# (Very/Ultra) High Energy Astrophysics
# II – Gamma Ray Astronomy

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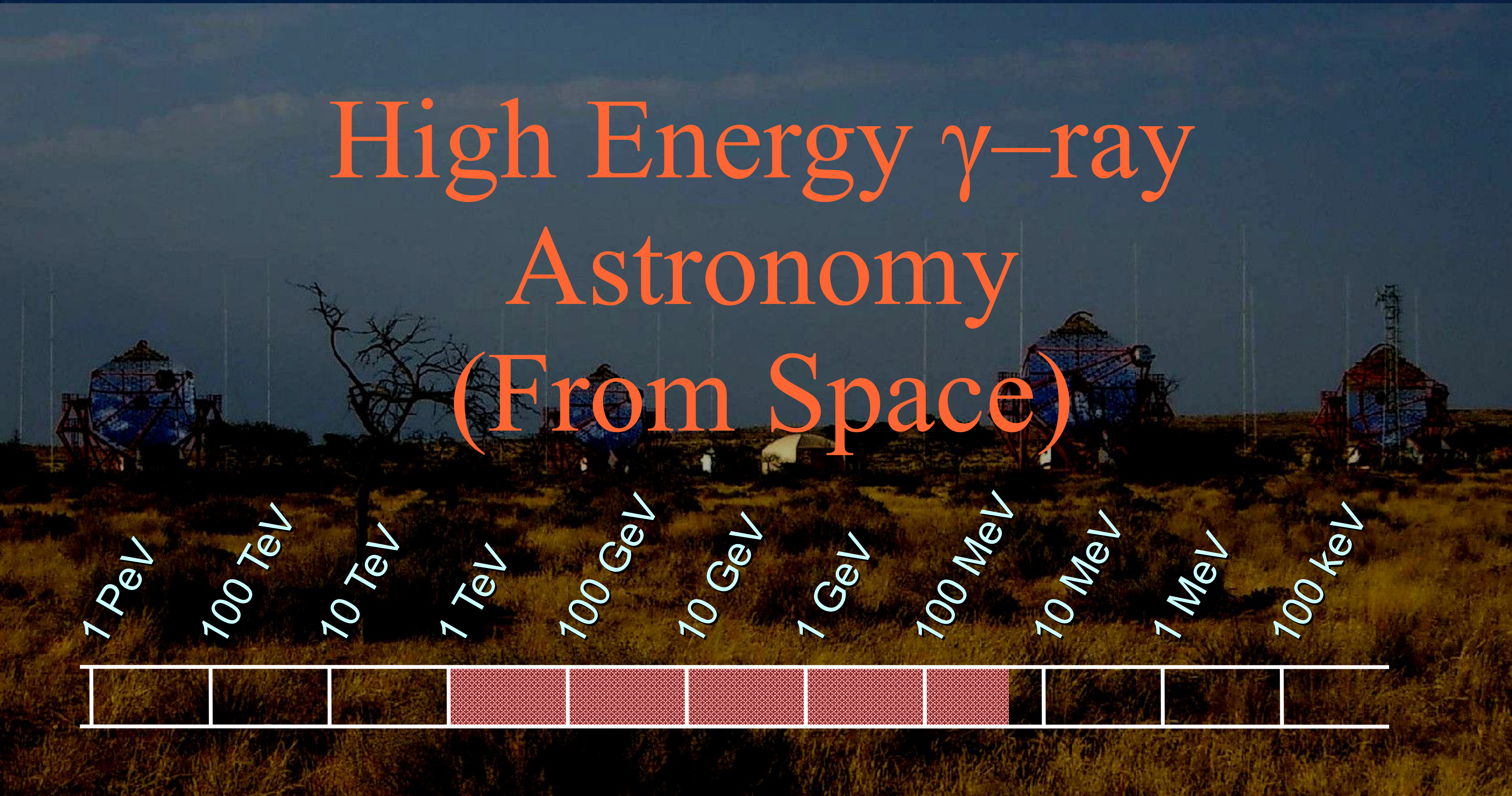
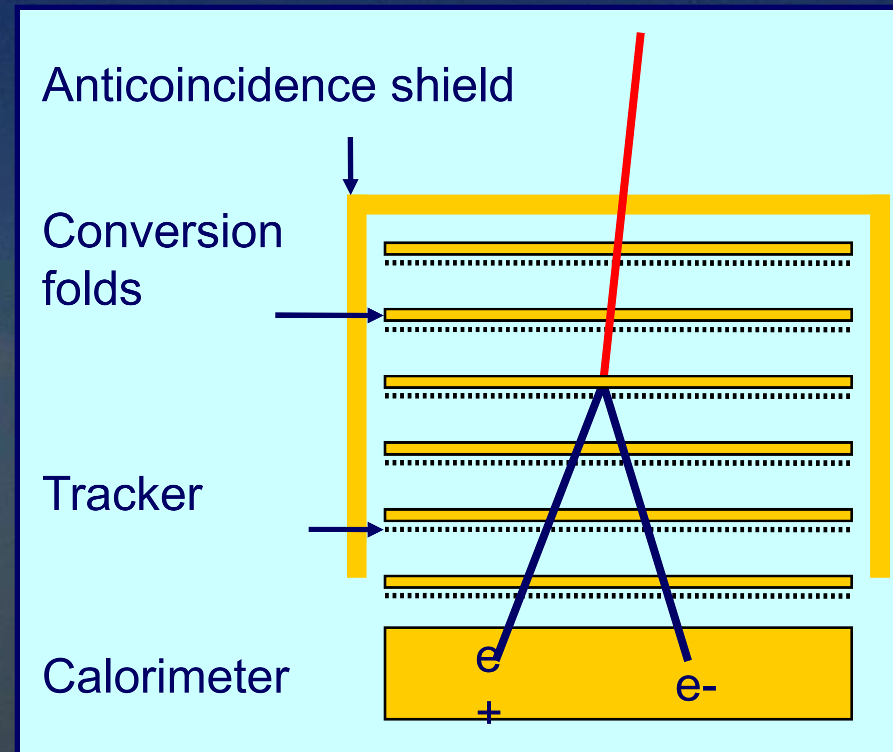
- High Energy Gamma-Ray Astronomy from Space
- Atmospheric Showers
- Very High Energy Gamma-Ray Astronomy from ground

# High Energy γ–ray Astronomy (From Space)



# Pair Creation Telescopes

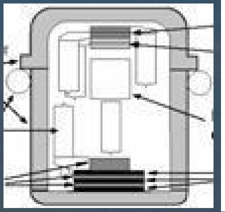
- Atmosphere is opaque to gamma rays
- Conversion of γ into pair e+ e-
  - Threshold $E_\gamma > 2\, m_e c^2$ (1.022 MeV)
  - Angular resolution better as energy increase
    $\theta \sim 1.5°$ @ 100 MeV
    $\theta \sim 0.1°$ > 10 GeV
  - Almost no deviation for $E\gamma \gg 2\, m_e c^2$ ,
- e+ e- reconstructed in a tracker ⇒ incident γ ray
- Anti-coincidence shield against charged cosmic rays



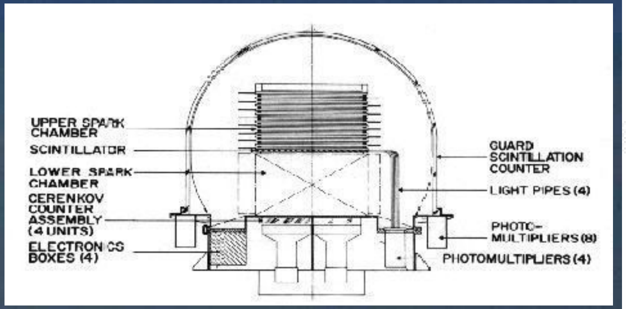
# History of pair creation telescopes

- **1967-1968**, OSO-3
  **621 γ,**
  **Galactic Plane**
- **1972-1973**, SAS-2,
  **~8,000 γ,**
  **3 sources**
- **1975-1982**, COS-B
  **~200,000 γ,**
  **25 sources (3C 273)**
- **1991-2000**, EGRET
  **>1.4 × $10^6$ γ,**
  **271 sources**
- **2007-** AGILE
- **2008-** FERMI

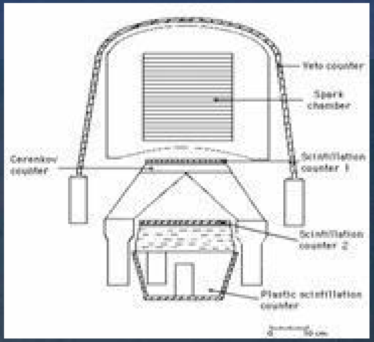
OSO-3



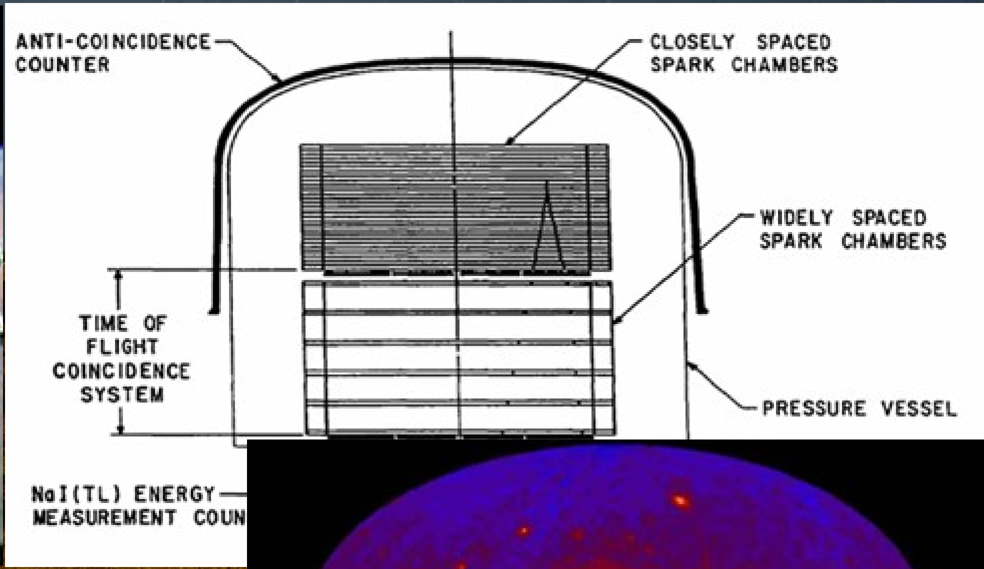
SAS-2

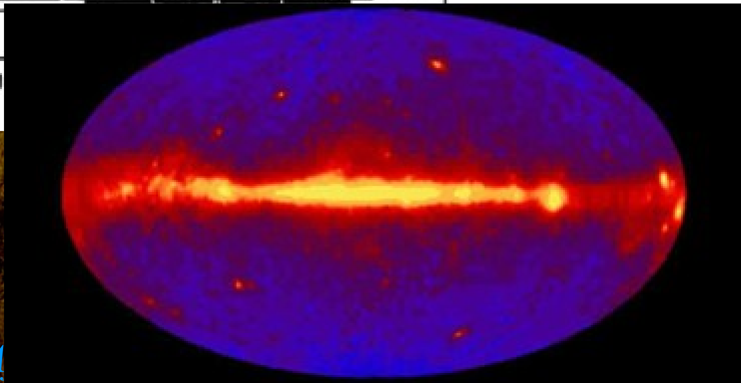



COS-B



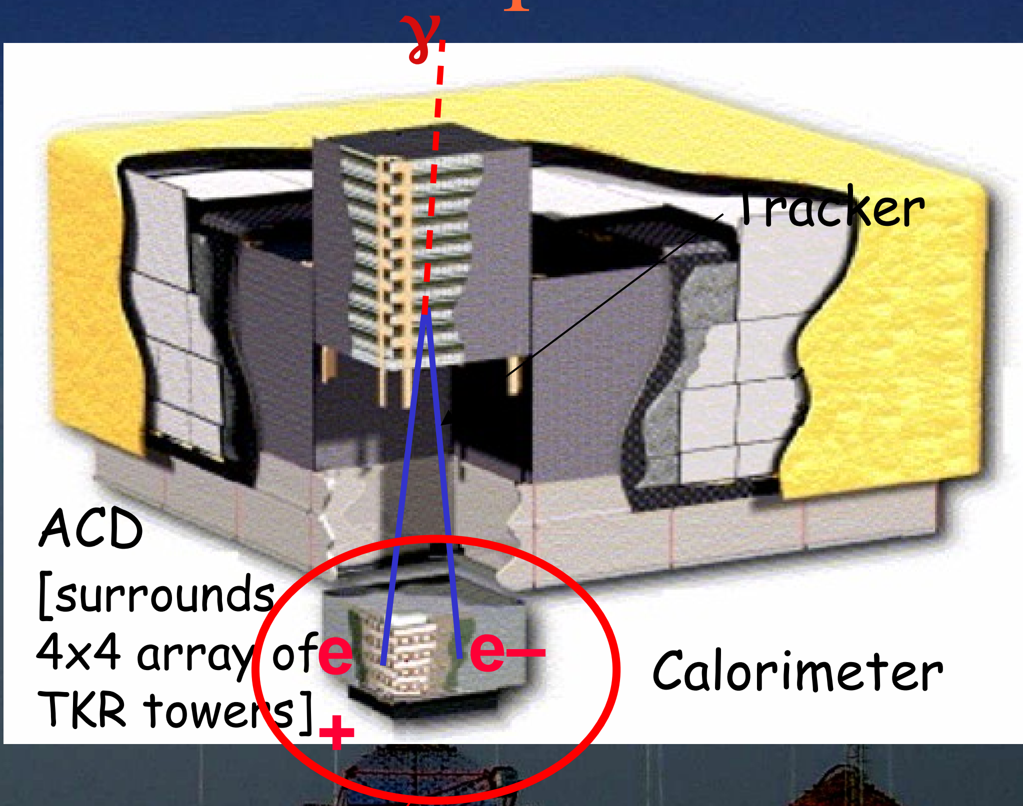

EGRET

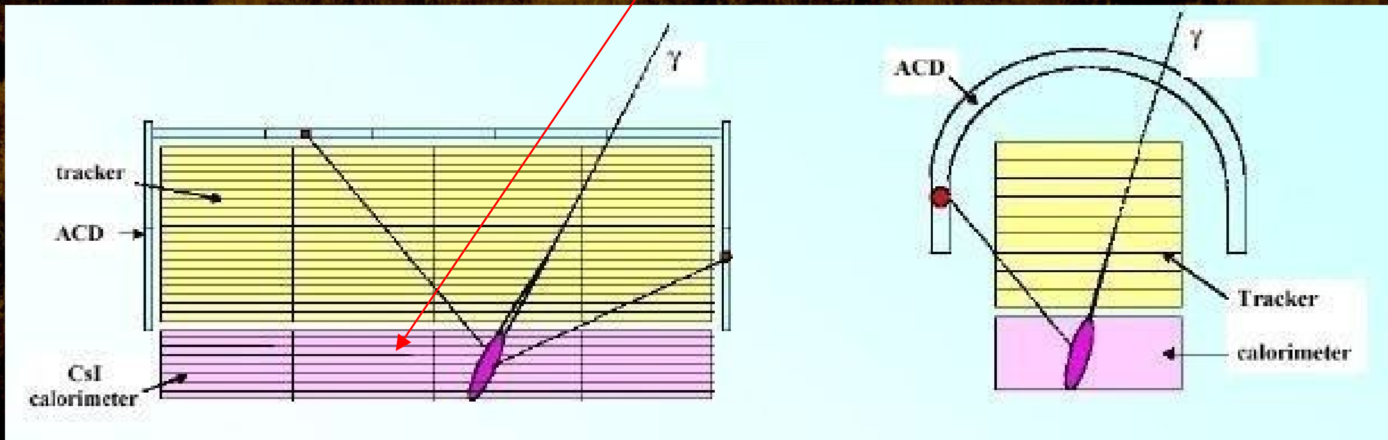


# FERMI Large Area Telescope

- High precision tracker
  - 18 X/Y planes, Si strips (228 µm)
  - 900 000 channels
  - Triggers on 3 X/Y planes
- Hodoscopic Calorimeter
  - 1536 CsI(Tl) cristals(8 layers)
  - Shower imaging capabilities
- Anti-coïncidence shield
  - Segmented to avoid self-veto,
  - 89 folds

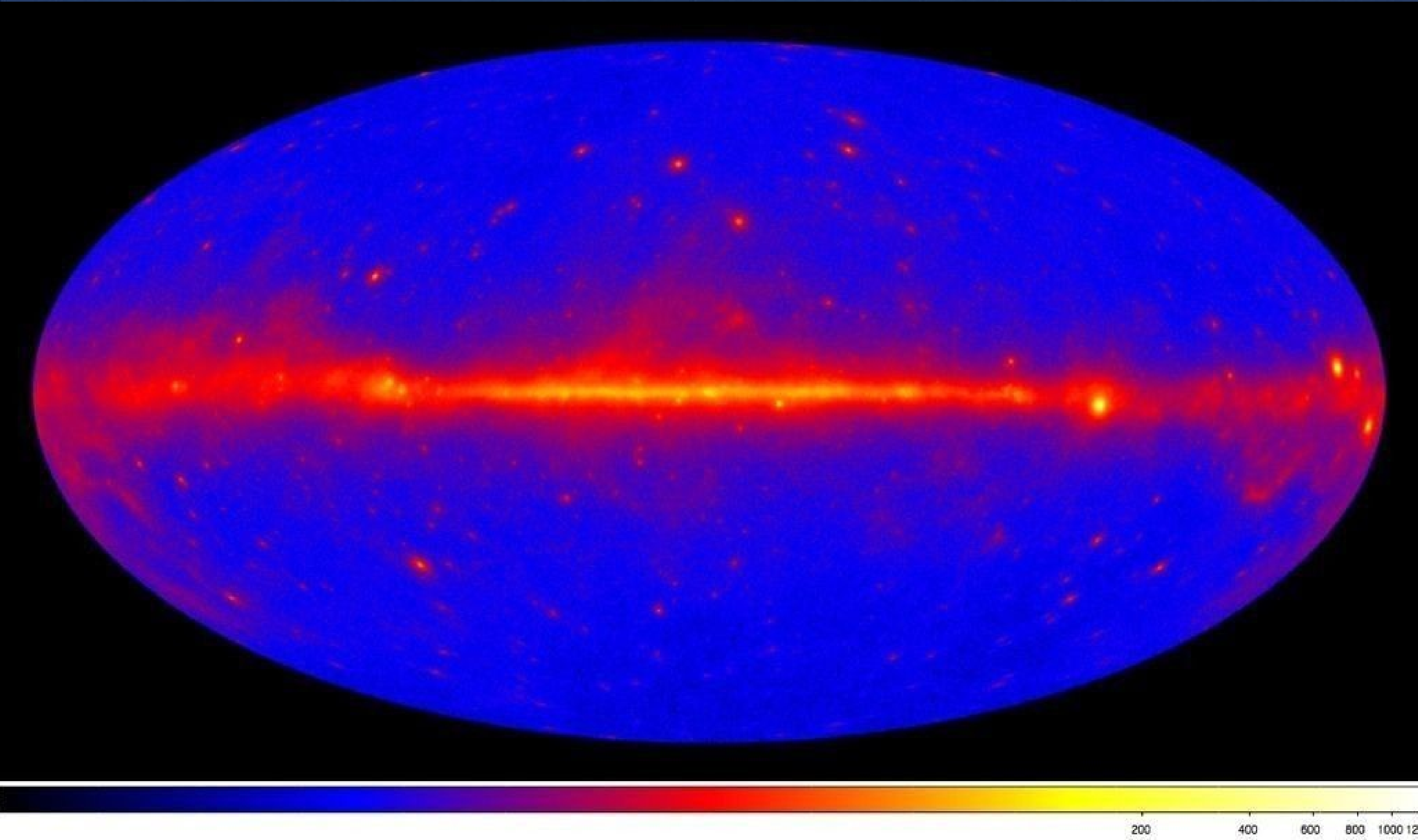



Mathieu de Naurois

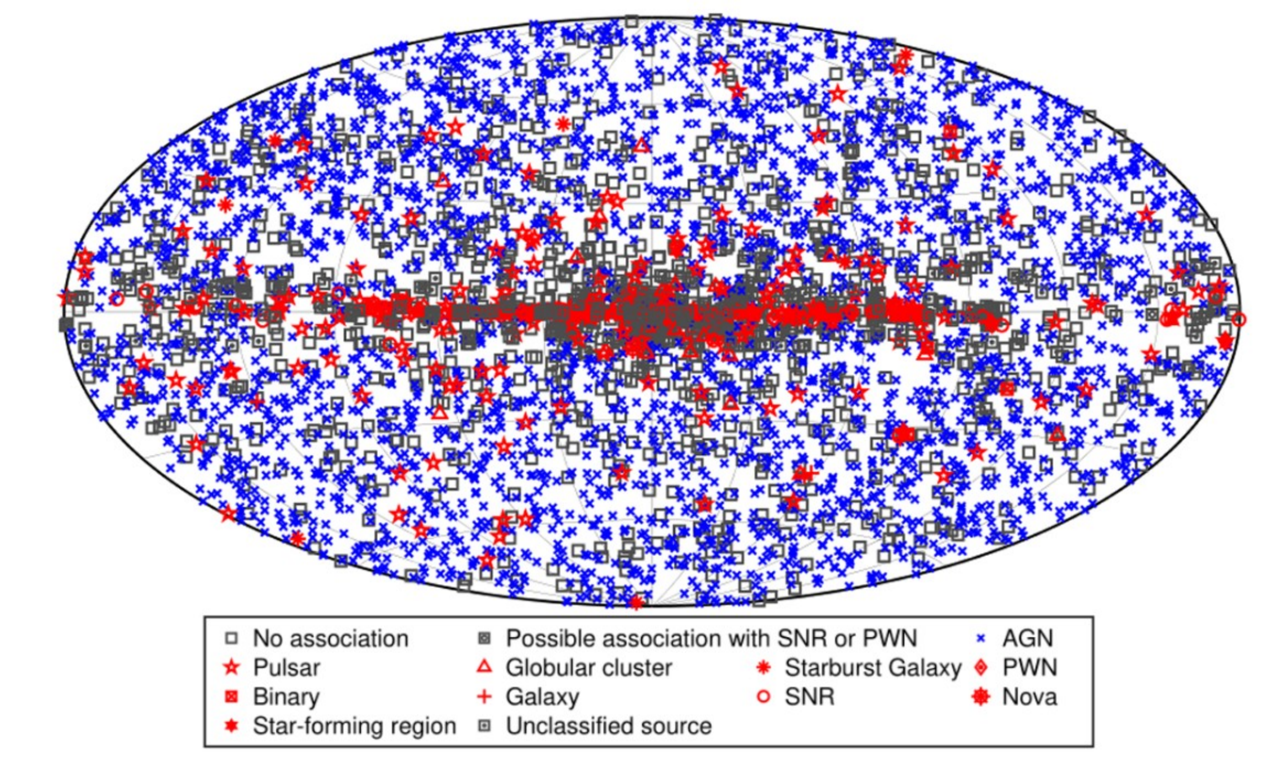
# Fermi LAT > 100 MeV

- 3×10$^7$ photons, <E> = 800 MeV, ΔE/E = 100 %



# 4FGL Catalogue

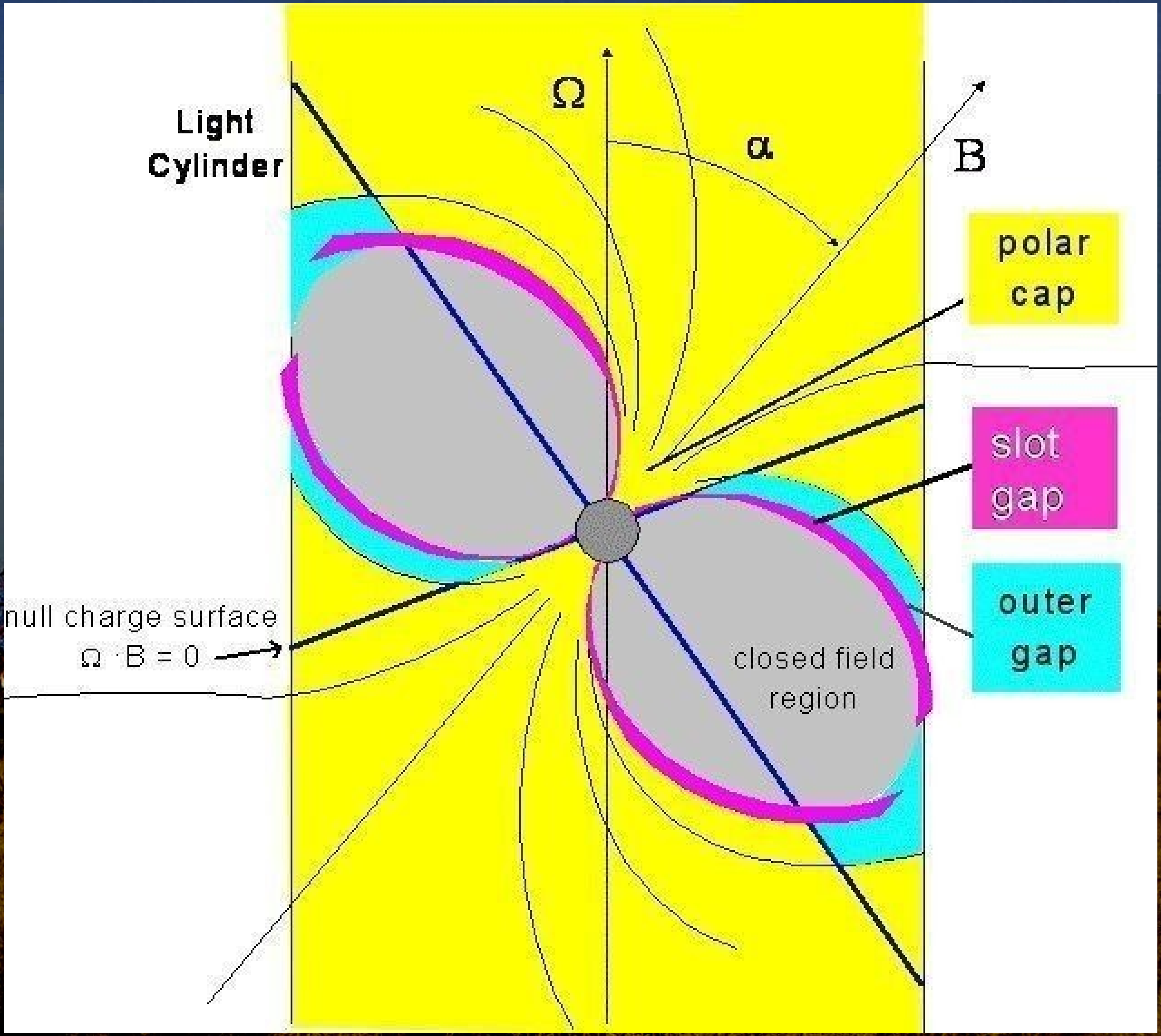
- Release February 2019
  https://arxiv.org/abs/1902.10045
  - 5064 sources
  - 232 pulsars (with pulsations)
  - 17 PWNs
  - 40 SNRs
  - 11 binaries
  - ~ 3130 blazars
  - 42 radio galaxies
  - 7 starburst galaxies
  - 15 globular clusters
  - 1336 unassociated




- Updated June 22th, 2022 (4FGL - DR3)
  https://arxiv.org/abs/2201.11184
  - 6658 sources

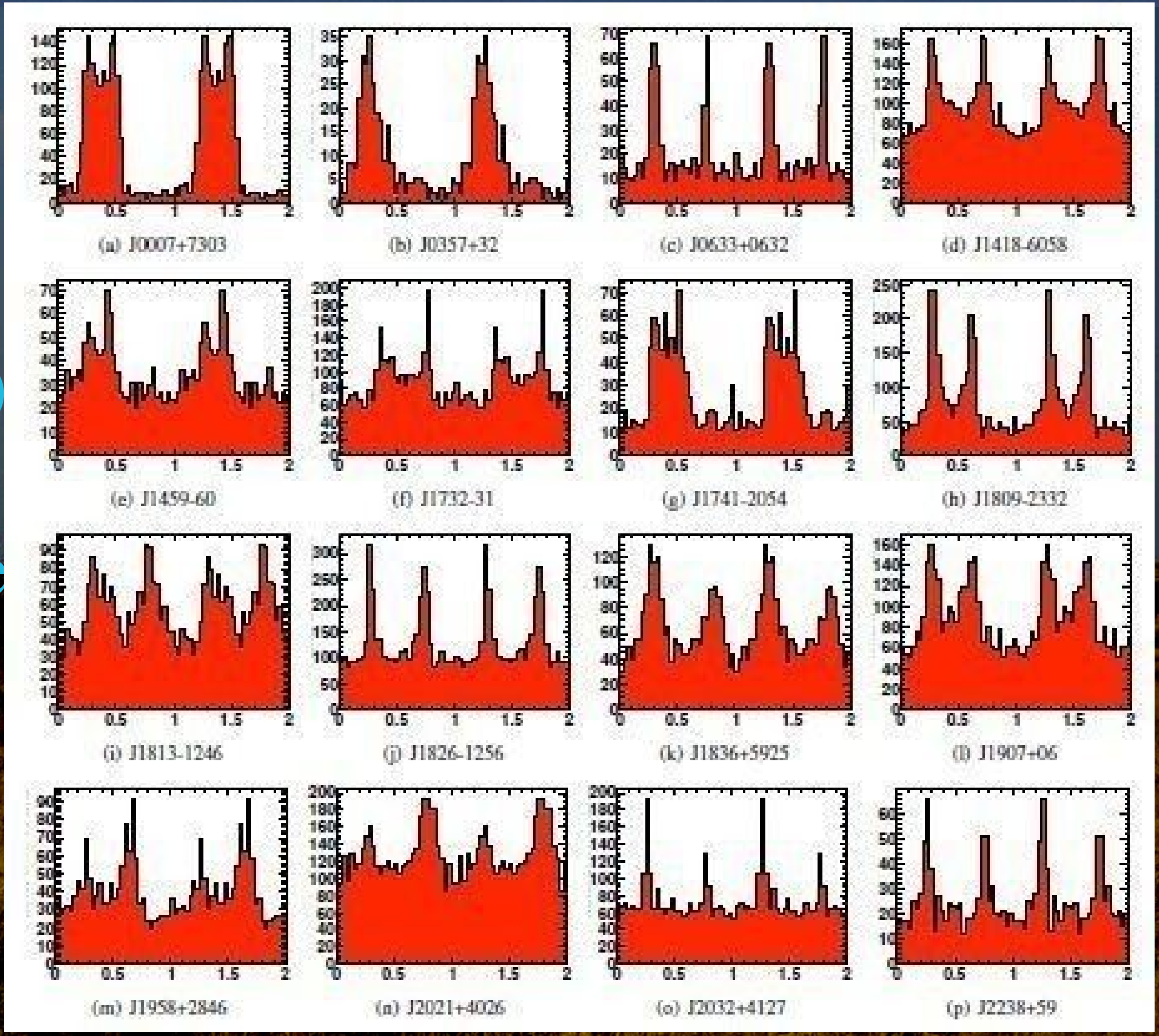
# Pulsars

- Compact object (neutron star) highly magnetized, rapidly rotating:
  - R ~ 10 km
  - M ~ 1.4 $M_{\odot}$
  - Period ms ⇒ s
- Several possible acceleration regions

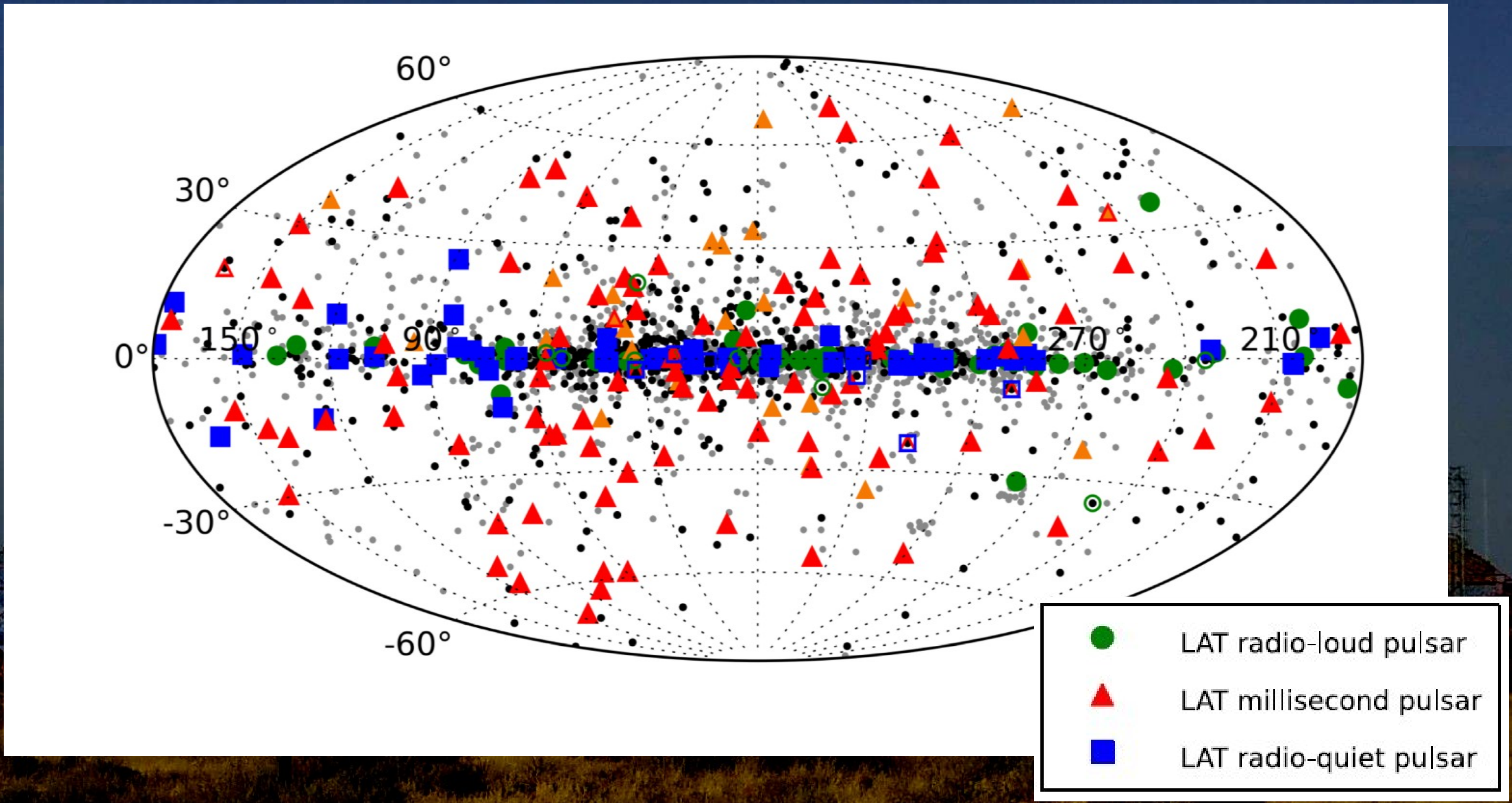


# Gamma-ray pulsars

- Gamma-ray pulsar: seen only in GeV.
- EGRET: A single gamma-ray pulsar (Geminga) out of 8 pulsars
- Fermi: discovery of a full population (16 in 6 month)
- Strong constraints on the geometry of emission zone (cone opening angle vs energy)

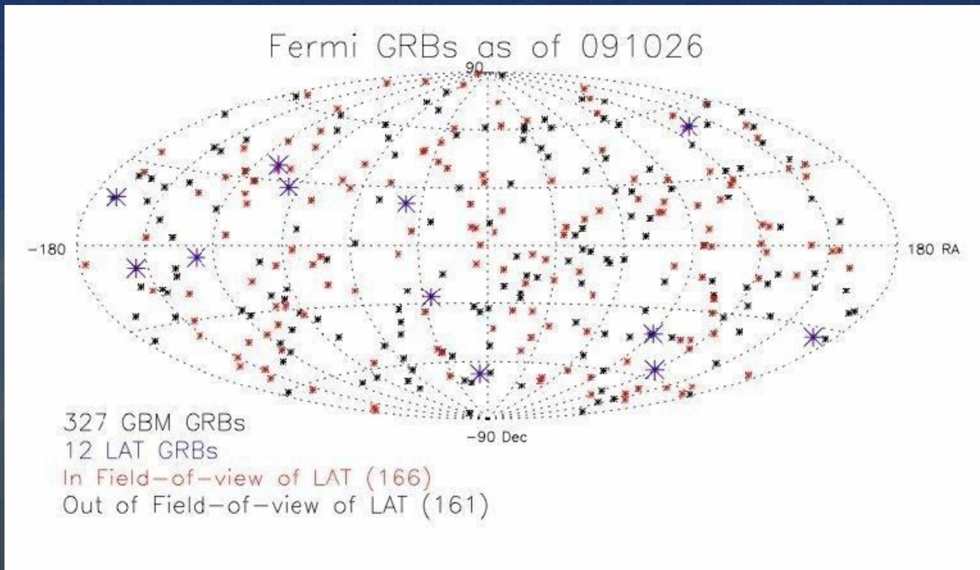


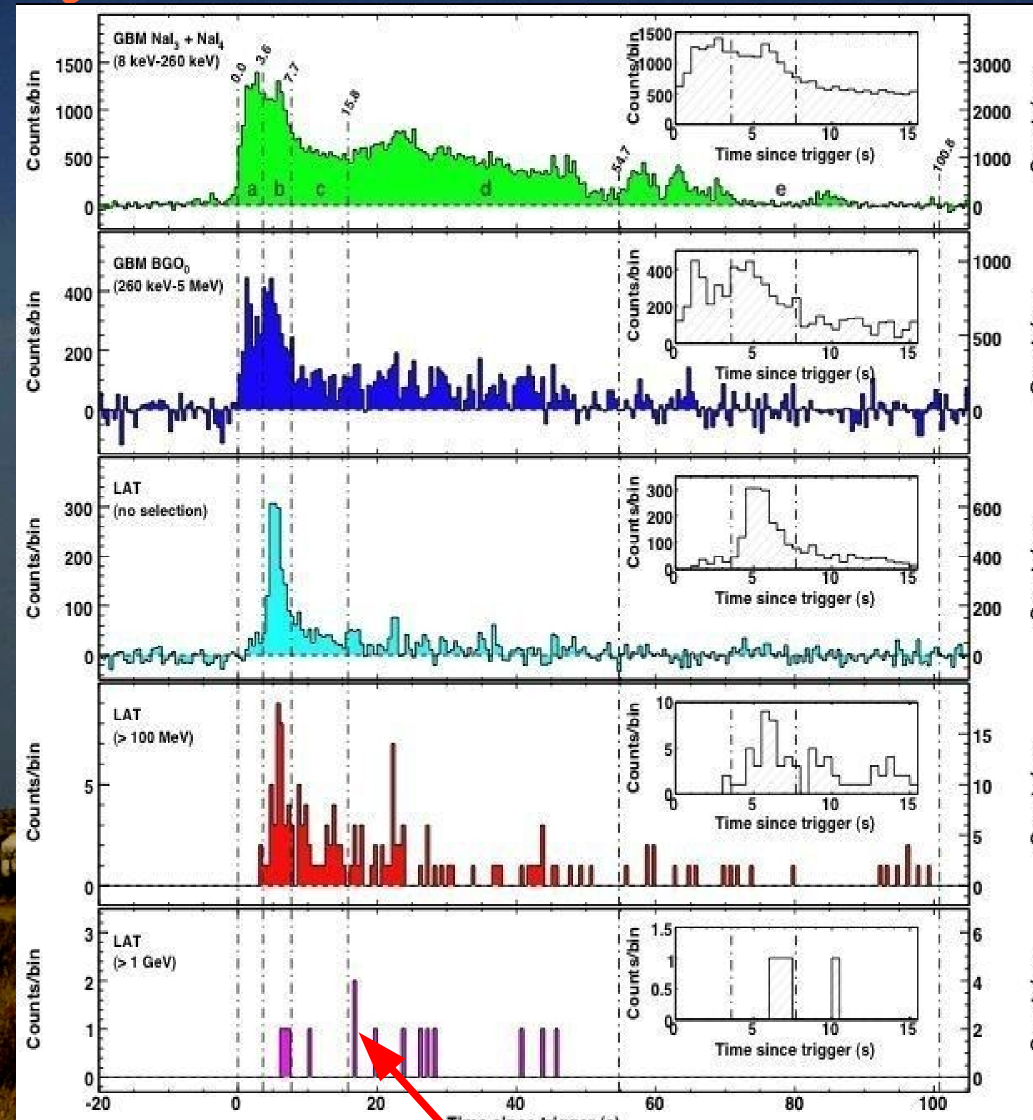
# Pulsar catalog




- Population growing rapidly (> 240 in 2018)
- Millisecond pulsars: re-accelerated (in binary systems)
- Cutoff energy measurement, ...

# Gamma-ray bursts



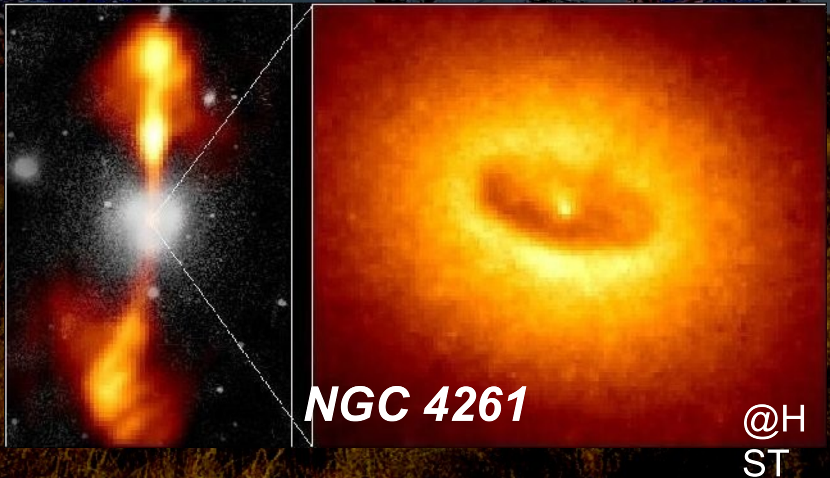



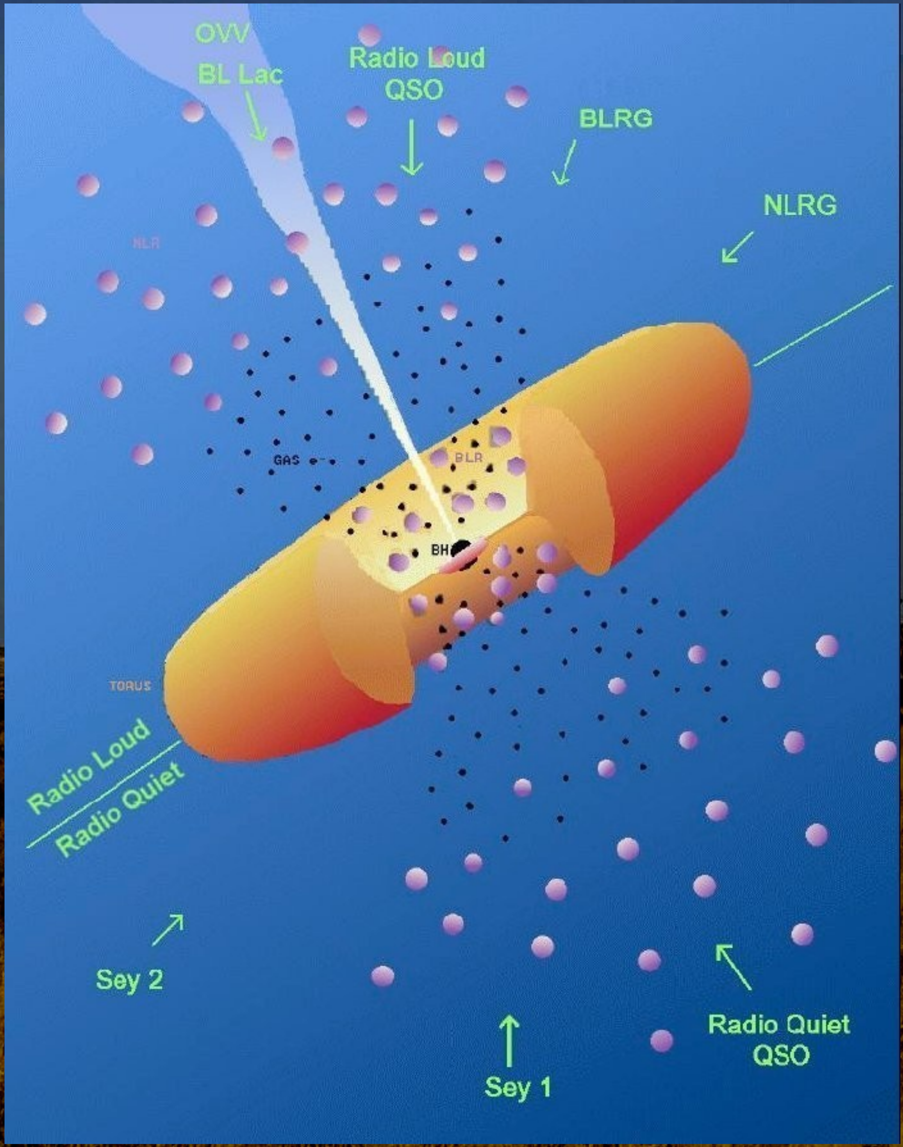

13.6 GeV

- Shorts burst of radiation (0.1 → 100 s)
  - Binary Mergers
  - "Hypernova"
- Several hundreds of GRB
  - A dozen seen in LAT
  - Time resolved spectra
  - Prompt emission > 10 GeV

# Blazars

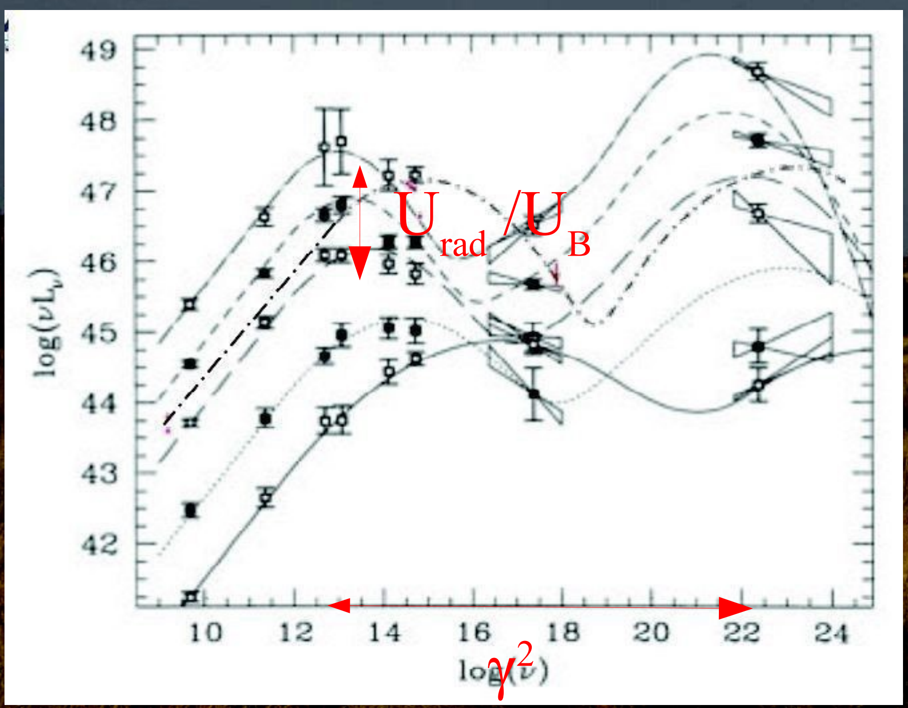
- Active Galactic Nuclei
  - Supermassive black hole surrounded by an accretion disk
  - Ultrarelativistic jets (Mpc)
  - Blazars: jets pointing towards the earth
  - Highly variable TeV emission: two model classes:
    - Leptonic
    - Hadronic (through $\pi^0$ decay)
  - Possible connection with UHECRS

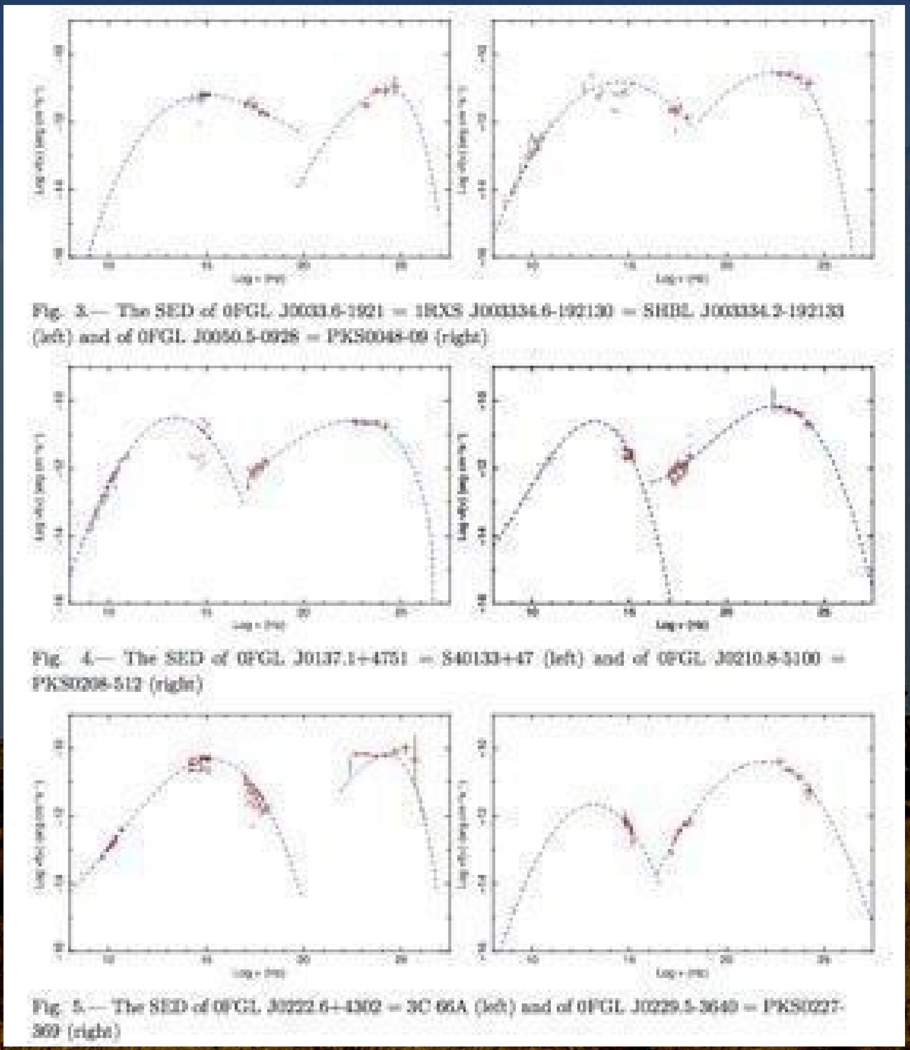


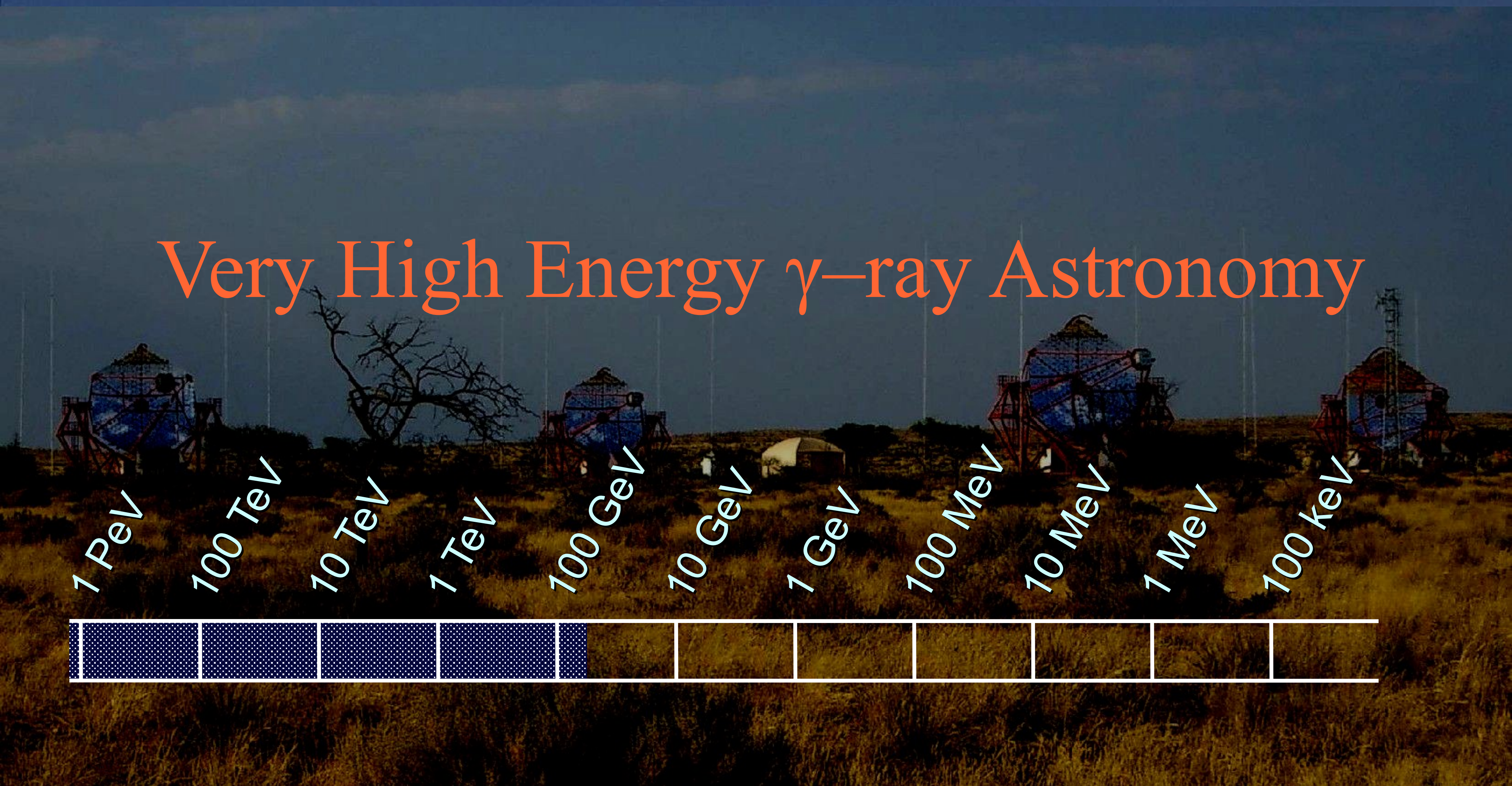
# Blazars

- Good quality MWL data
- Sequence of blazars emerging
- Population studies
- Tests of models (correlations X/γ,...)



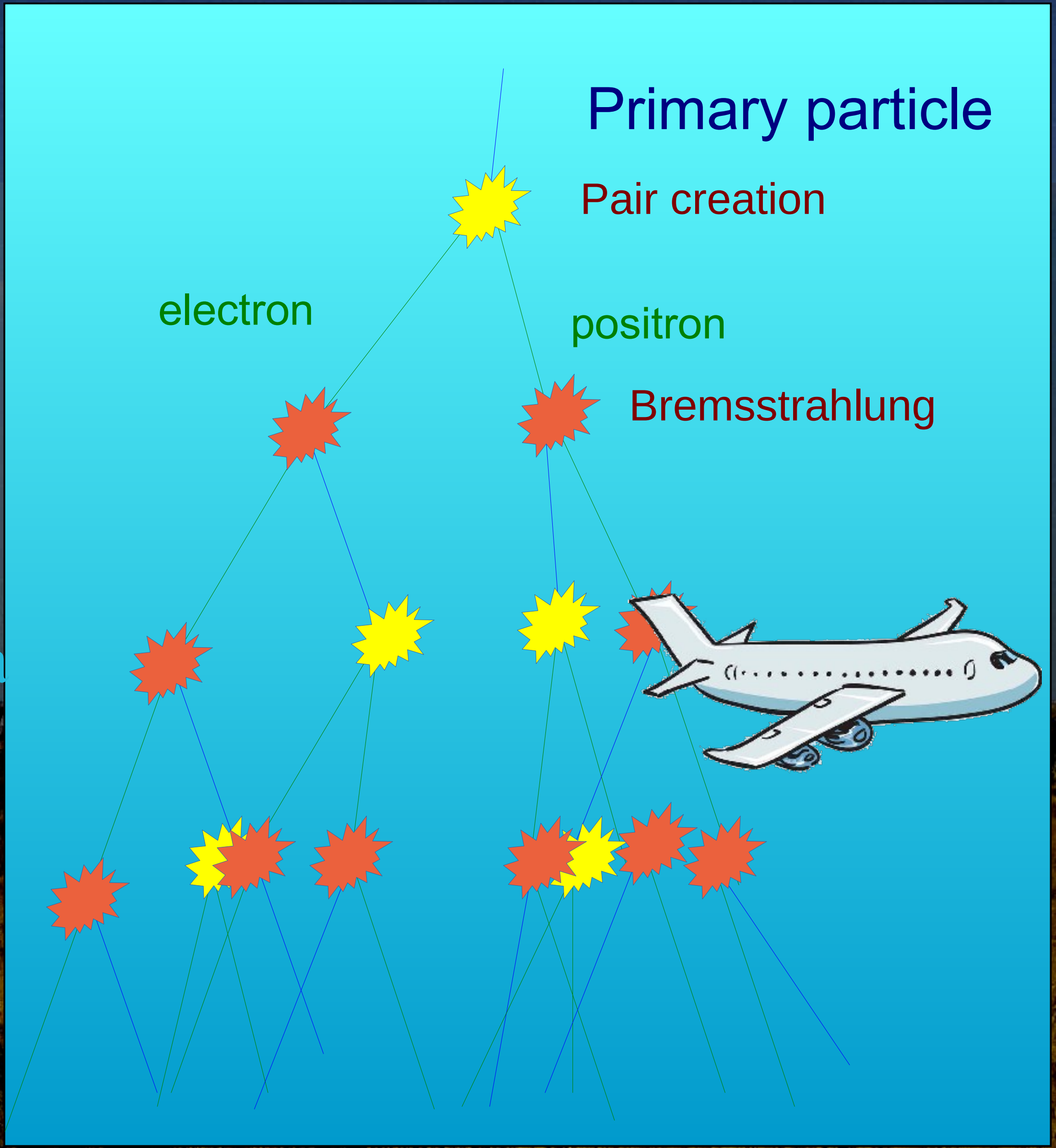



# Very High Energy γ–ray Astronomy



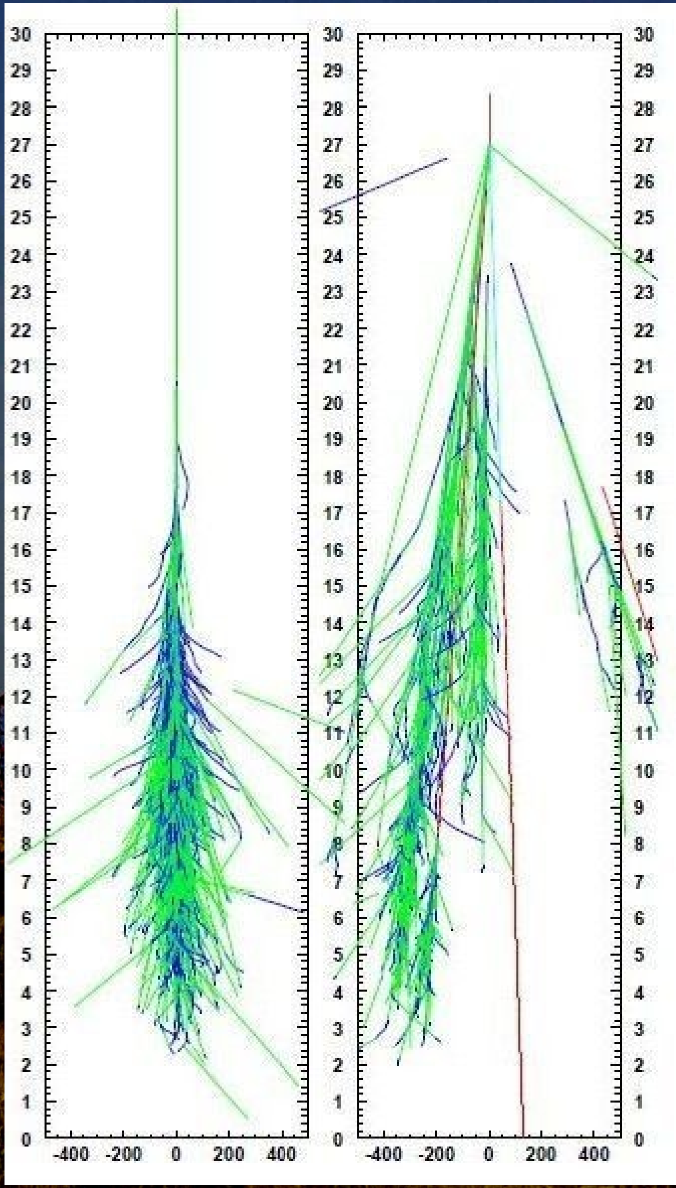
# Atmospheric Showers

- Interaction of primary particle with a nucleus in the atmosphere (~ 10 km altitude)
- Creation of pairs (electron & positrons) & bremsstrahlung processes redistribute the energy to a large number of particles

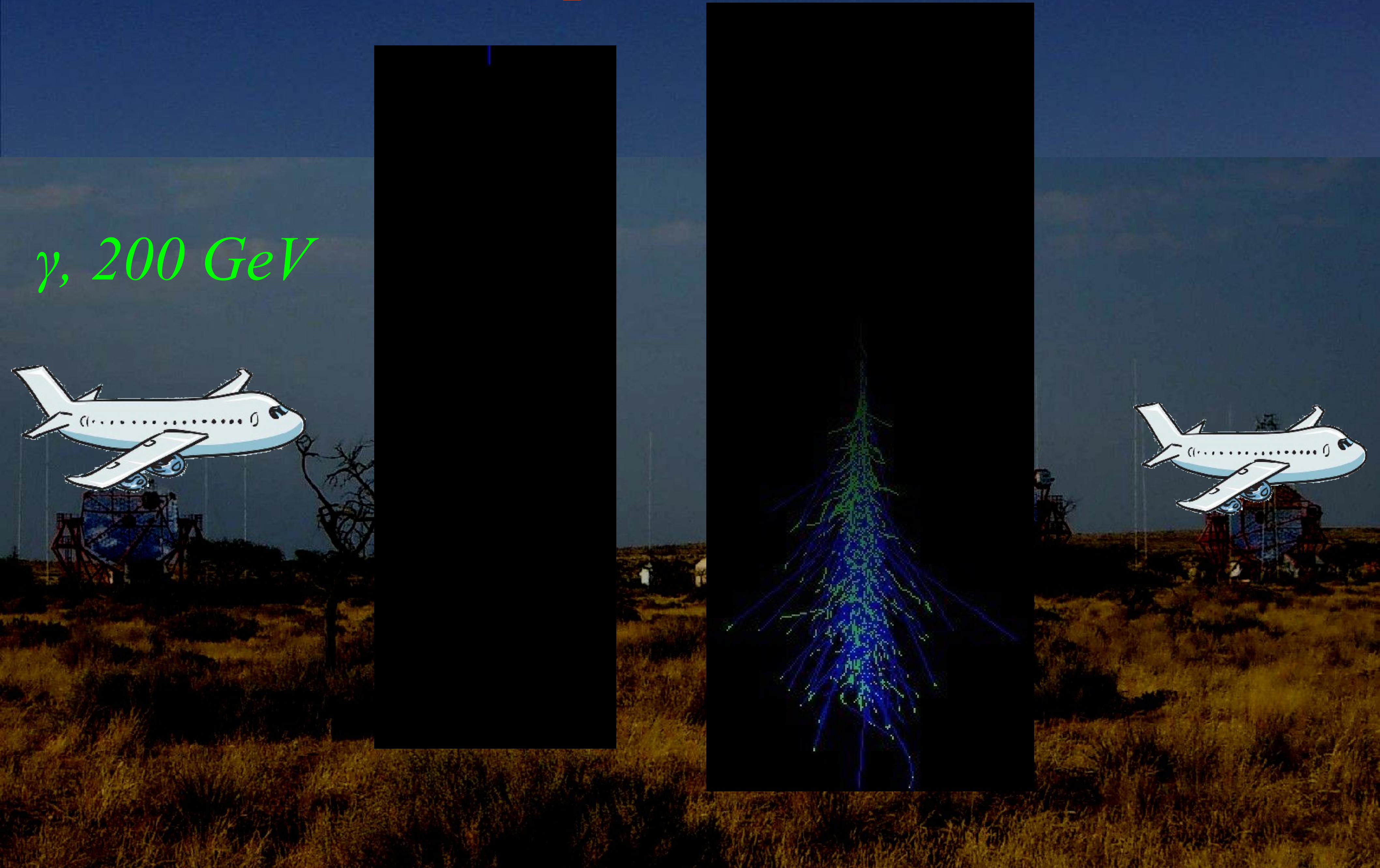


# Atmospheric Showers

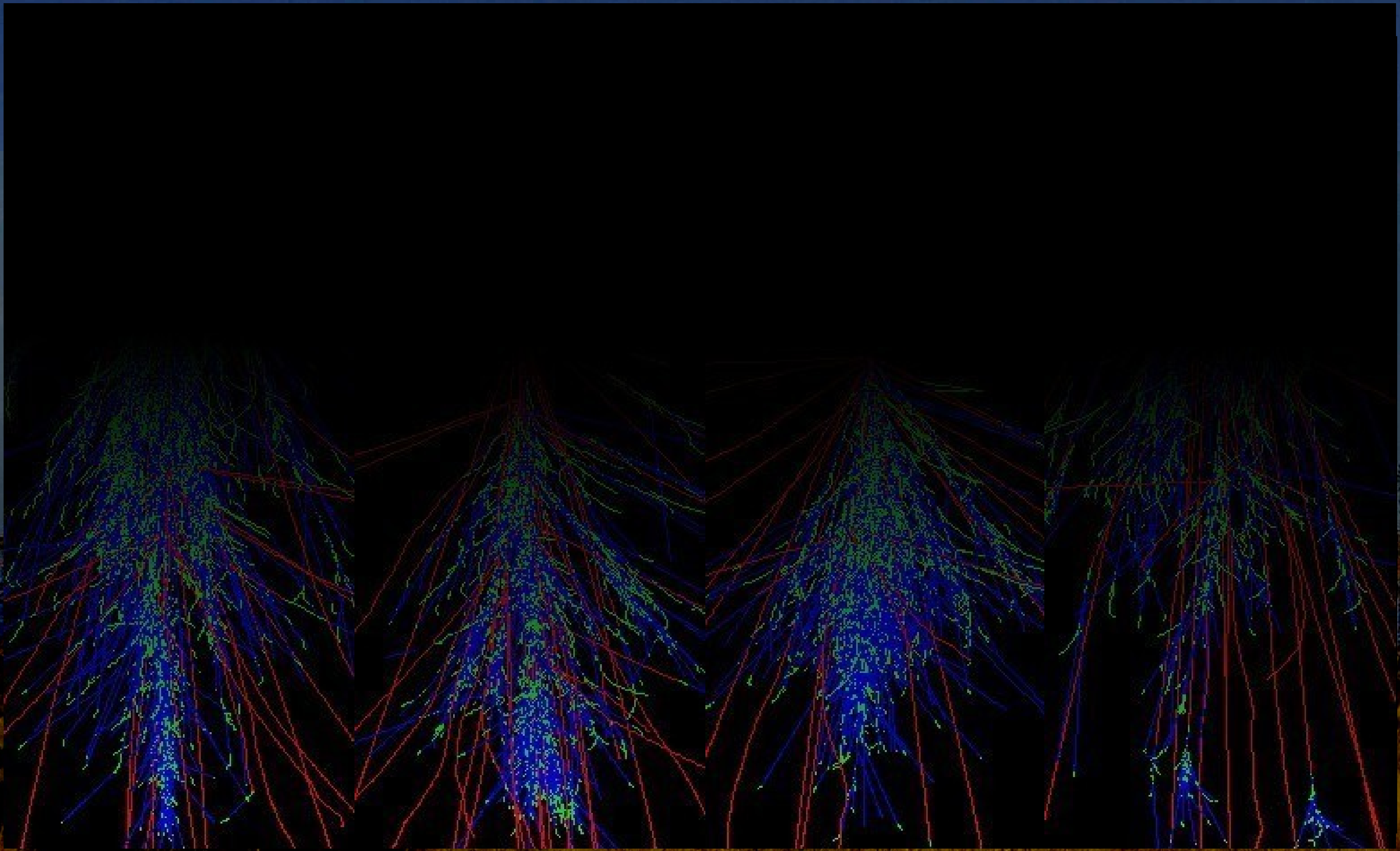
- Primary interaction in the high atmosphere
  - Shower of secondary particles, detectable up to a few 100 m
  - Large effective areas (>$10^5$ m$^2$, increasing with energy)
  -  High energies (≥ 1000 TeV)
- Atmosphere used as an inhomogeneous calorimeter.
- Observables: charged particles, Cerenkov light, fluorescence light, radio emission
- Reconstruction: Energy, direction, impact, nature of primary particle (γ-hadron ; light (p, He) – heavy nuclei (Fe))



# Atmospheric Showers

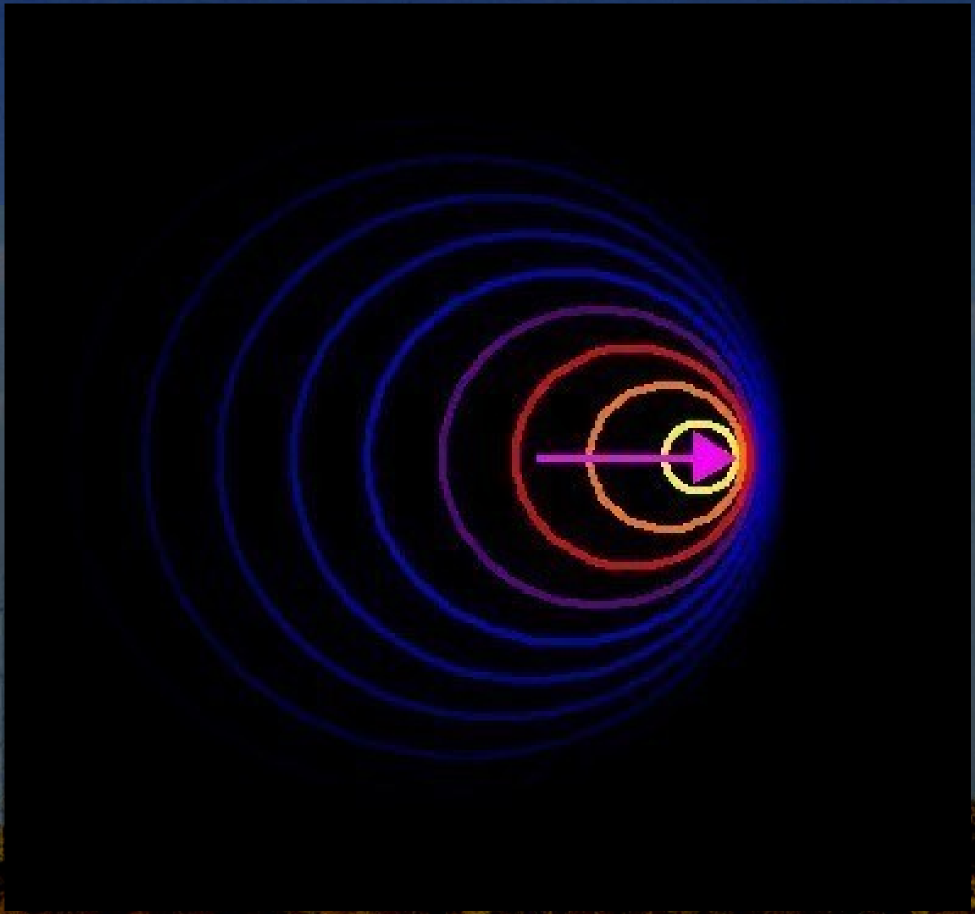


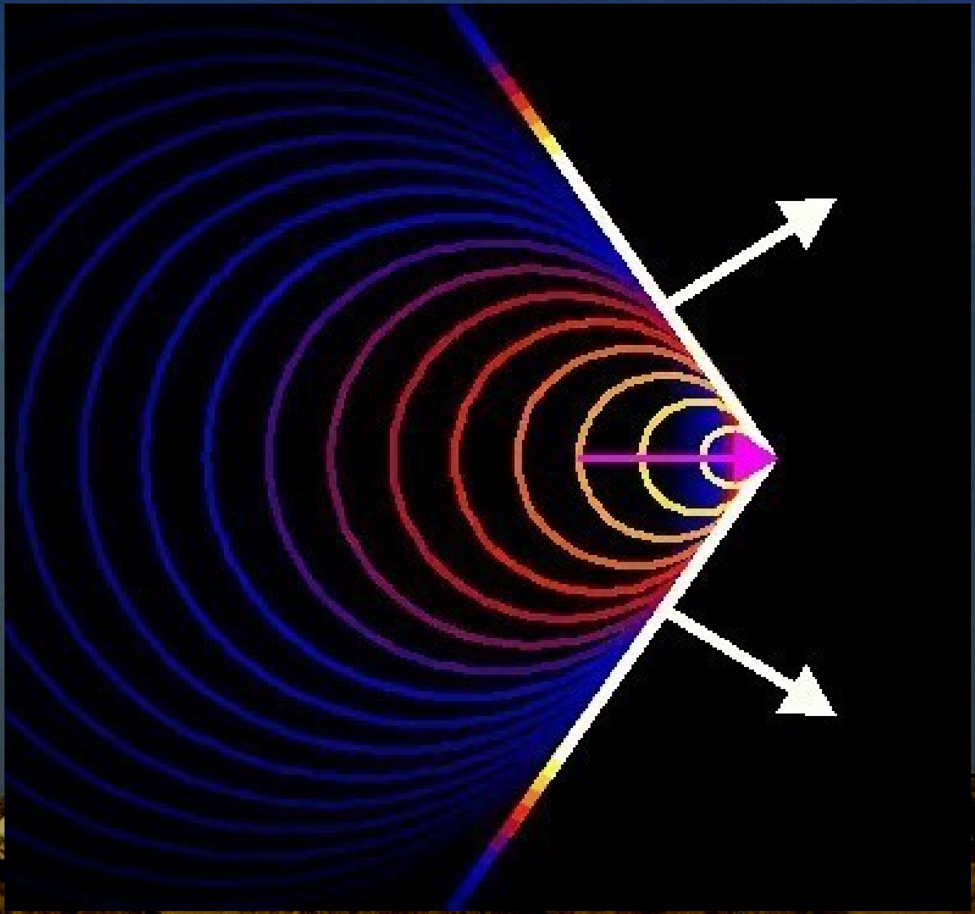
# Atmospheric Showers



- Atmospheric showers initiated by protons and nuclei fluctuate more, and contain penetrating particles (muons)

# Sound Wall

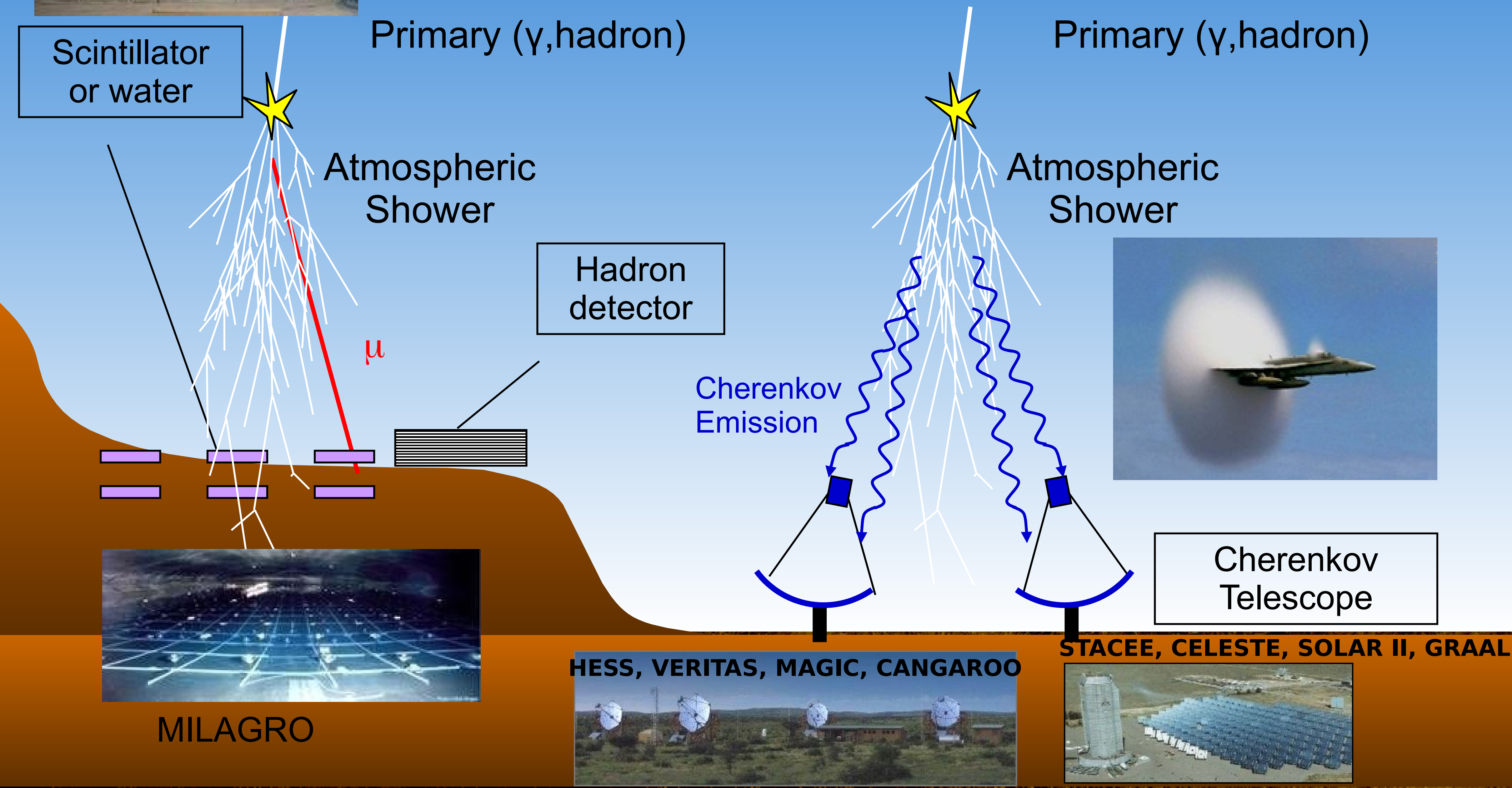




- When a plane flies faster than speed of sound, sound emitted at each time accumulate on a cone → Sonic Boom

TIBET

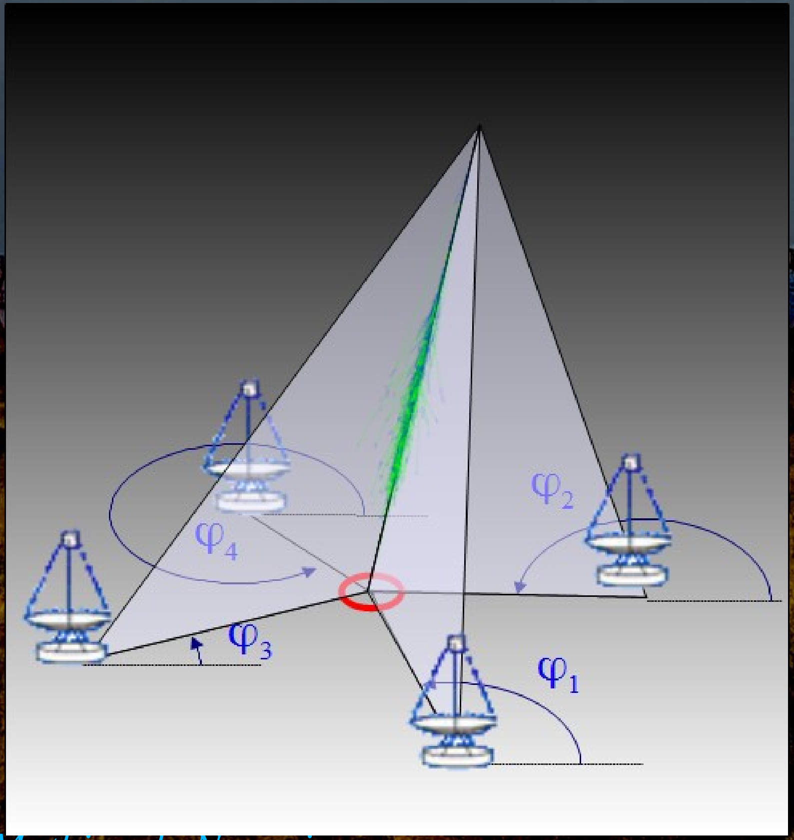
# Observables and experimental techniques ( E > 10 GeV )



# 2 Complementary Techniques

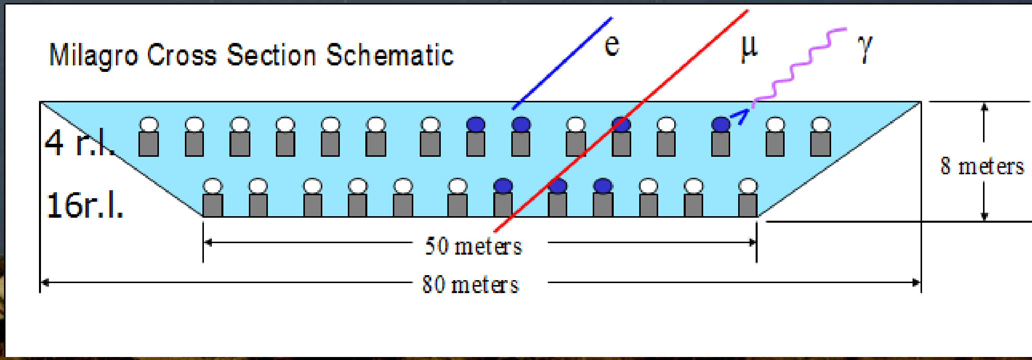
- Atmospheric Cherenkov Telescopes:
  - Small F.O.V.
  - Low duty cycle
  - High rejection
  - High resolution

Detailed study of a few sources

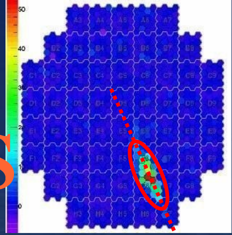



- Sampling experiments (Water Cerenkov, Particle Arrays,…)
  - Large F.O.V.
  - High duty cycle
  - Poor rejection
  - Poor resolution

Long term survey instruments

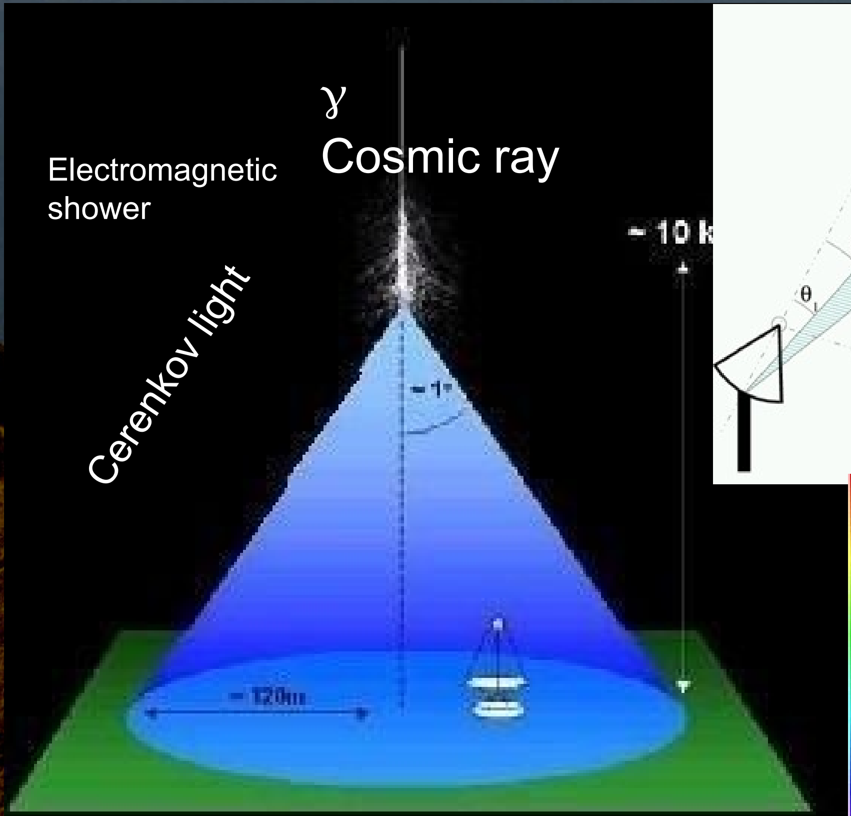


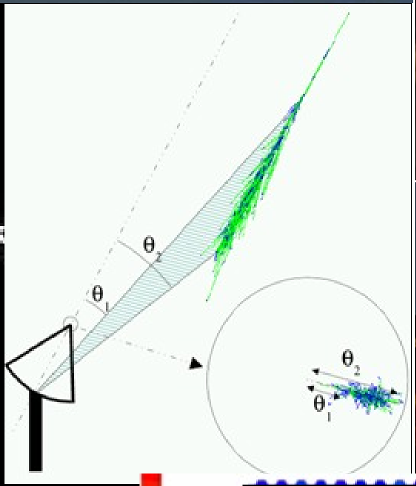

# Atmospheric Cherenkov Telescopes

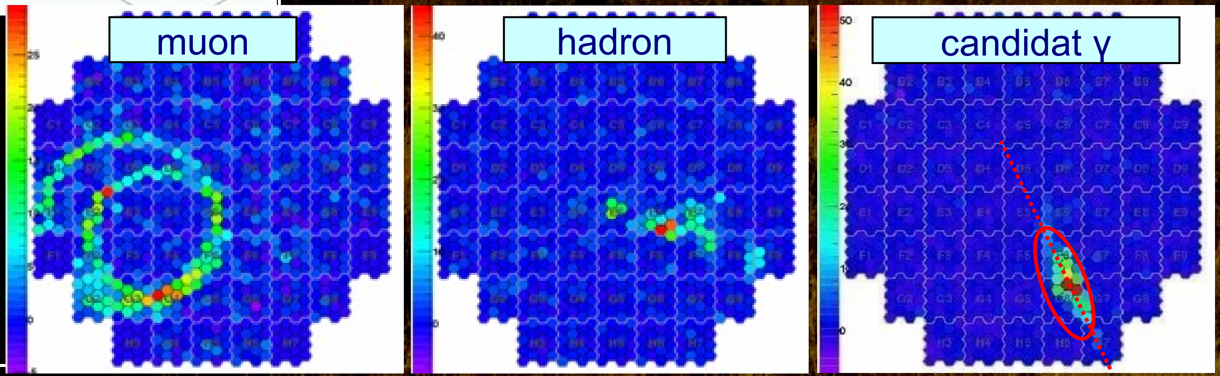


- Cherenkov light-pool ~ 120 m
- Image the shower on a fact camera (ΔT ~ 2ns)
- Large effective area ($10^5$ $m^2$) even with modest reflector

- Key parameter : speed (< 10 ns)
- Image shape used in discrimination



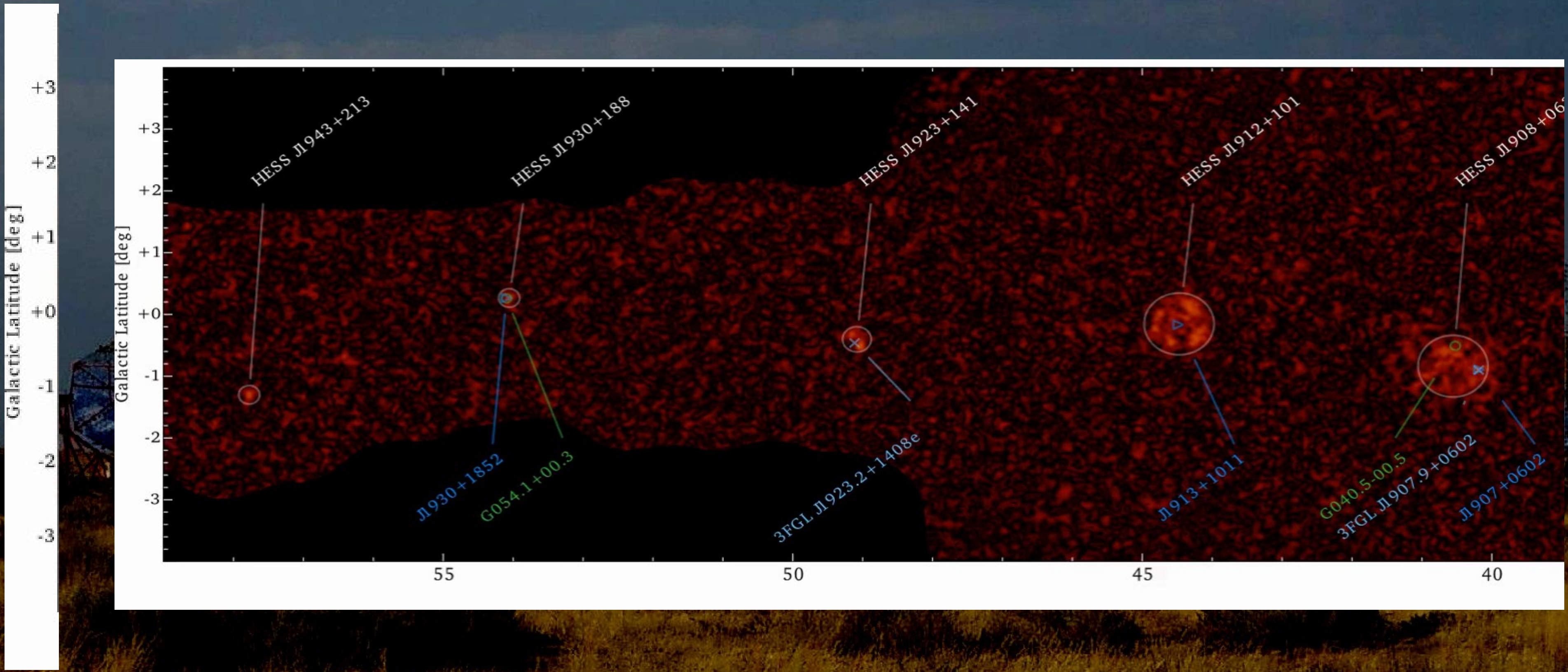
# VHE γ-ray world

# High Energy Stereoscopic System

- H.E.S.S. phase 1:
  - 4 telescopes: Ø 12 m,107 m$^2$
  - 960 pixels/camera, FOV : 5°
  - Observations : ~1000h/an
  - Localisation accuracy : ~ 10”
- H.E.S.S. phase 2:
  - 5$^{th}$ telescope, Ø 28 m, 600 m$^2$
  - 2048 pixels, FOV : 3.5°
  - Ponting in < 1 min for 50 % sky
  - Extended energy range

# HESS Galactic Plane Survey

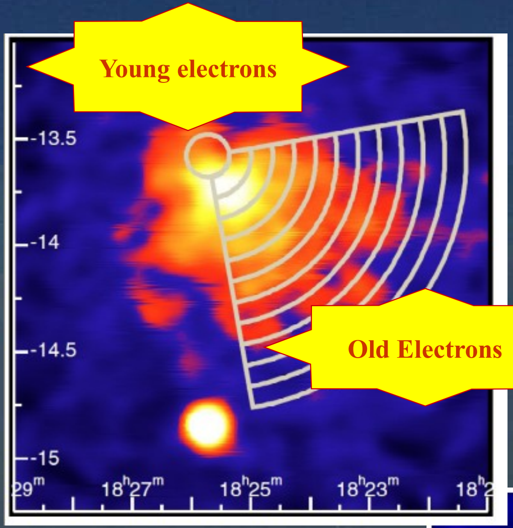
- Major HESS project: 2700 h of data (2004 – 2010)

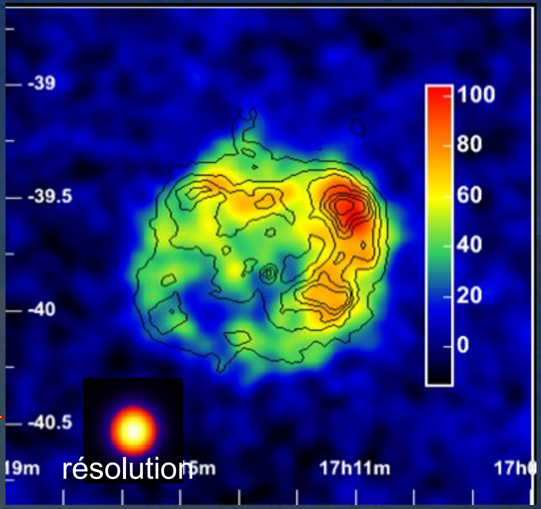


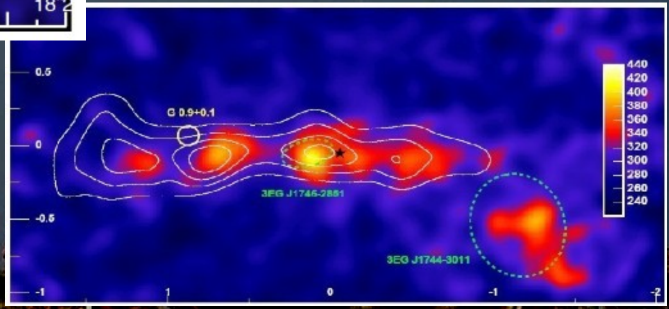

- 78 sources of different types (SNRs, PWNs, Binaries, …)
- VHE Universe much richer than expected

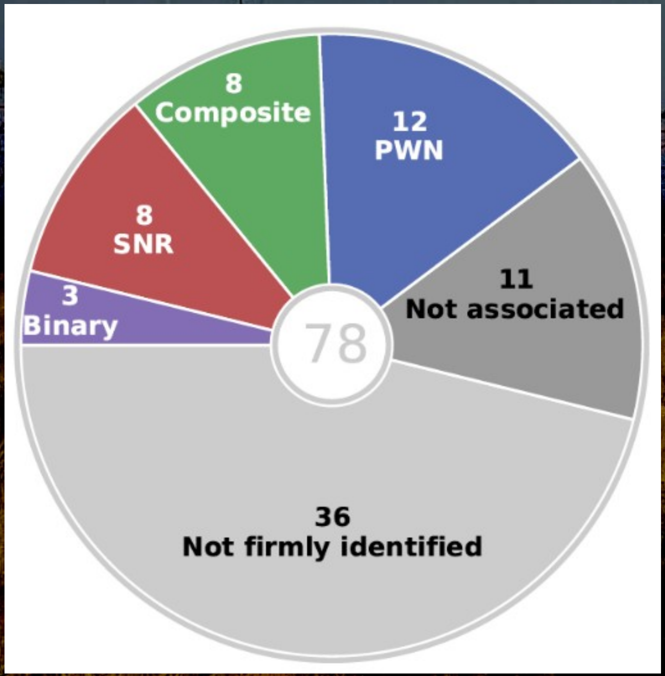
# Galactic Bestiary in a nutshell

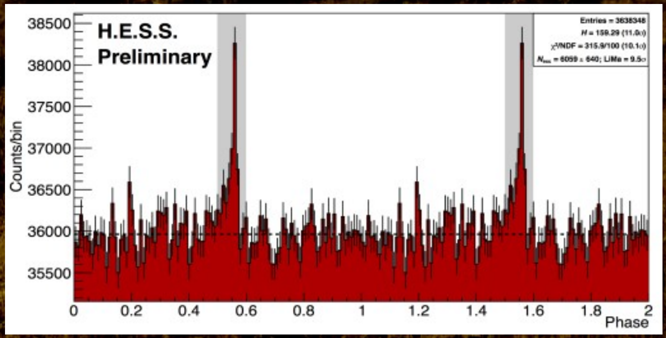
- A complete zoo :
  - Supernova Remnants
  - Galactic Centre
  - Pulsar Wind Nebular
  - Interacting Binary Systems
  - Young, Energetic Pulsars
  - Diffuse Galactic Emission



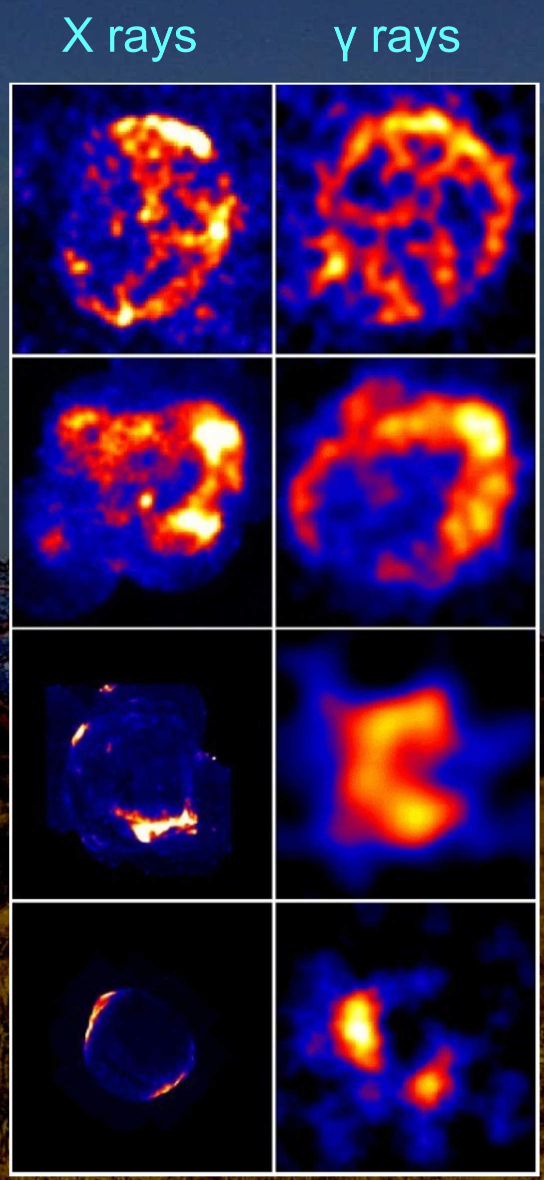
# Supernova Remnant

*Artist's view (ESA/Nasa)*

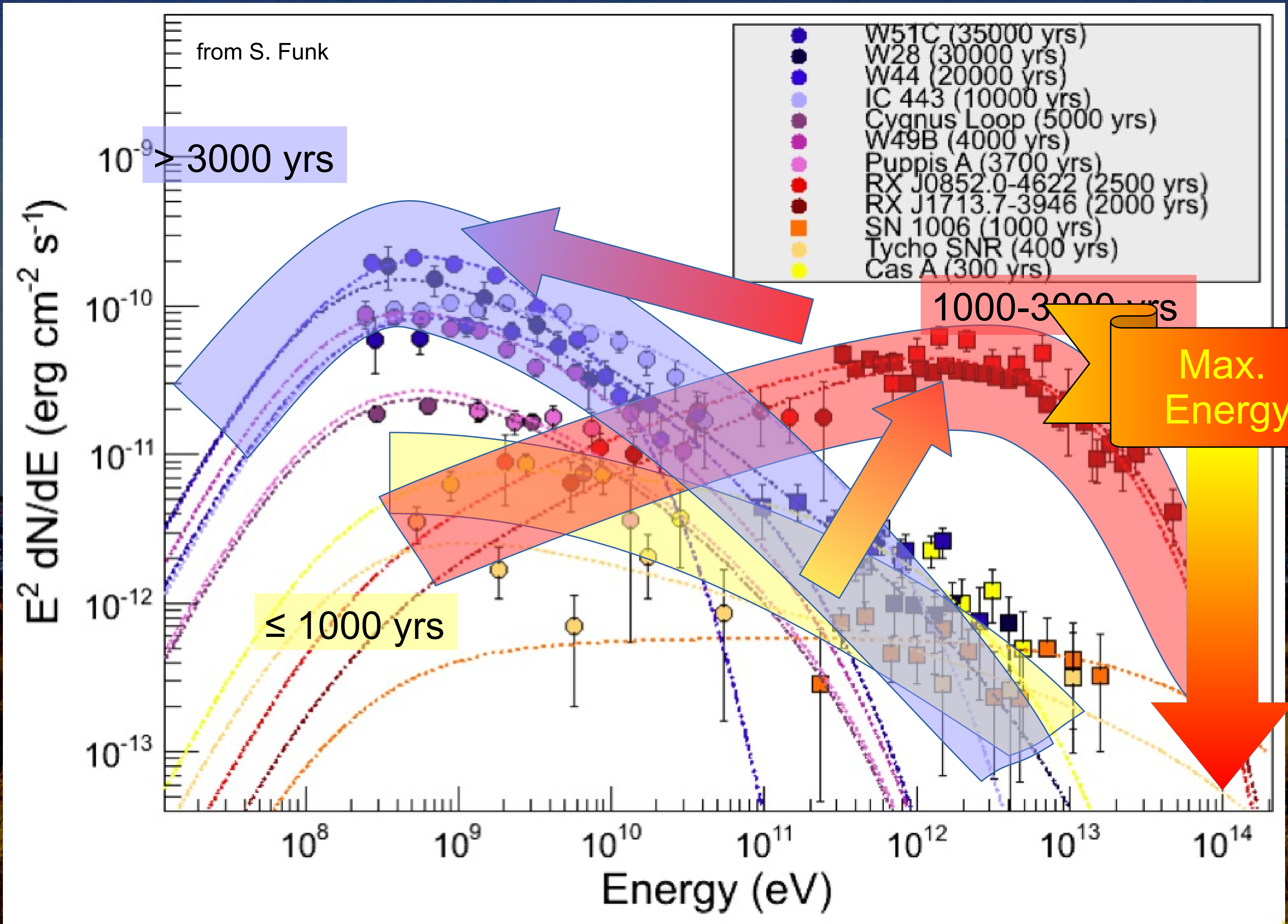
- Remnant of the explosion of a massive star
- Shock wave (> 1000 km/s) sweeping up interstellar medium
- Thermal emission from hot material inside the shell in X rays ($10^6$ K)
- Place of heavy element nucleosynthesis → at the origin of life!
- Enormous Released energy $\sim 10^{44}$ J ($10^{16} \times$ Hiroshima )
- Best candidates for galactic cosmic rays
  - Matching rate 1 SNR/Galaxy/century
  - Conversion efficiency ~10%

# State of the art

- SNRs are the second population of VHE sources in the Milky Way
- Morphologies in X/γ-rays are often very similar, suggesting that the same particles give rise to the two emissions
- Maximum acceleration energy around 100 TeV

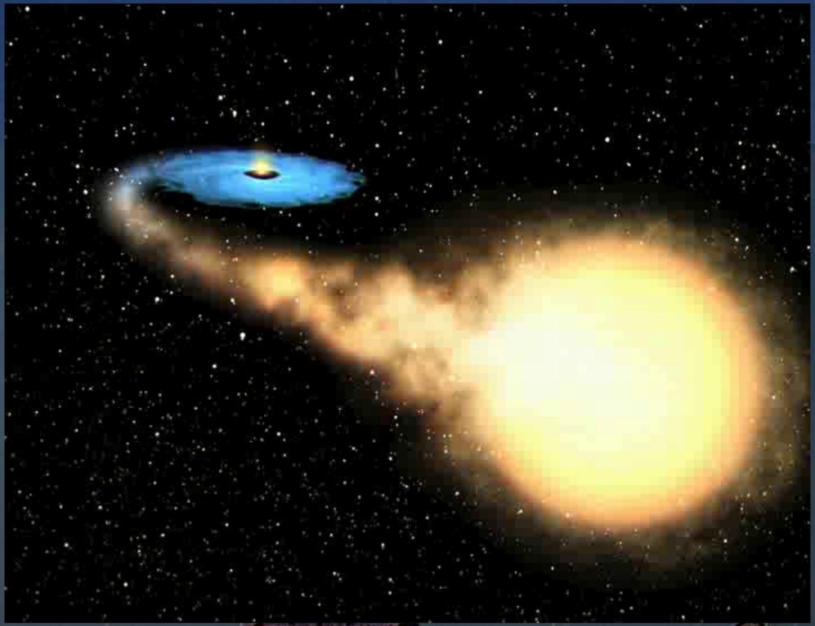


# Supernova Remnant Evolution



# Binary Systems

*Artist's view (ESA/NASA)*

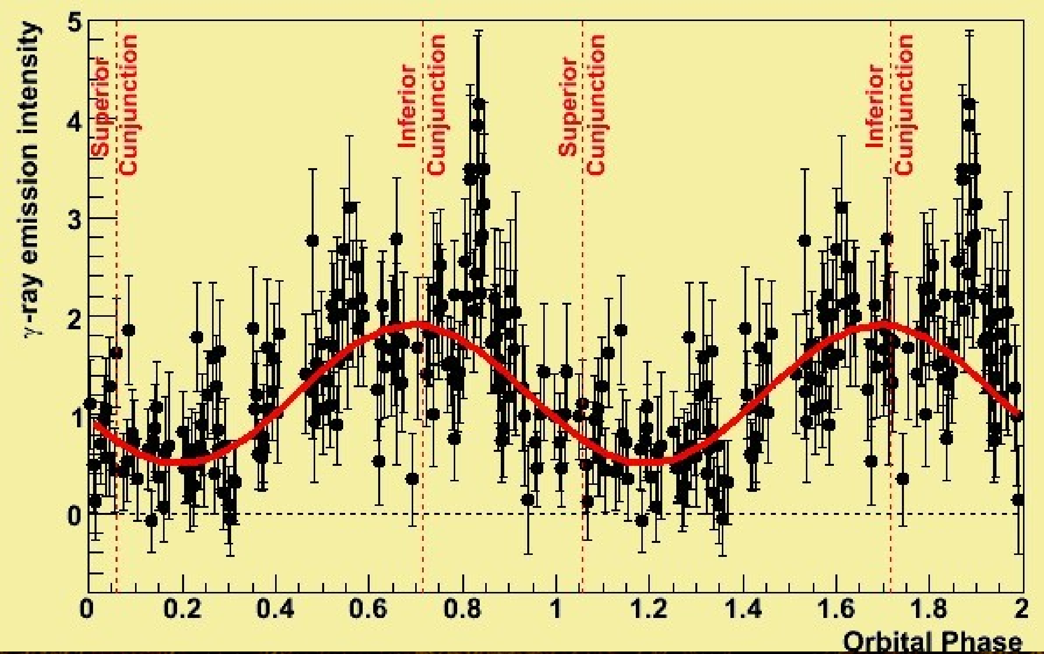


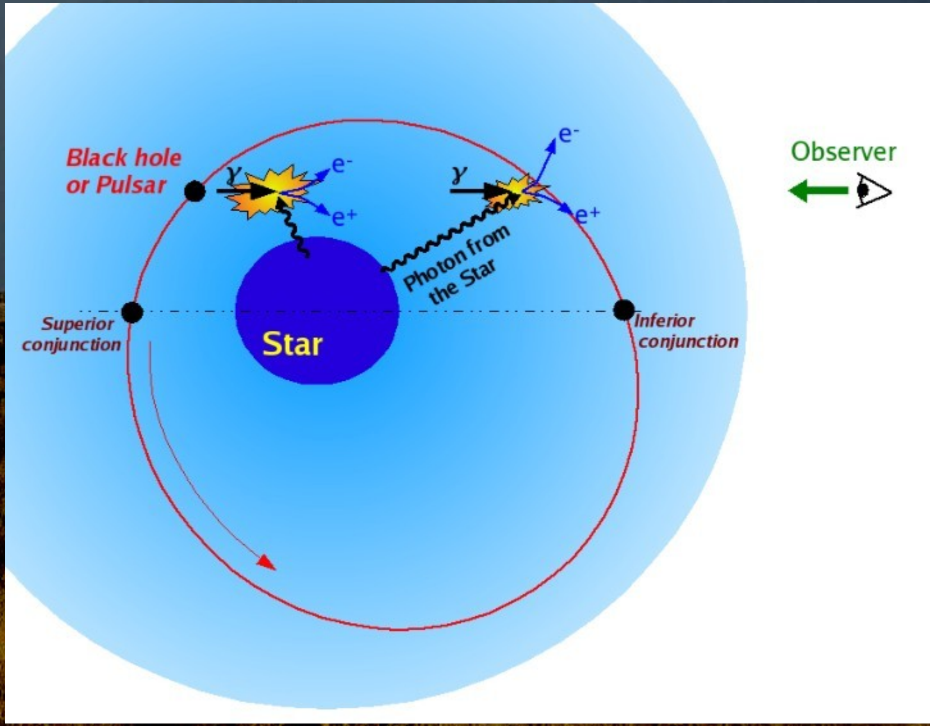
- 70% of stars in the Galaxy live in couples of 2 or more!
- Binary systems are formed of :
  - A compact object (black hole or neutron star)
  - A companion star
  - An accretion disk
  - Sometimes jets of plasma
- Complex physics, variable systems
- 5 VHE gamma-ray systems known.

*Tatooine (Star War)*

# LS 5039 : light is opaque to light !

- Compact binary system with tight orbit (0.1 A.U) and massive (20 $M_{\odot}$), UV (17 000 K) star
- γ-rays are absorbed by pair creation on the stellar photons ($\gamma + h_{\upsilon} \rightarrow e^{+} + e^{-}$)
- Geometry introduces a modulation of VHE emission



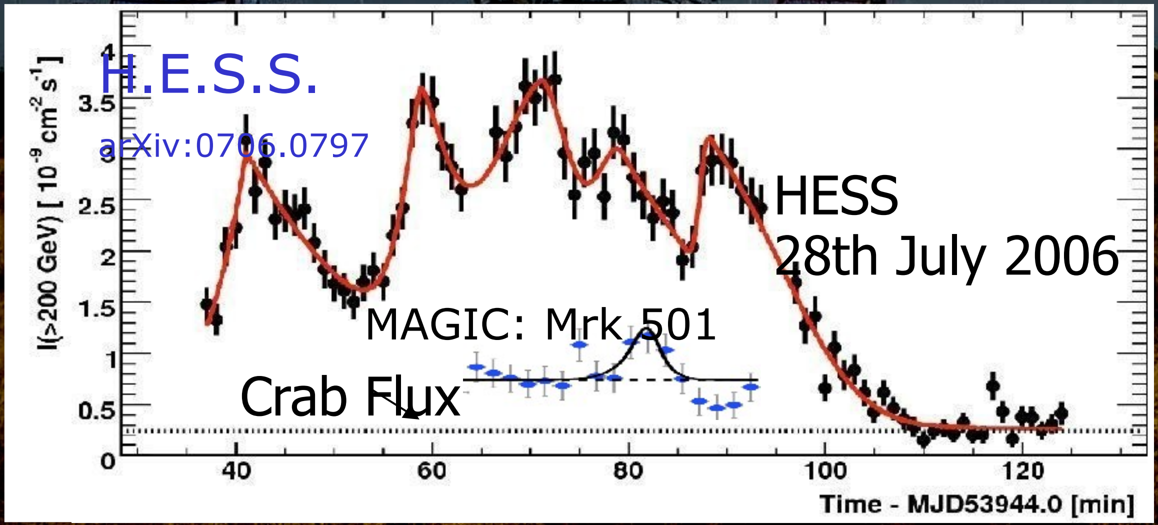
# Active Galactic Nuclei

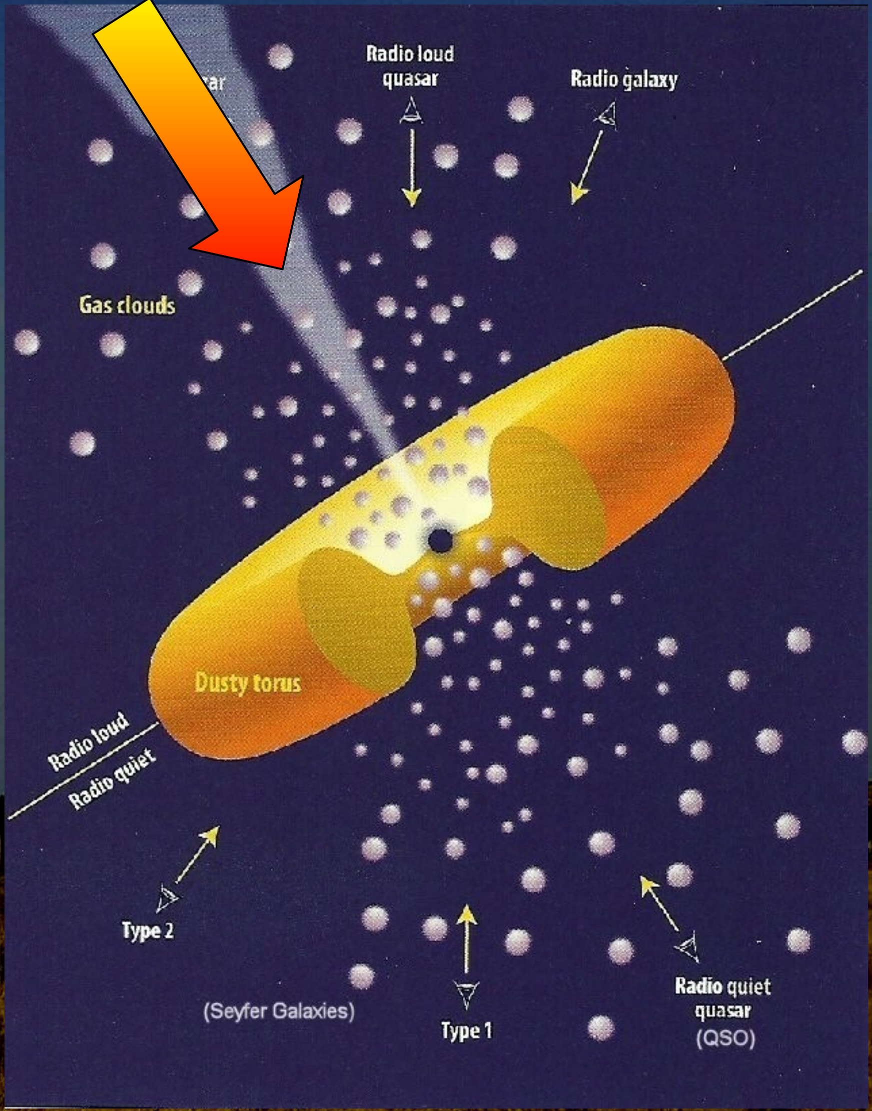
- Supermassive black hole ($10^6$-$10^9$ $M_\odot$) surrounded by accretion disk
- Giant ultra-relativistic jets of plasma (size ~Mpc)

*Artist's view (ESA/NASA)*

# Blazars

- Active Galactic Nuclei, seen face-on
- Jets outshine completely the galaxy & accretion disk
- Very variable emission, on short time scales (< min)
- Can be used to check that the speed of light is really a constant (not depending on light energy)

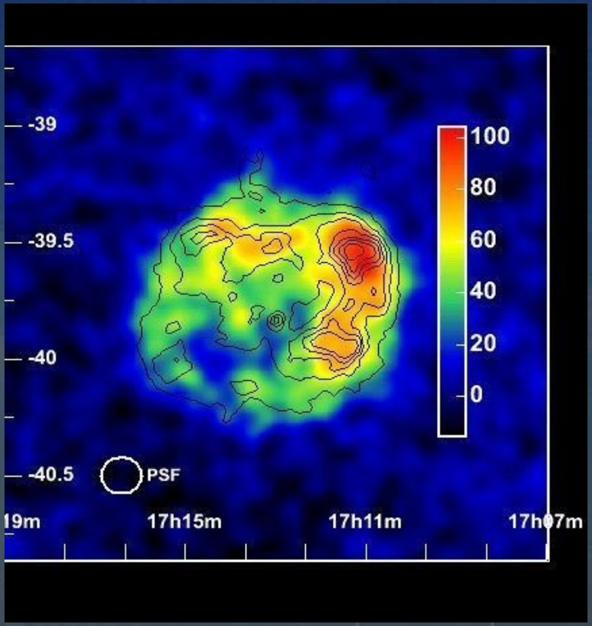


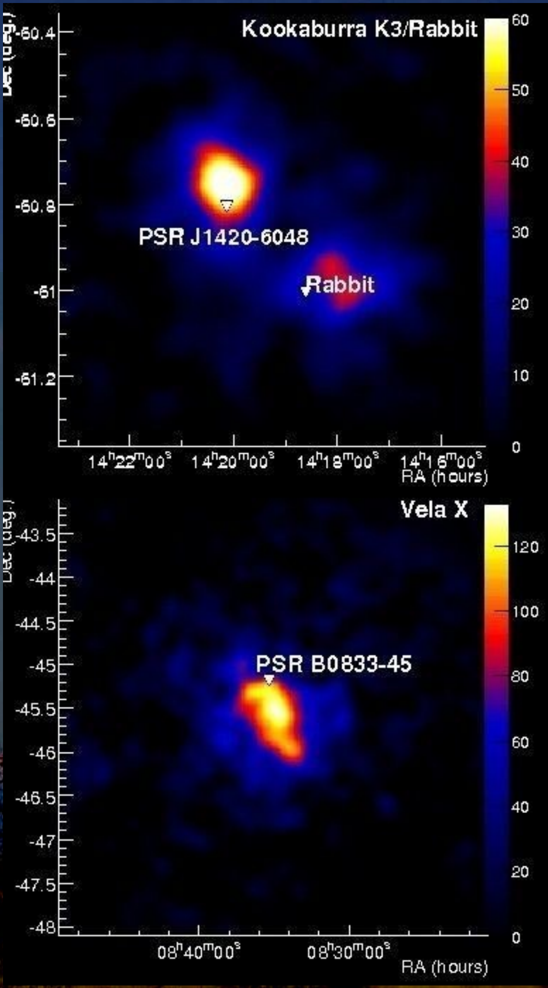




$$c' = c\left(1 \pm \xi \frac{E}{E_P} \pm \zeta^2 \frac{E^2}{E_P^2}\right)$$

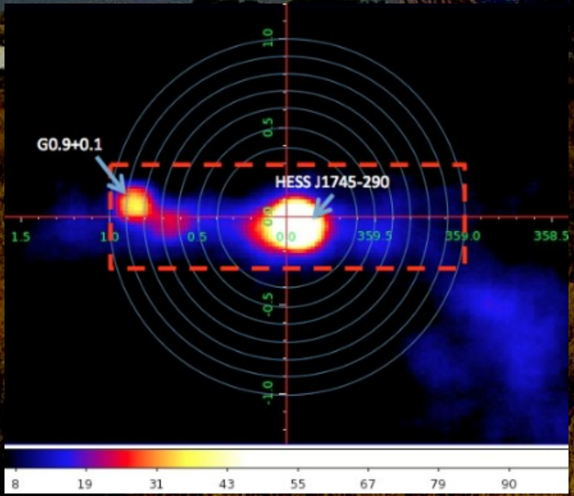
# Results – Many Others

- Wealth of results:
  - Supernova remnants
  - Plerions
  - Galactic Center
  - Binary Systems
  - Interacting Stellar Winds
  - Starburst galaxies
  - Huge flares from blasars,
    Tests of Lorentz Invariance
  - Indirect dark matter searches,
  - ….

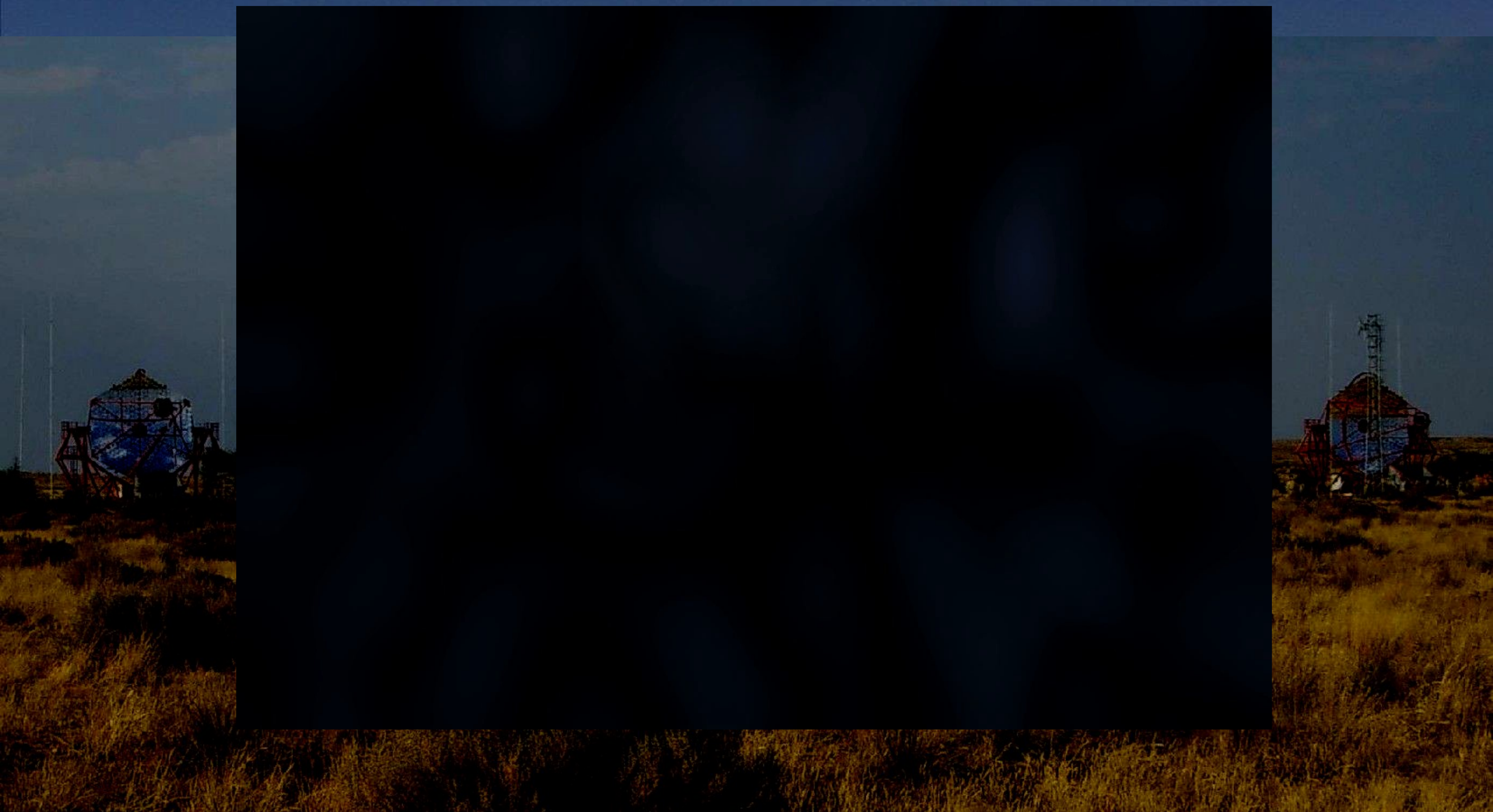



Unveiling the sources of cosmic rays!

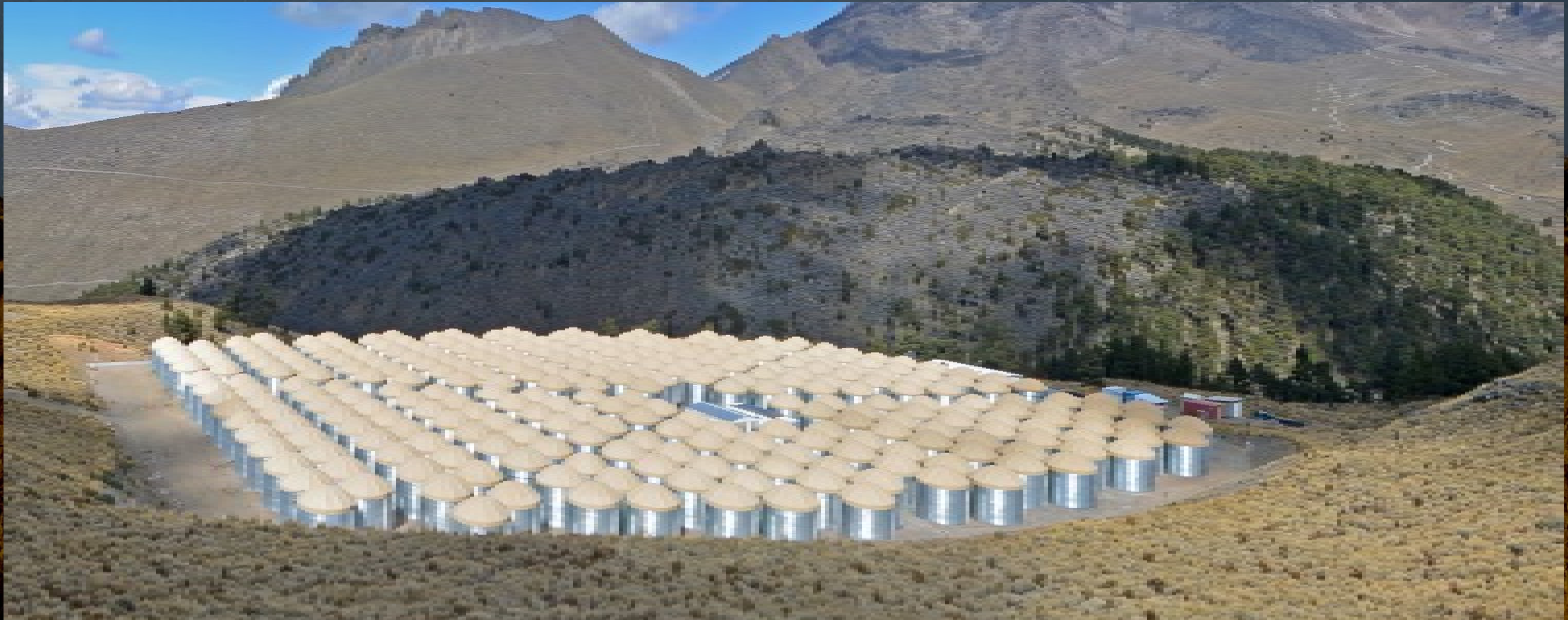


# Cherenkov Telescope Array



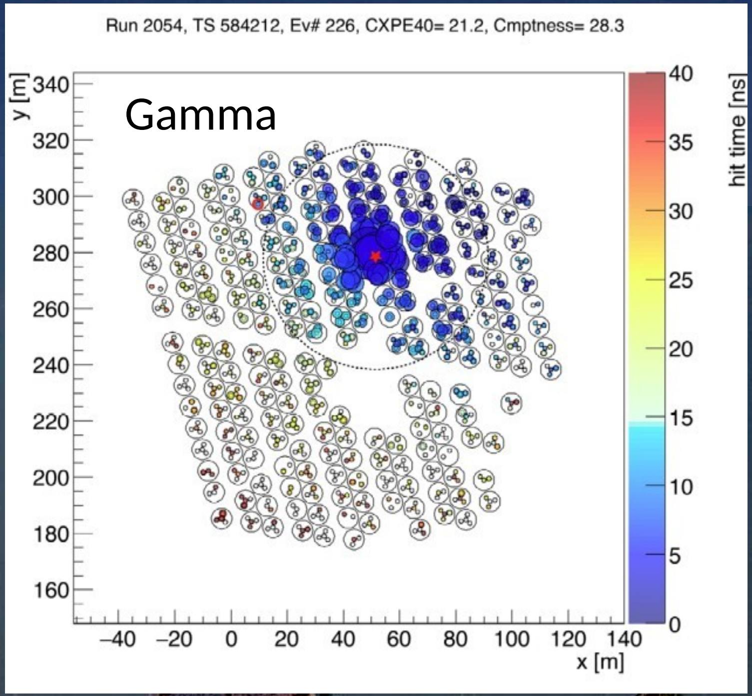
# HAWC

- High altitude Water Cherenkov detector
- Array of water tanks
  - 900 tanks each 4.3 m high and 5 m diameter 1 PMT at bottom
  - 150 m x 150 m array
  - 75% ground coverage
- Sierra Negra, Mexico, alt: 4100 m      lat: +19°

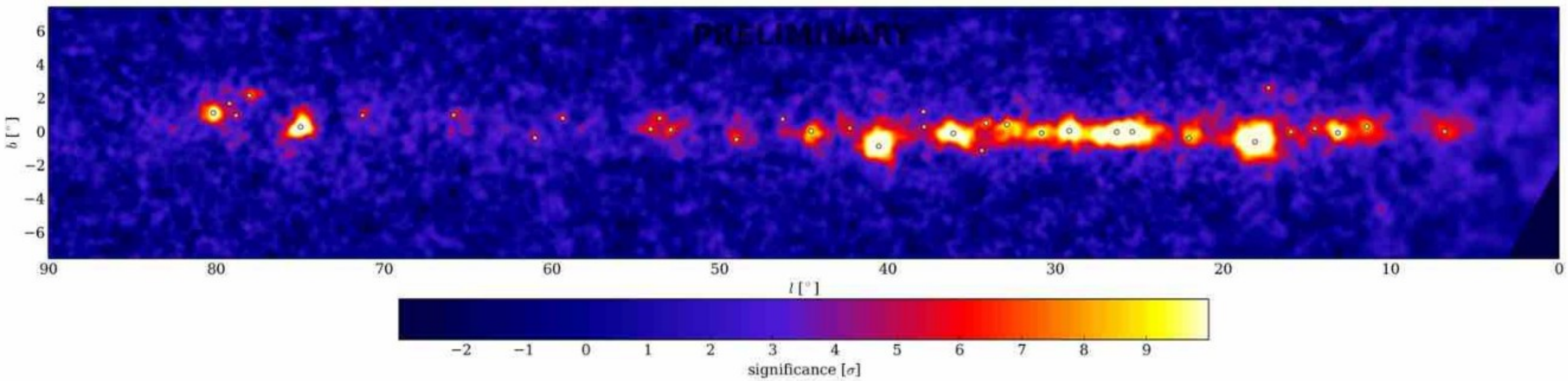


# HAWC

- Advantages:
  - Wide field of view
  - 100% duty cyle
- Drawbacks
  - Sensitivity much lower than IACTs
  - Angular resolution ~ 1°
  - Bad energy reconstruction




- Complementary to IACTs, starting to produce results



# Conclusions

- Gamma-ray astronomy (from ground & space) underwent a revolution in the last ~ 15 years
  - New window in the Universe opened: violent phenomena, sources of cosmic rays
  - H.E.S.S. in Namibia leader of the field
  - Lots of unexpected results (binary systems, millisecond pulsars, ..;)
- Major project to come in the field: Cherenkov Telescope Array