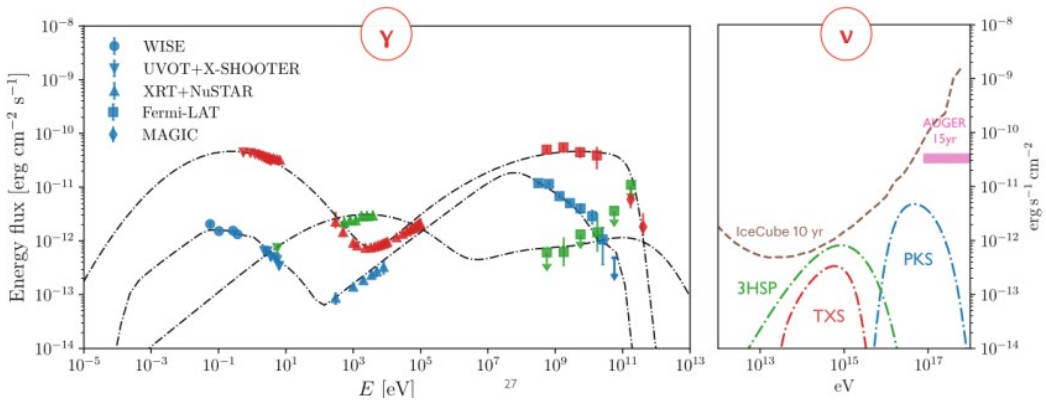


Blazars - Multi-messenger observations

- Emerging associations between neutrinos & AGN
  - IC 170922A: One neutrino coincident with Flaring Blazar TXS 0506+056 + Burst of neutrinos in archival data
  - IC 190730A ⇒ PKS 1502+106
  - IC 200107A ⇒ 3 HSP J0955+3551
- Possible neutrino from Tidal Disruption Event (AT2019dsg)

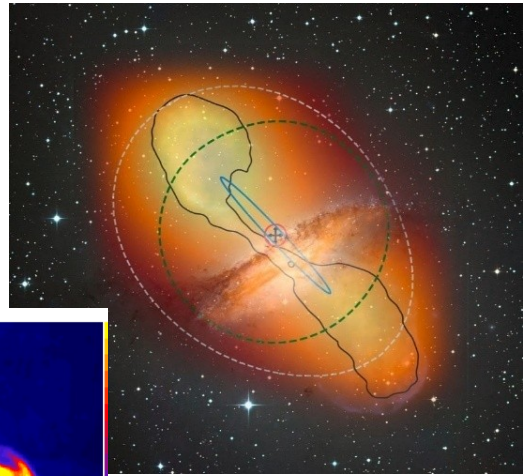


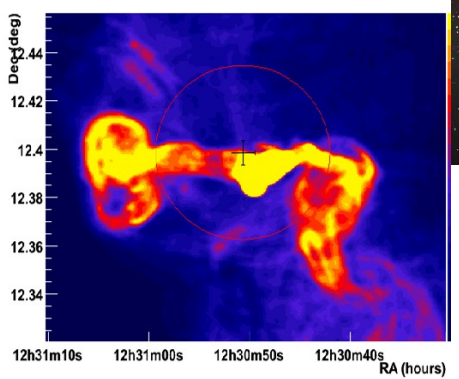




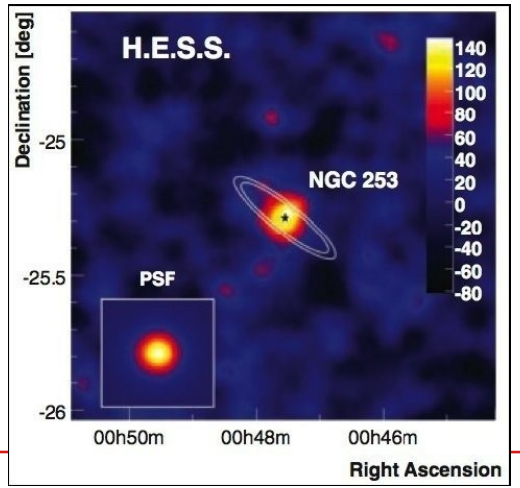
Other extragalactic Sources

- Radio-Galaxies: Possibility to measure the extension and pin-point the region of acceleration (Centaurus A)
  - Continuous acceleration of particles along the jet





- Starburst Galaxies
  - Regions of intense stellar formation activity (e.g. NGC 253)

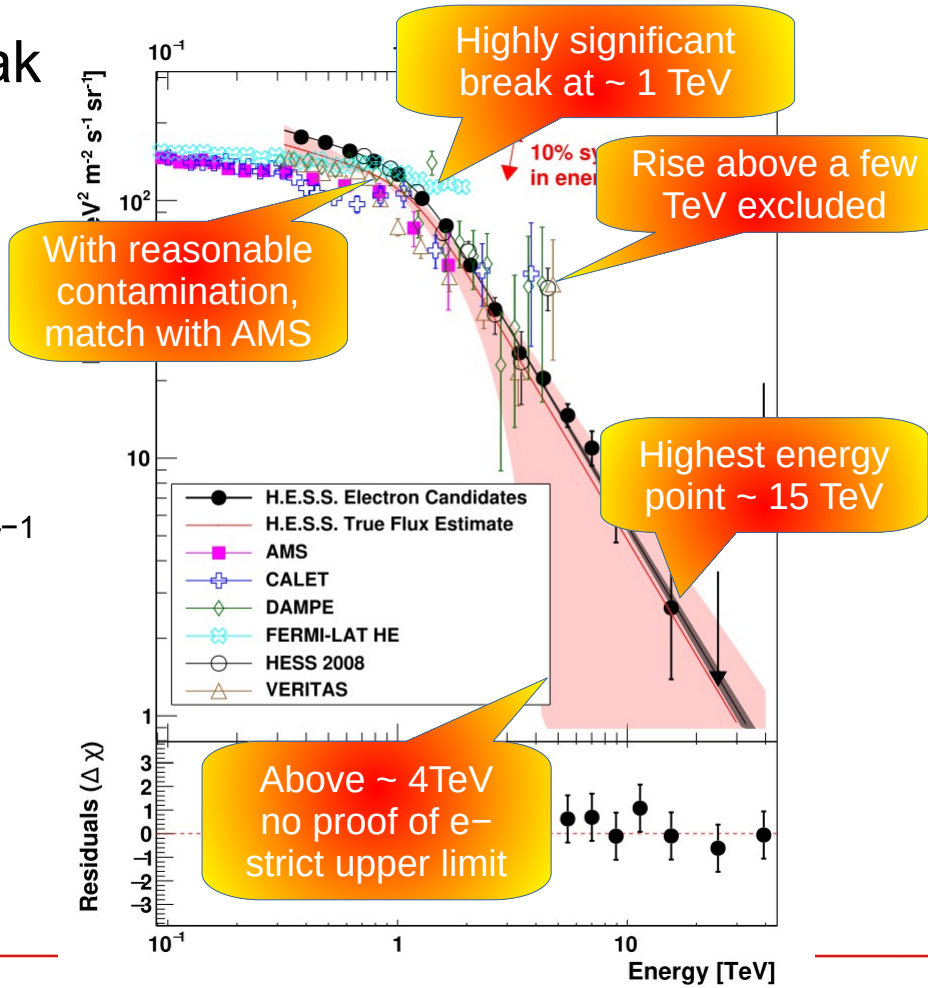


- Tomography of the Universe (measure of EBL) & Fundamental physics (Lorentz Invariance)

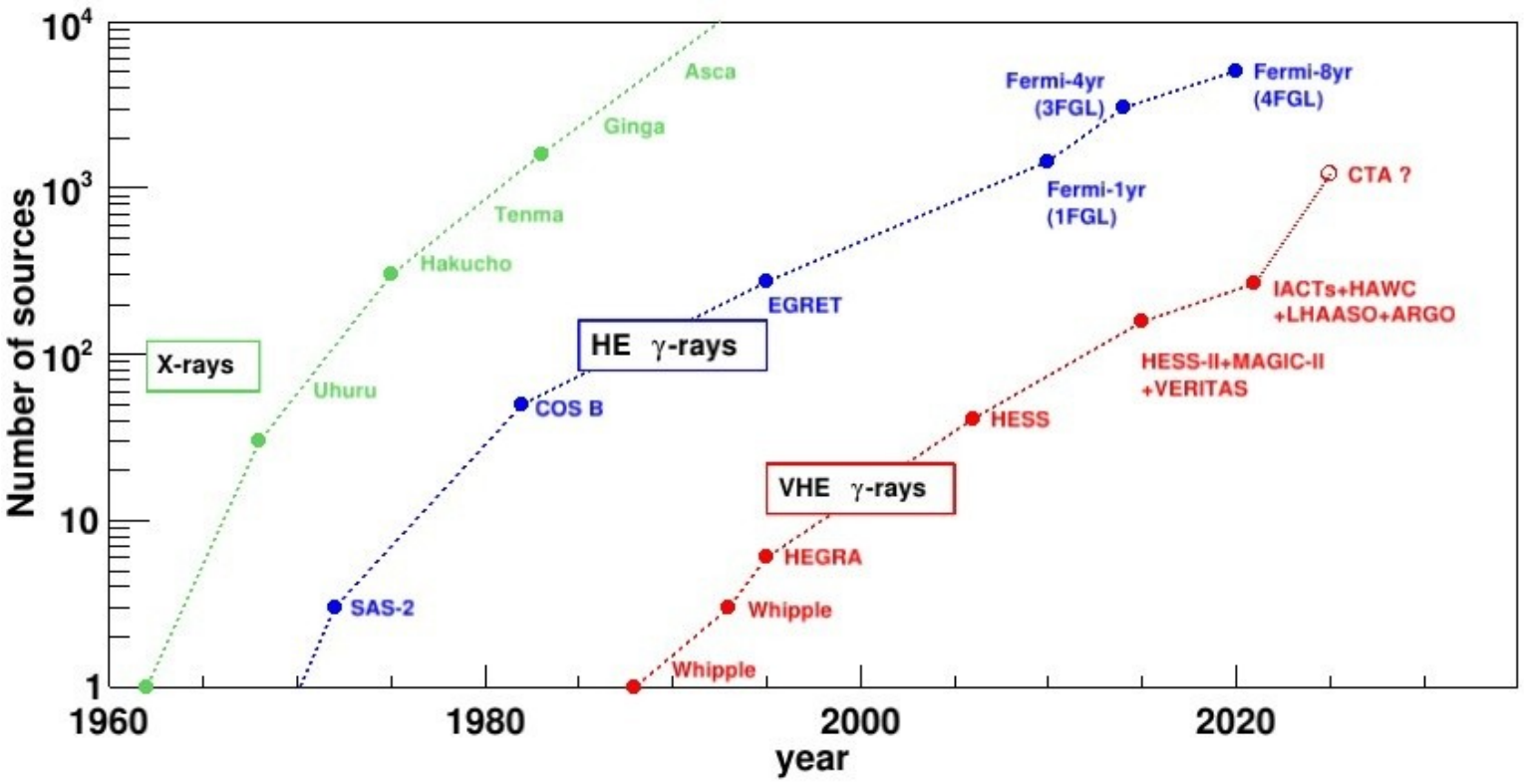
Beyond γ-rays: Cosmic Electron Spectrum

- Highly significant (> 100 σ) spectral break
- Best fit parameters:
  - $\Gamma_1 = 3.25 \pm 0.02_{stat} \pm 0.2_{syst}$
  - $\Gamma_2 = 4.49 \pm 0.04_{stat} \pm 0.2_{syst}$
  - $E_{break} = (1.17 \pm 0.04_{stat} \pm 0.1_{syst})$ TeV
  - Sharpness $s = 0.21 \pm 0.02_{stat}$
  - @ 1 TeV:
    $E^3 \times \Phi(E) = (126.1 \pm 0.5_{stat})$ GeV^2 m^{-2} s^{-1} sr^{-1}
    (not corrected for contamination)

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \Phi_0 \times \left(\frac{E}{E_0}\right)^{-\Gamma_1} \times \left(1 + \left(\frac{E}{E_{\mathrm{cut}}}\right)^{1/s}\right)^{s\times(\Gamma_1-\Gamma_2)}$$

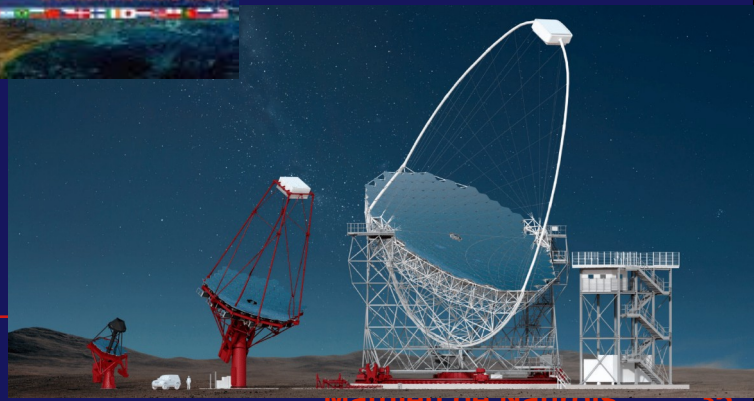


Evolution of the field – “Kifune” Plot



Number of sources vs time [T. Kifune]

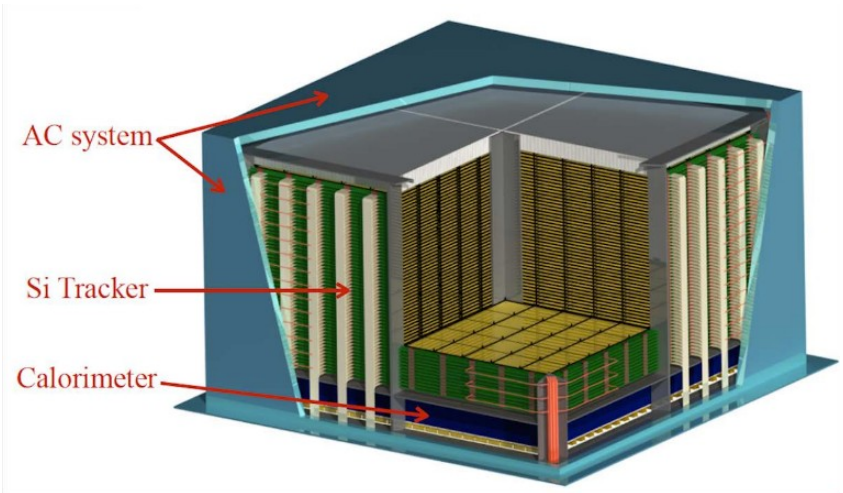
Perspectives



Future MeV-GeV mission?

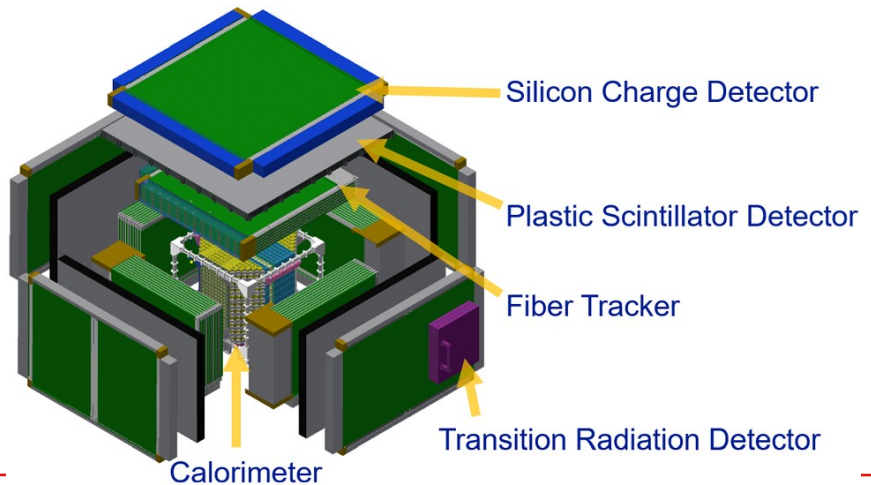
e-AstroGam

- High resolution Tracker + Calorimeter (0.3 MeV – 3 GeV)
- Access to polarimetry, Exploits Compton event
- Proposed to ESA M5 call



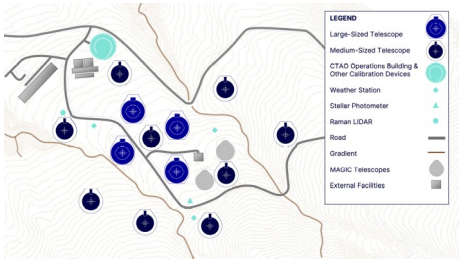
HERD

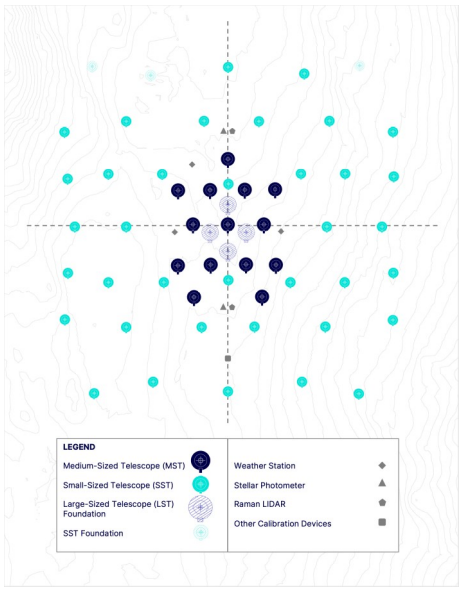
- Fibre tracker + Calorimeter + TRD detector
- Energy range > 1 GeV
- Proposed for the future Chines Space Station (2027 –)

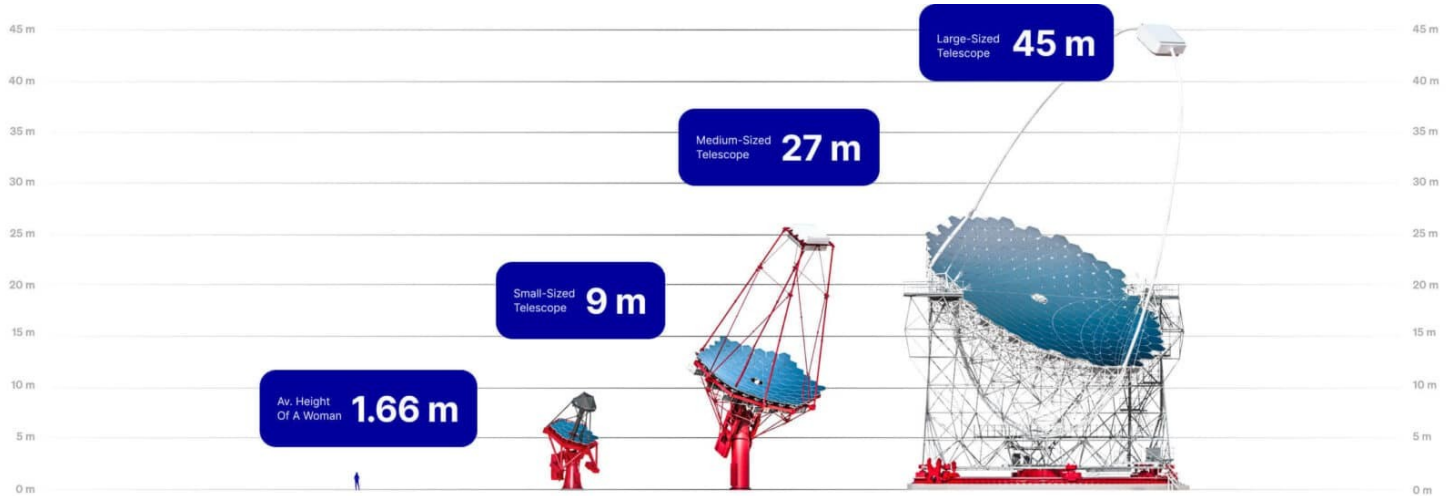


CTAO

- Next generation IACTs
- 2 sites, 3 sizes of telescopes (LST, MST, SST)
  - Canary Island: 0.5 km², 4 LST, 9 MST
    focus on extragalactic science
  - Chile, 3 km², 14 MST, 37 SST (+ 4 LST?)
    focus on pevatrons & galactic science
- ERIC signed January 7th, 2025







Southern Wide-field Gamma-ray Observatory – SWGO

- Water Cherenkov detector in the Southern Hemisphere
- Potential site Atacama Astronomical Park, Chile.
- At an altitude of 4770 m.
- Energy range from 100s of GeV up to the PeV scale

- Not funded yet