(Very/Ultra) High Energy Astrophysics II – Gamma Ray Astronomy
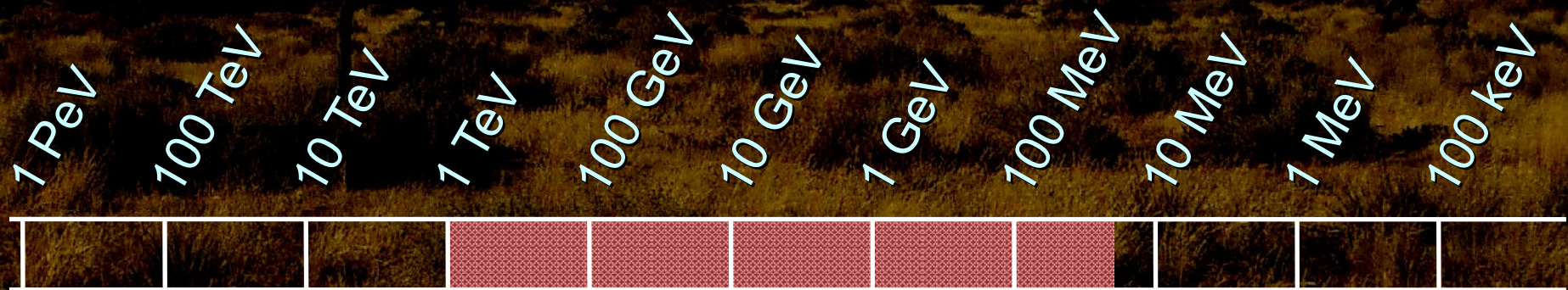
Mathieu de Naurois

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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)

1 PeV   100 TeV   10 TeV   1 TeV   100 GeV   10 GeV   1 GeV   100 MeV   10 MeV   1 MeV   100 keV

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

Anticoincidence shield

Conversion folds

Tracker

Calorimeter

e+   e-
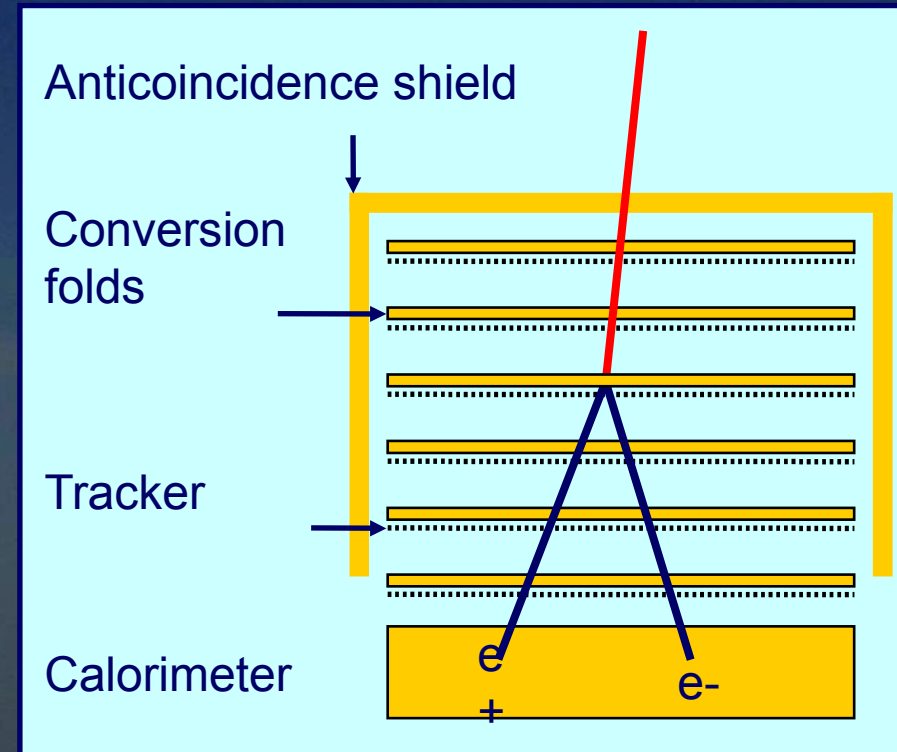
FERMI Large Area Telescope

- **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-coincidence shield**
  - Segmented to avoid self-veto,
  - 89 folds

Mathieu de Naurois
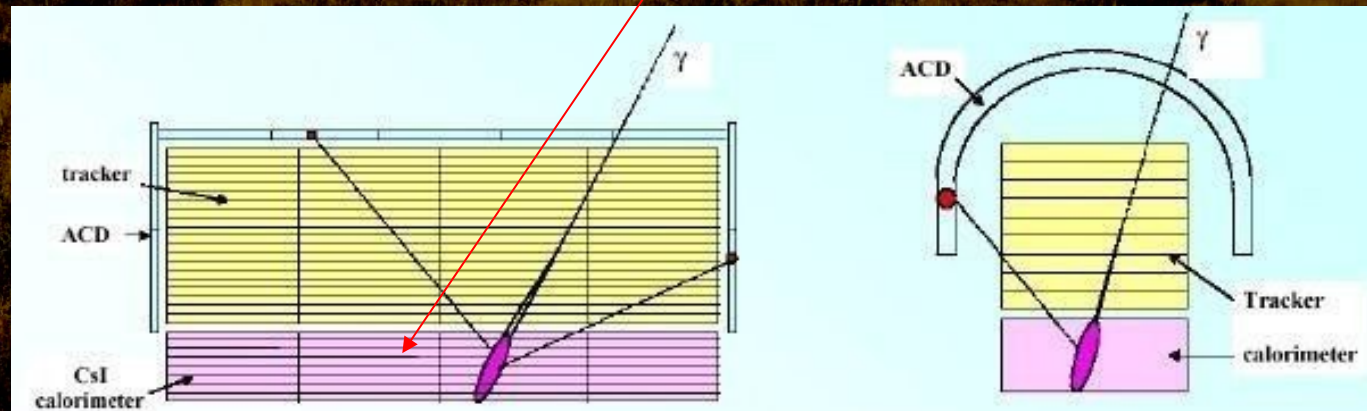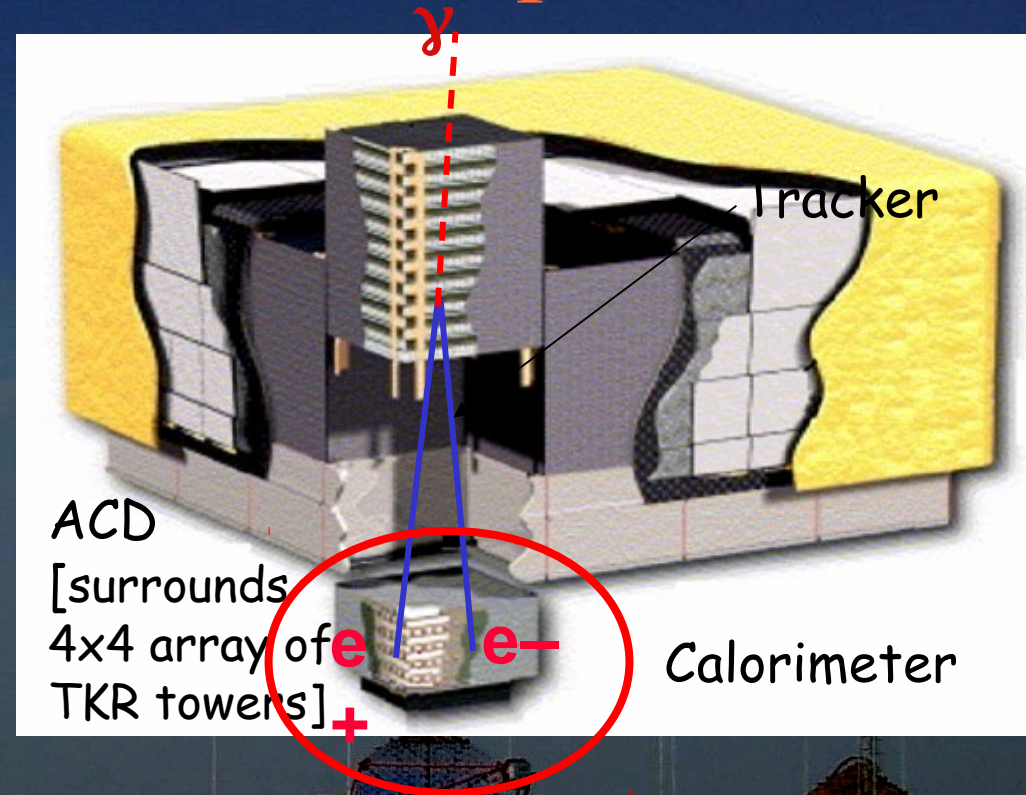
Fermi LAT > 100 MeV

❑ 3×10^7 photons, $\langle E \rangle = 800$ MeV, $\Delta E/E = 100$ %
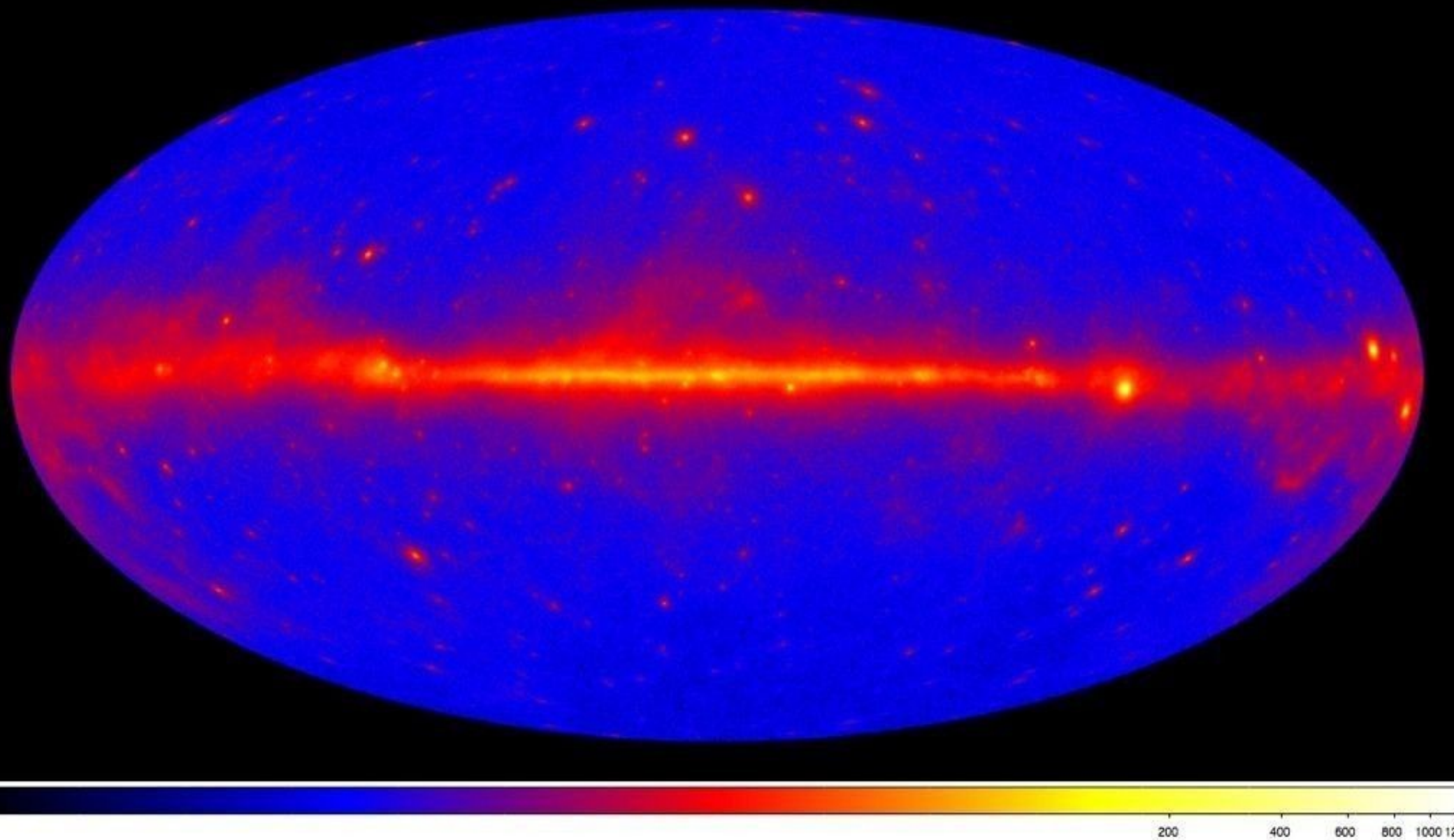
History of pair creation telescopes

- **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

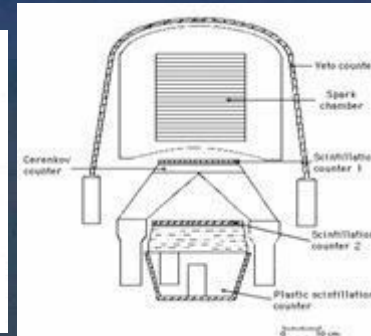 **>1.4 × 10⁶ γ, 271 sources**
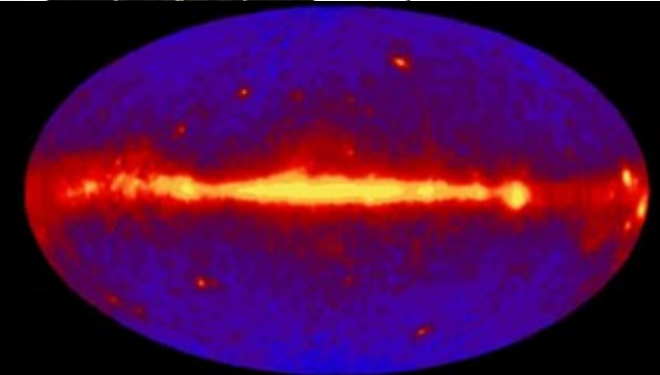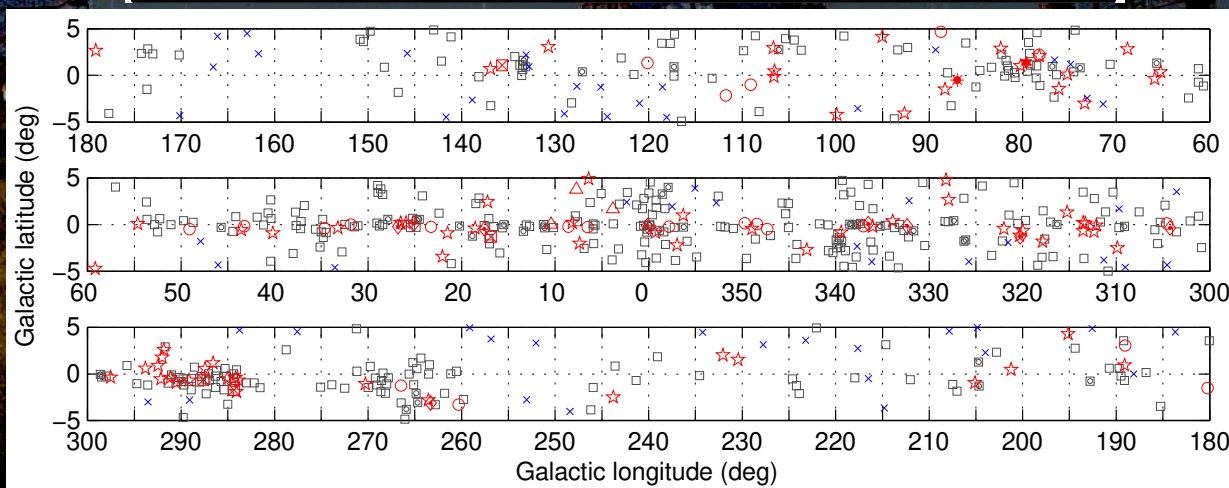
- **2007-** AGILE

- **2008-** FERMI

OSO-3
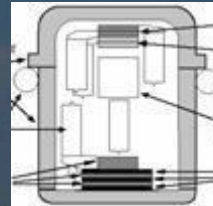
SAS-2
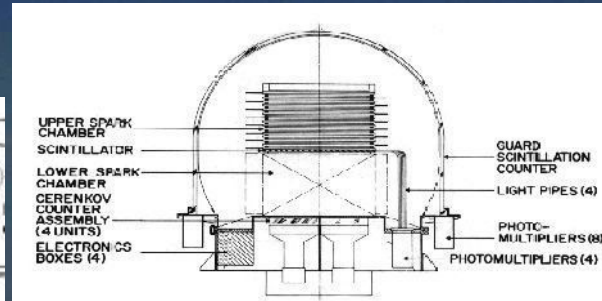
COS-B

EGRET
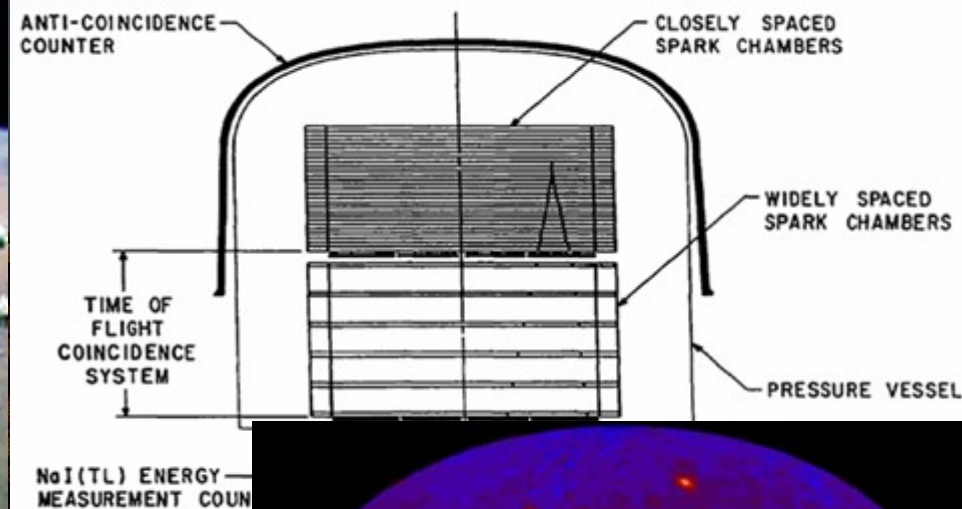
3FGL Catalogue

□ Release January 2015

http://arxiv.org/abs/1501.02003

- □ 2795 sources
- □ 143 pulsars (with pulsations)
- □ 9 PWNs
- □ 12 SNRs
- □ 3 binaries
- □ ~ 1500 blazars
- □ 12 radio galaxies
- □ 4 starburst galaxies
- □ 15 globular clusters
- □ 1010 unassociated
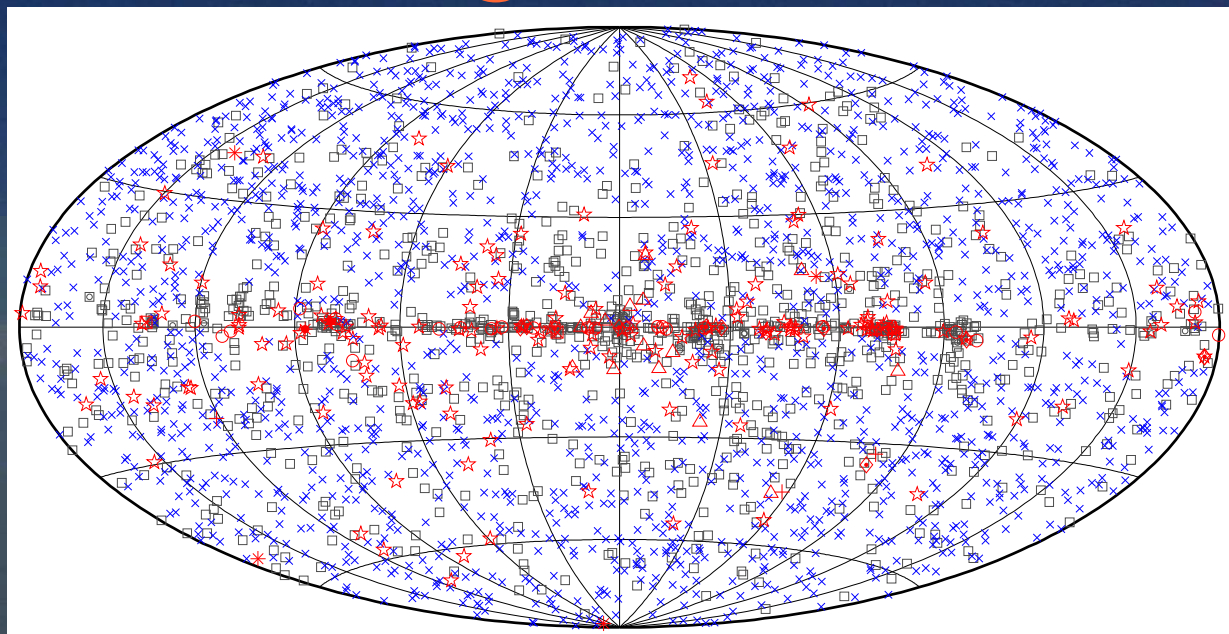
Pulsars

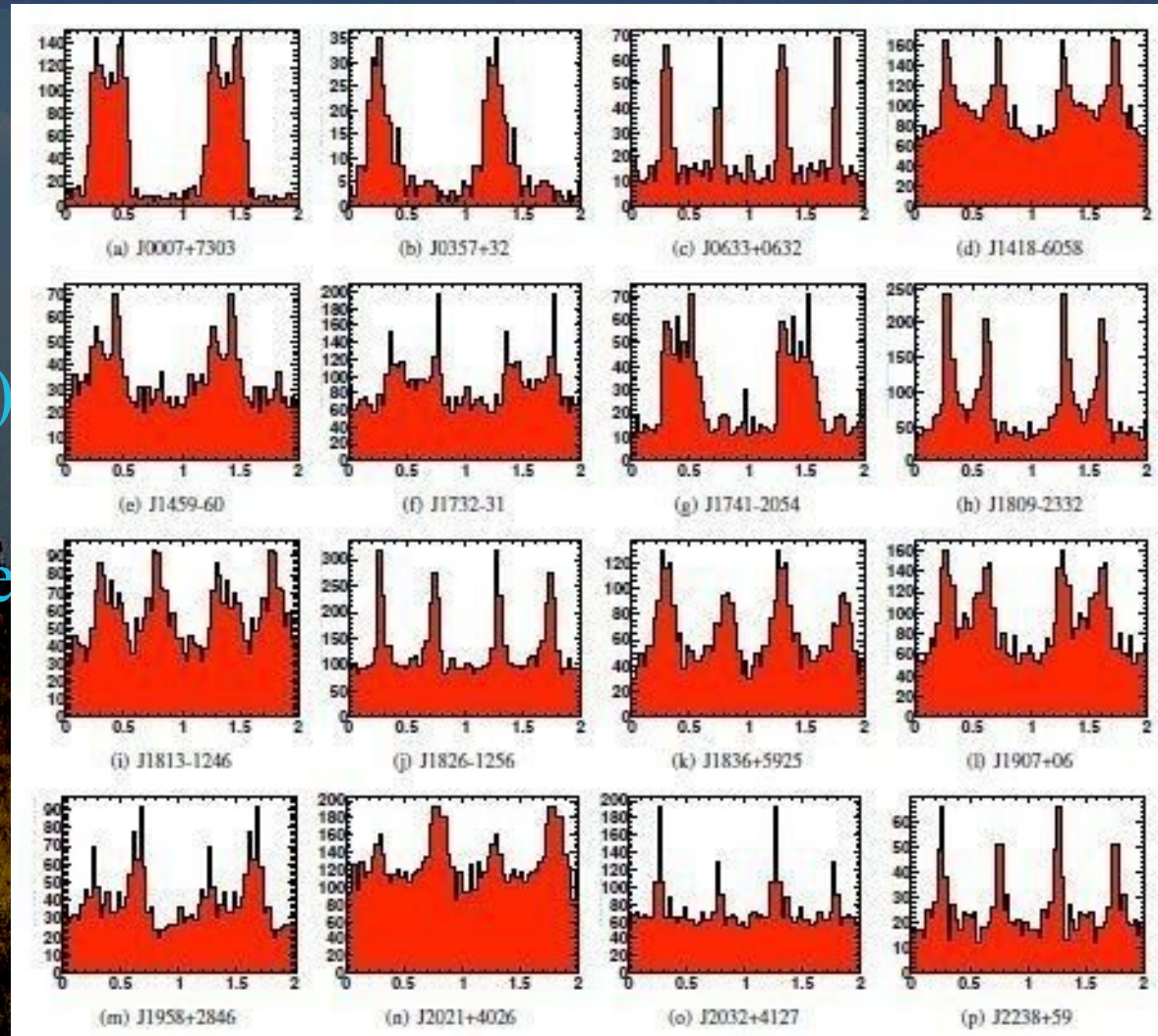□ Compact object (neutron star) highly magnetized, rapidly rotating:

   □ R ~ 10 km

   □ M ~ 1.4 $M_\odot$

   □ Period ms ⇒ s
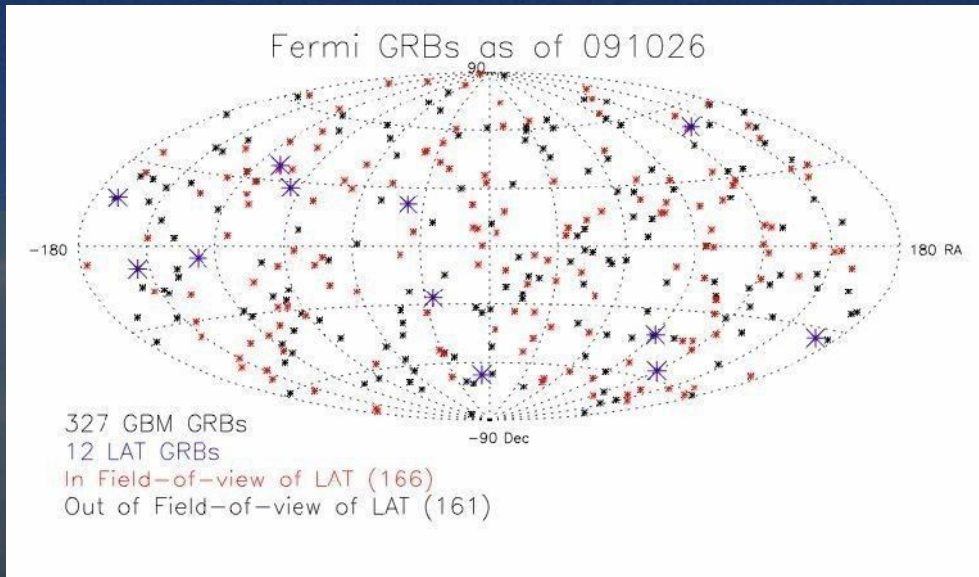
□ Several possible acceleration regions
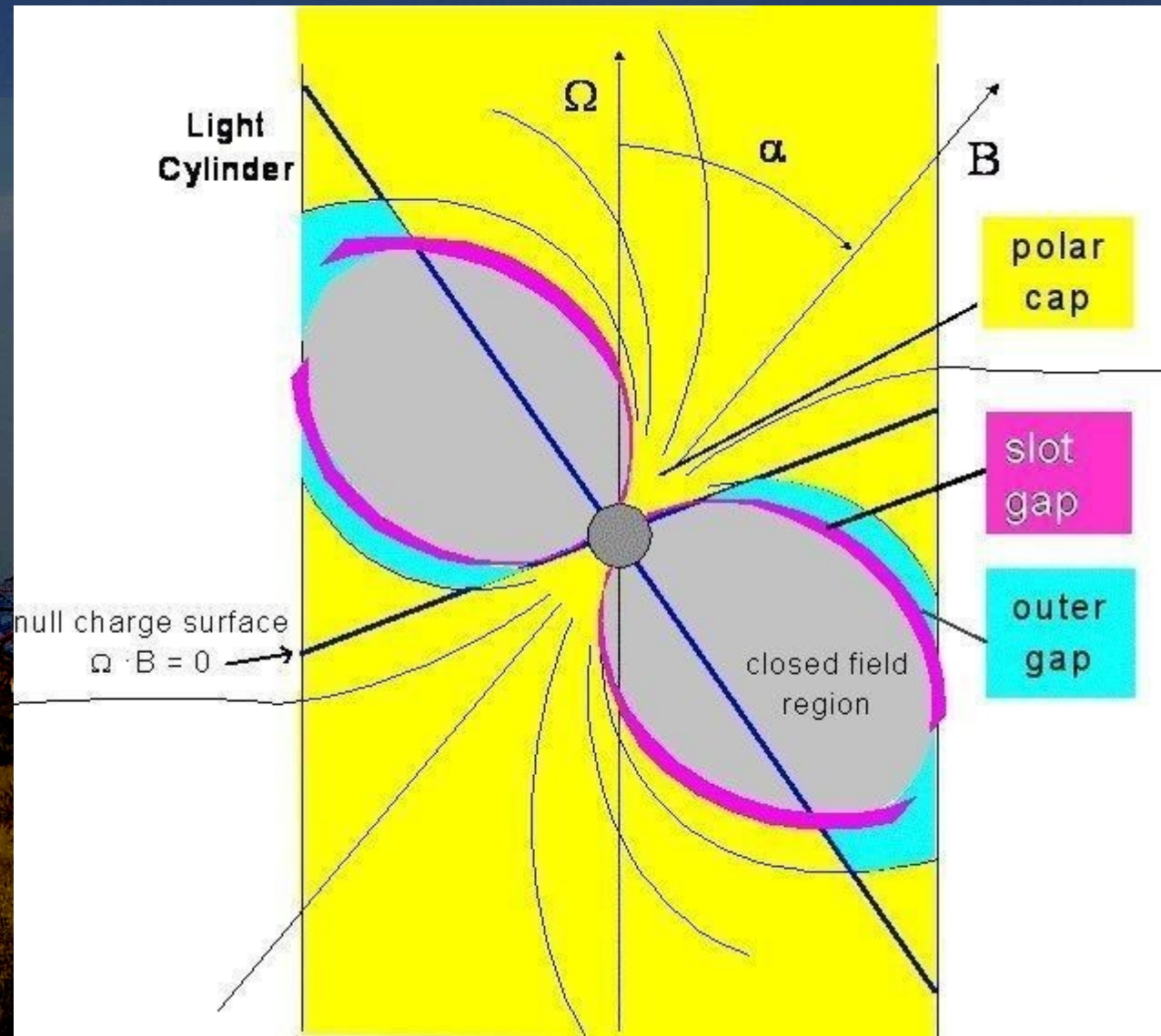
Gamma-ray pulsars

☐ 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)

Gamma-ray bursts

Fermi GRBs as of 091026

327 GBM GRBs
12 LAT GRBs
In Field-of-view of LAT (166)
Out of Field-of-view of LAT (161)


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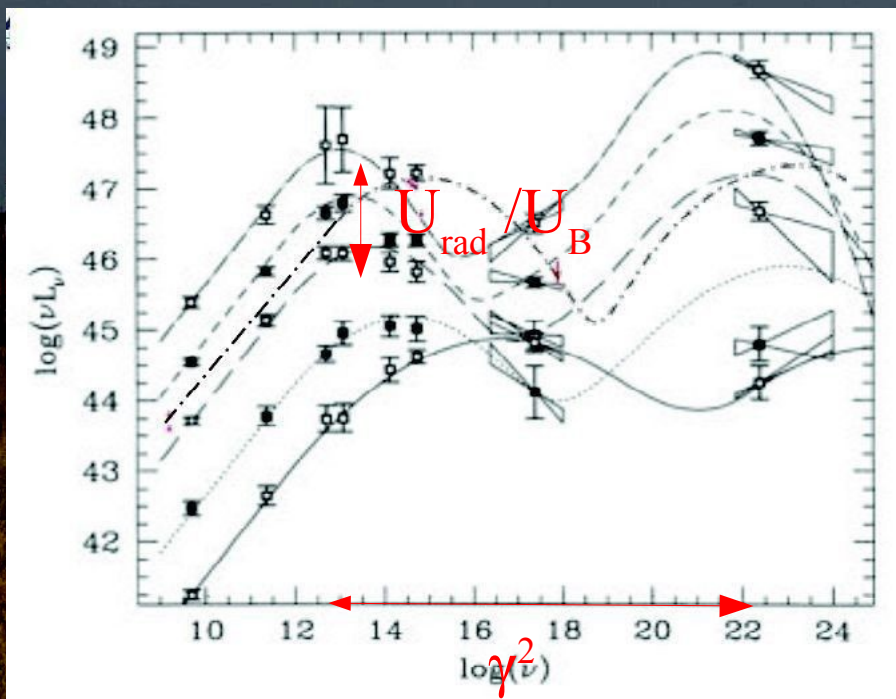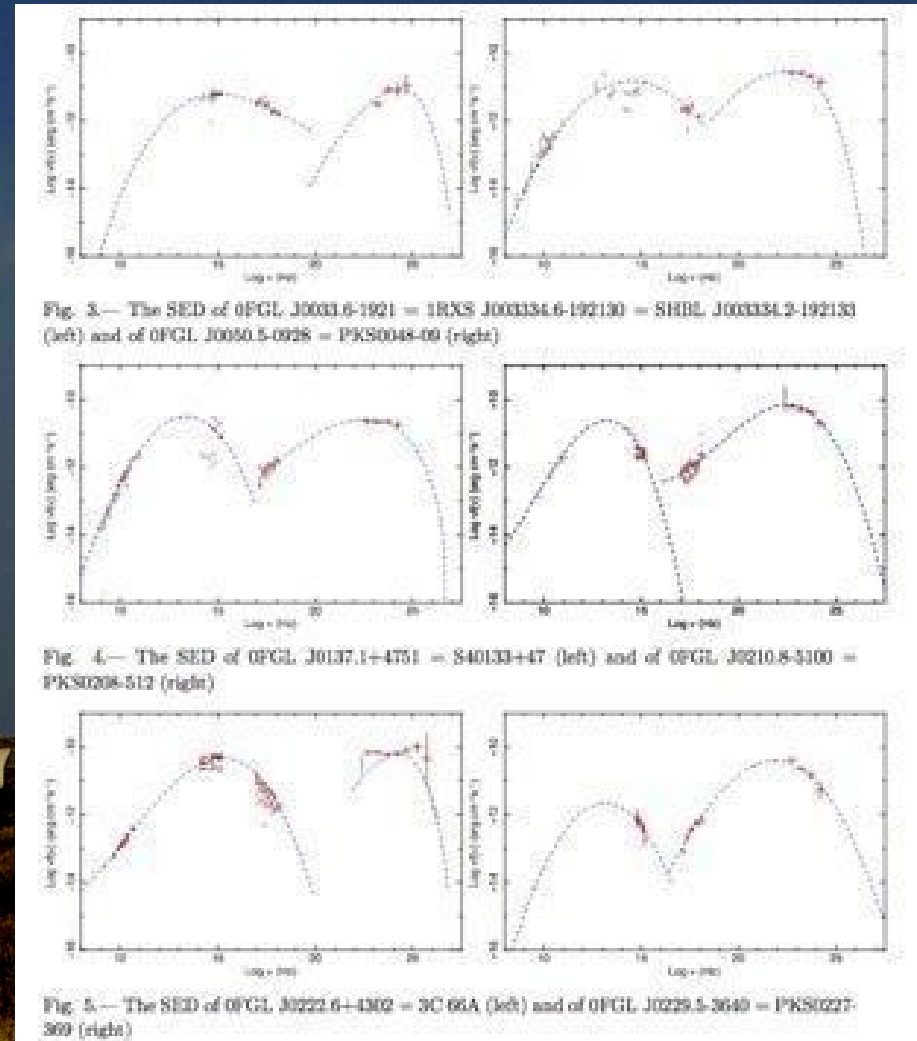 - ❑ Prompt emission > 10 GeV
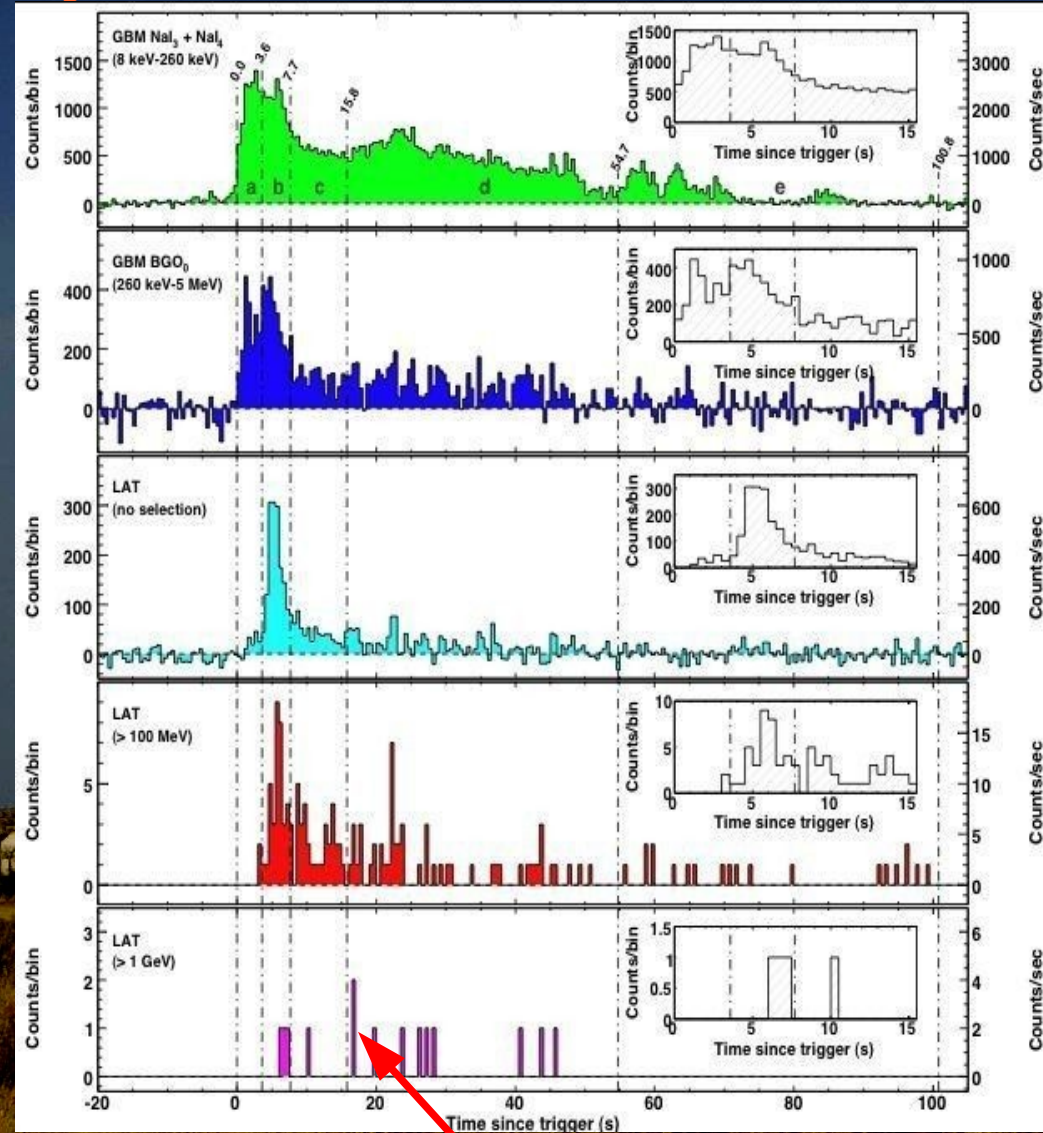
13.6 GeV

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 π^0 decay)
- ☐ Possible connection with UHECRS

NGC 4261

@HST
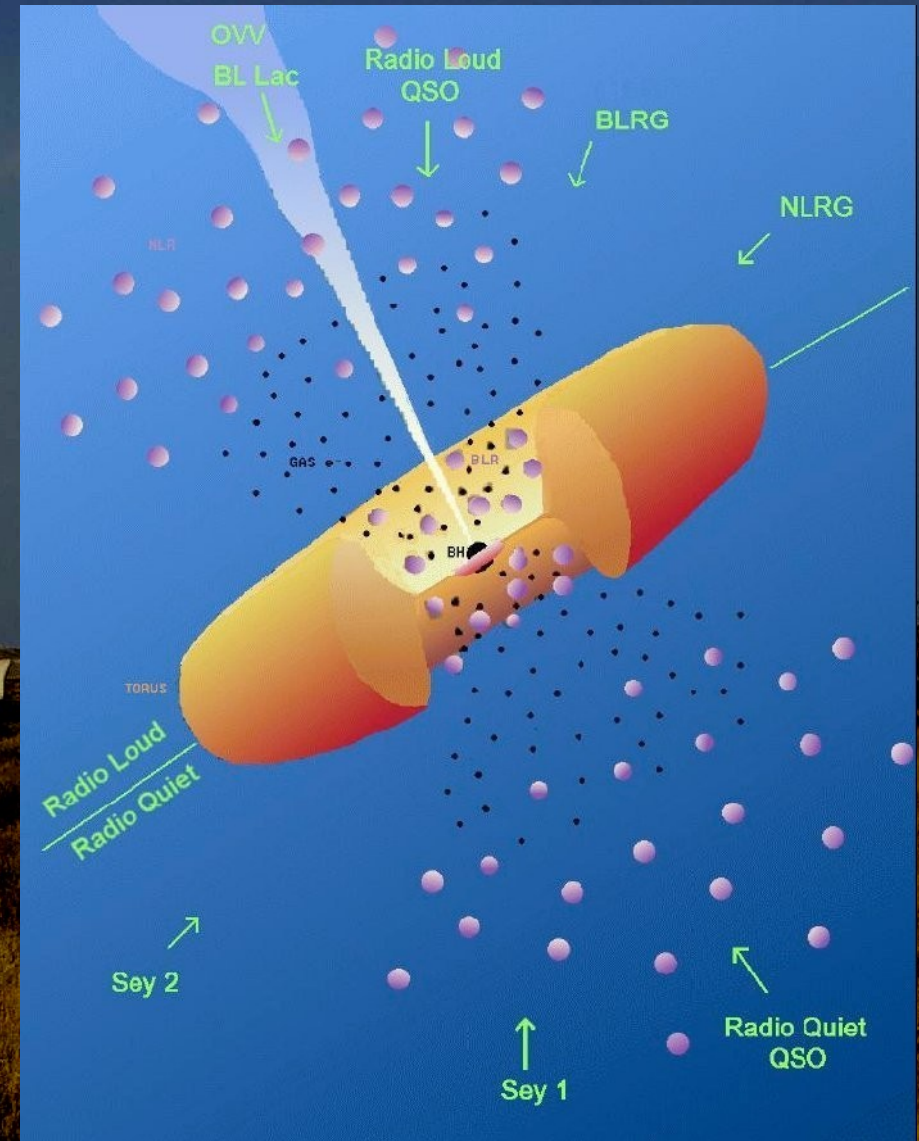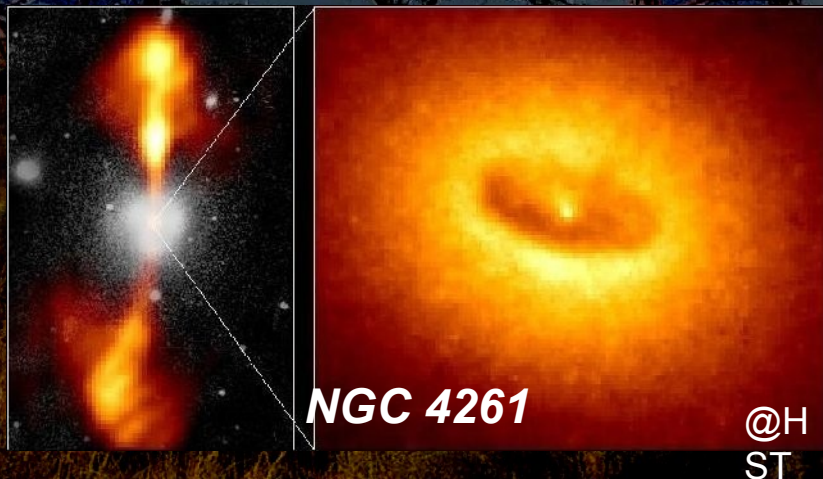
Blazars

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

U_{rad}/U_B

$\log(\nu L_\nu)$

$\log(\nu)$

Fig. 3.— The SED of 0FGL J0033.6-1921 = 1RXS J003334.6-192130 = SHBL J003334.2-192133 (left) and of 0FGL J0050.5-0928 = PKS0048-09 (right)

Fig. 4.— The SED of 0FGL J0137.1+4751 = S40133+47 (left) and of 0FGL J0210.8-5100 = PKS0208-512 (right)

Fig. 5.— The SED of 0FGL J0222.6+4302 = 3C 66A (left) and of 0FGL J0229.5-3640 = PKS0227-369 (right)

Very High Energy γ–ray Astronomy

1 PeV   100 TeV   10 TeV   1 TeV   100 GeV   10 GeV   1 GeV   100 MeV   10 MeV   1 MeV   100 keV
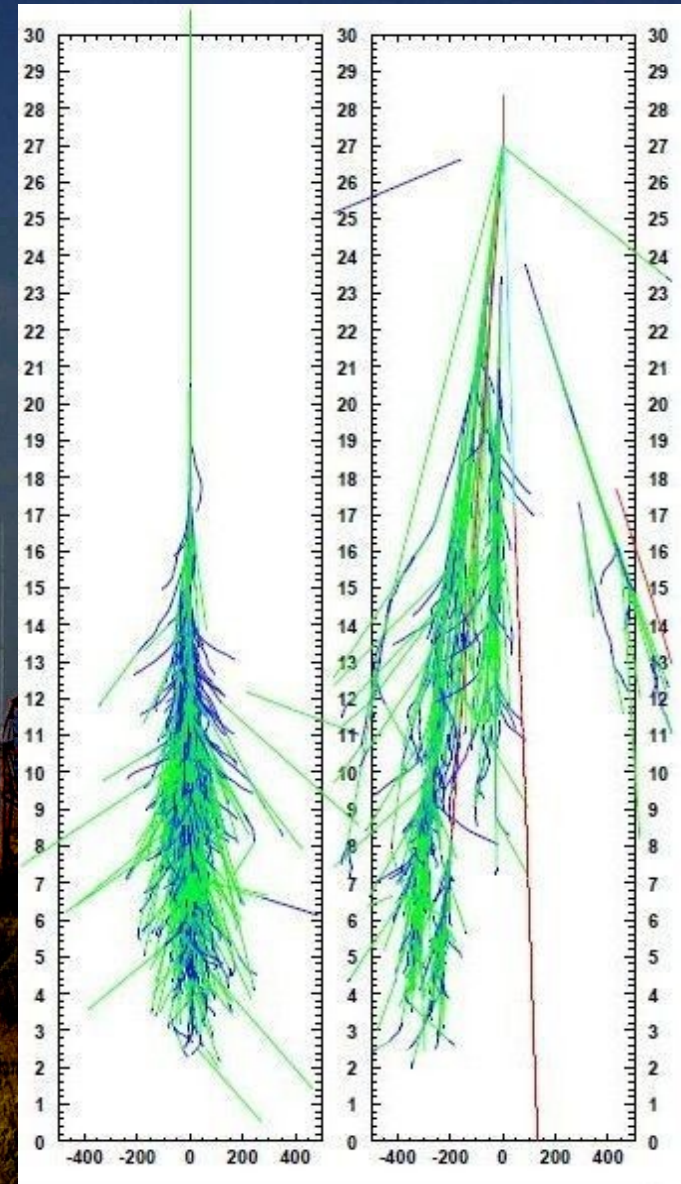
Atmospheric Showers

- 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

Primary particle

Pair creation

electron

positron

Bremsstrahlung
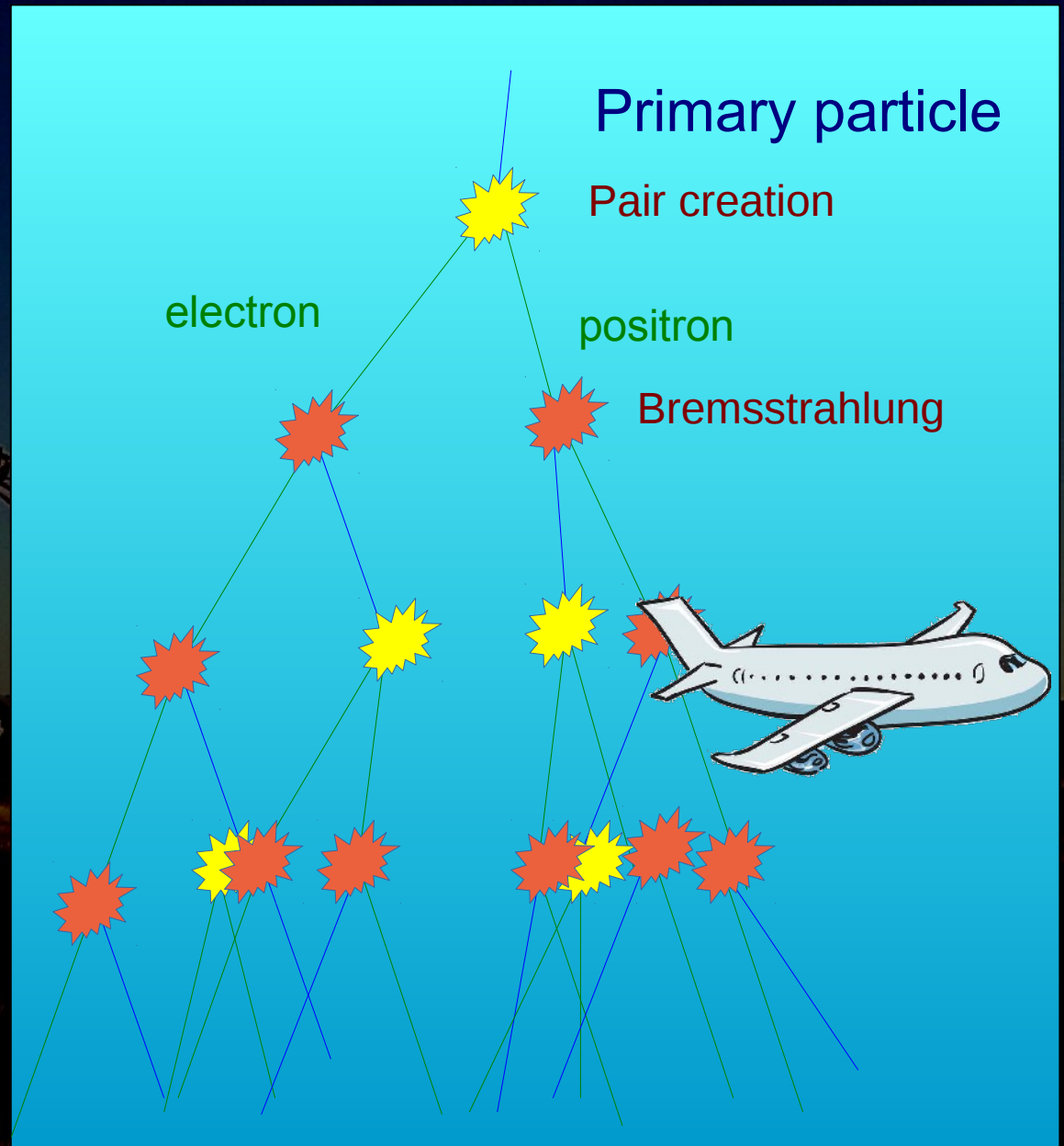
Atmospheric Showers

☐ 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)

   ☐ $\Rightarrow$ 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))
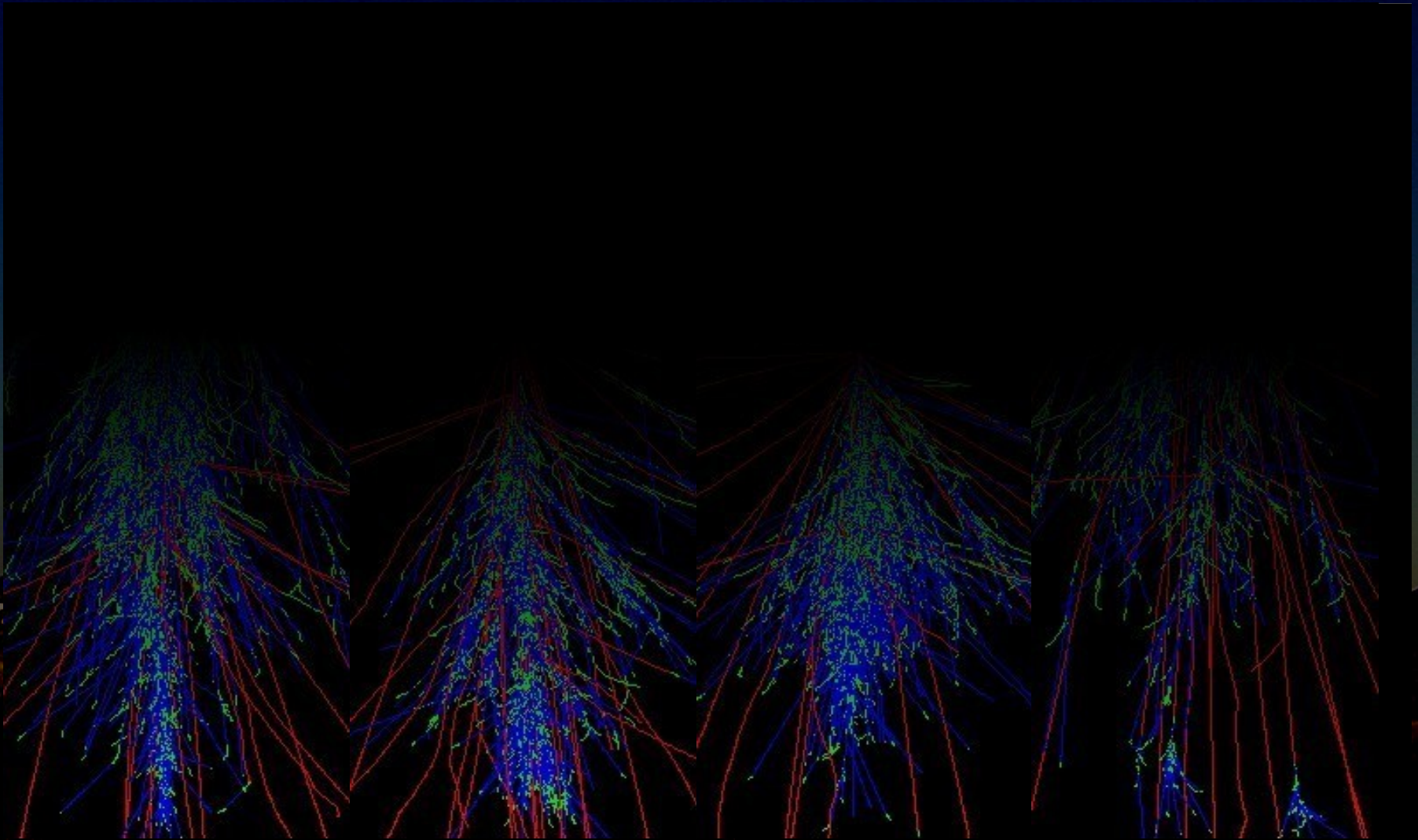
Atmospheric Showers
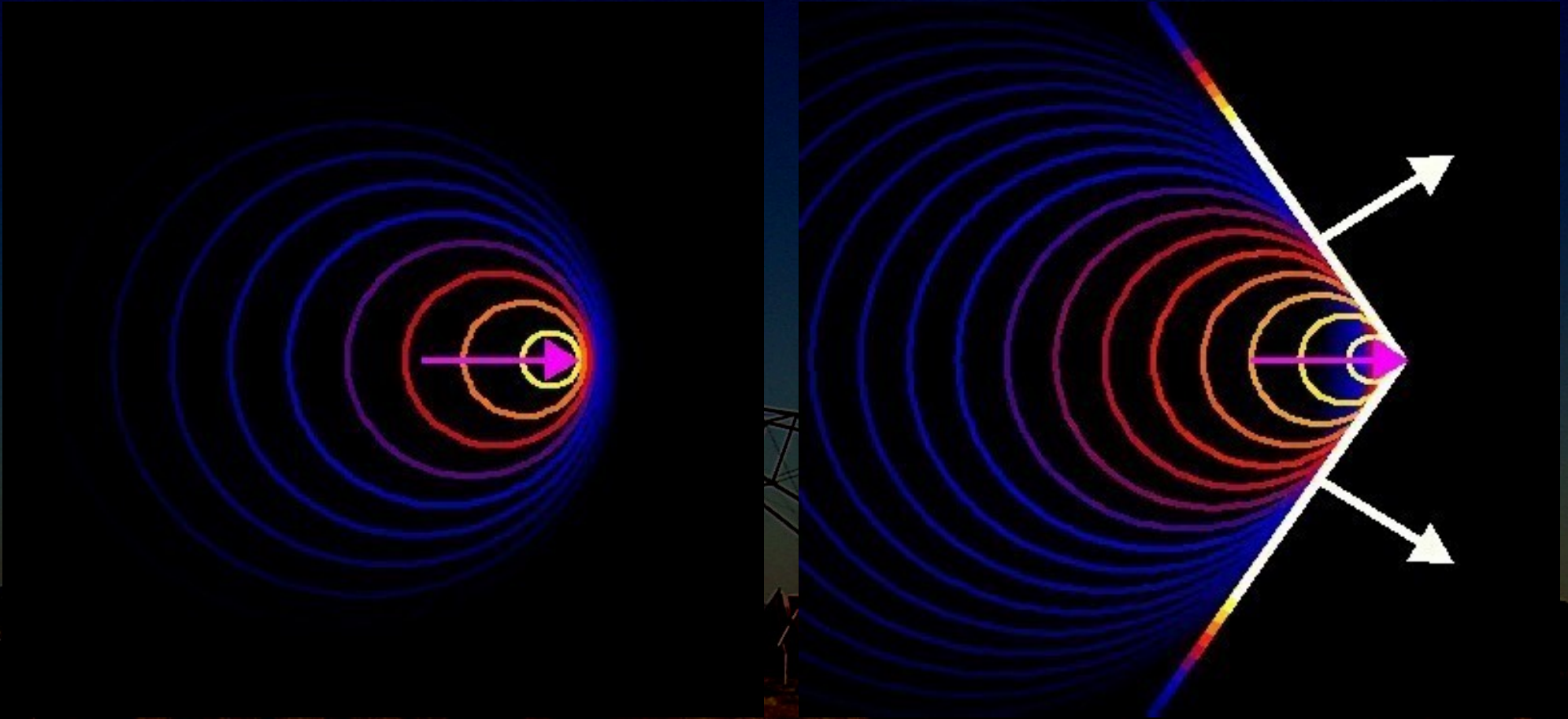
γ, 200 GeV
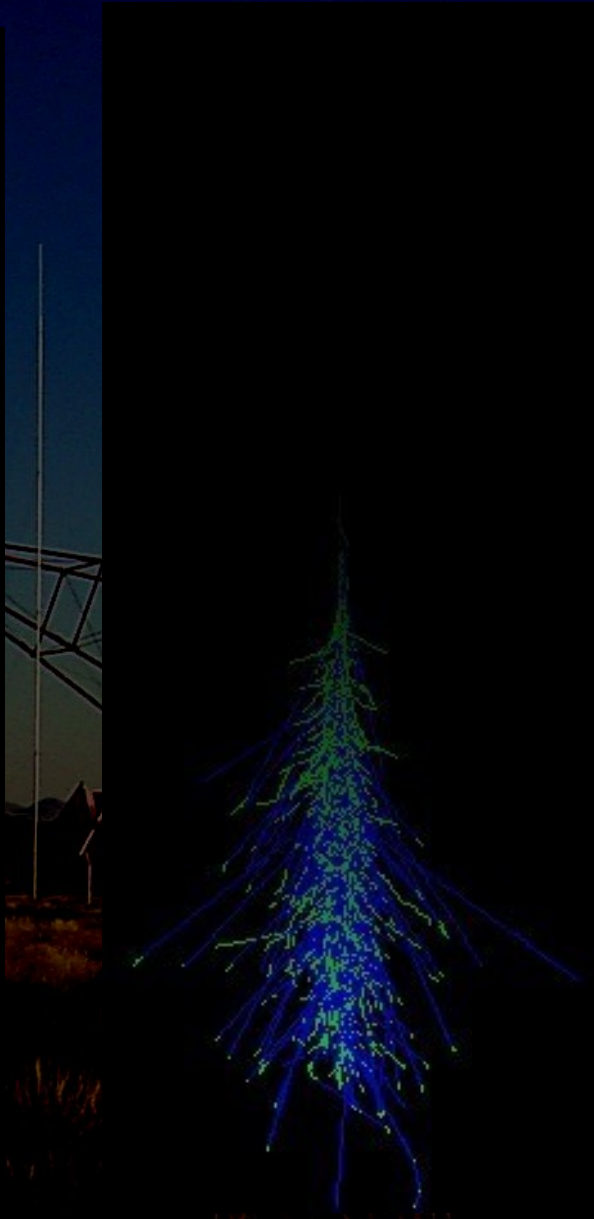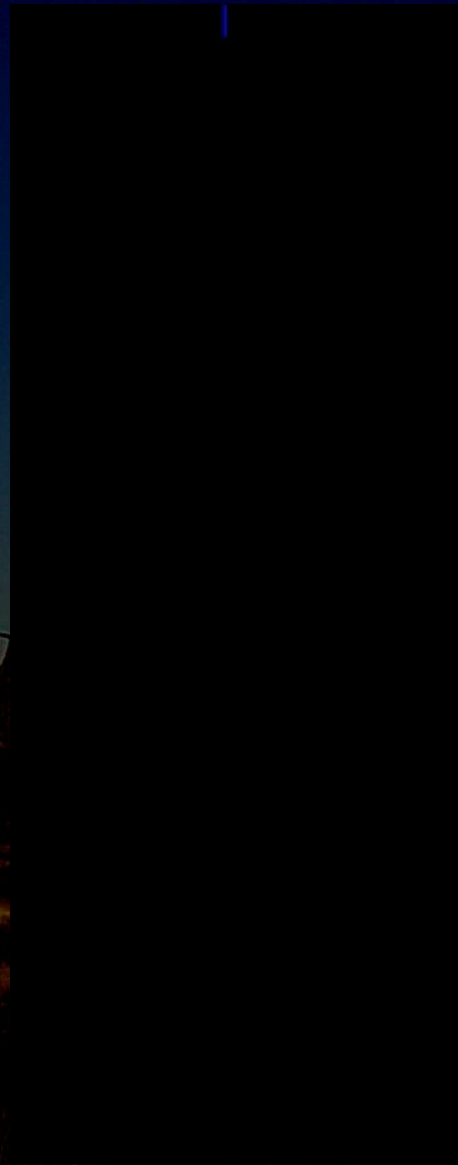
Atmospheric Showers

❑ 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

Observables and experimental techniques (E > 10 GeV)

TIBET

Primary (γ,hadron)

Primary (γ,hadron)

Scintillator or water

Atmospheric Shower

Atmospheric Shower

Hadron detector

μ

Cherenkov Emission

Cherenkov Telescope

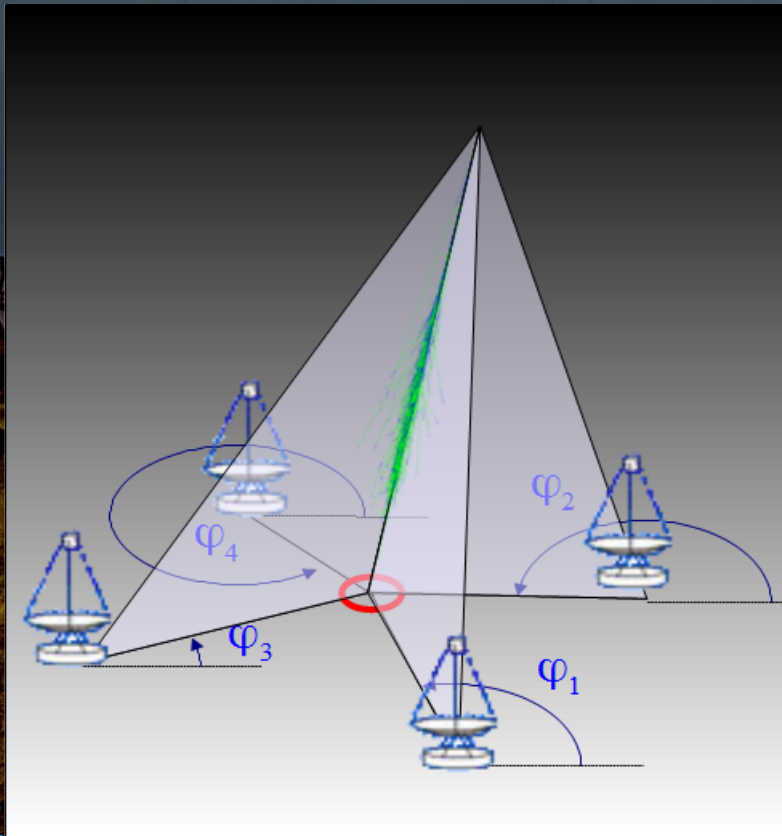MILAGRO

HESS, VERITAS, MAGIC, CANGAROO

STACEE, CELESTE, SOLAR II, GRAAL

2 Complementary Techniques

- Atmospheric Cherenkov Telescopes:
  - Small F.O.V.
  - Low duty cycle
  - High rejection
  - High resolution
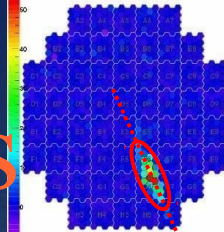
Detailed study of a few sources

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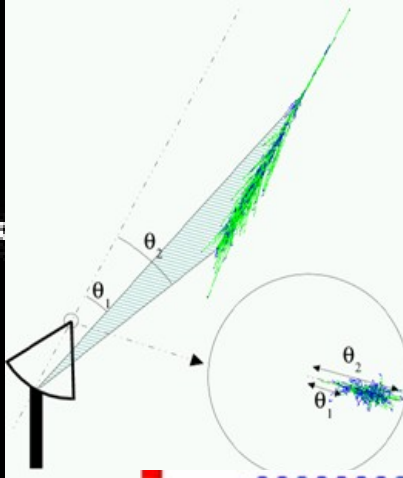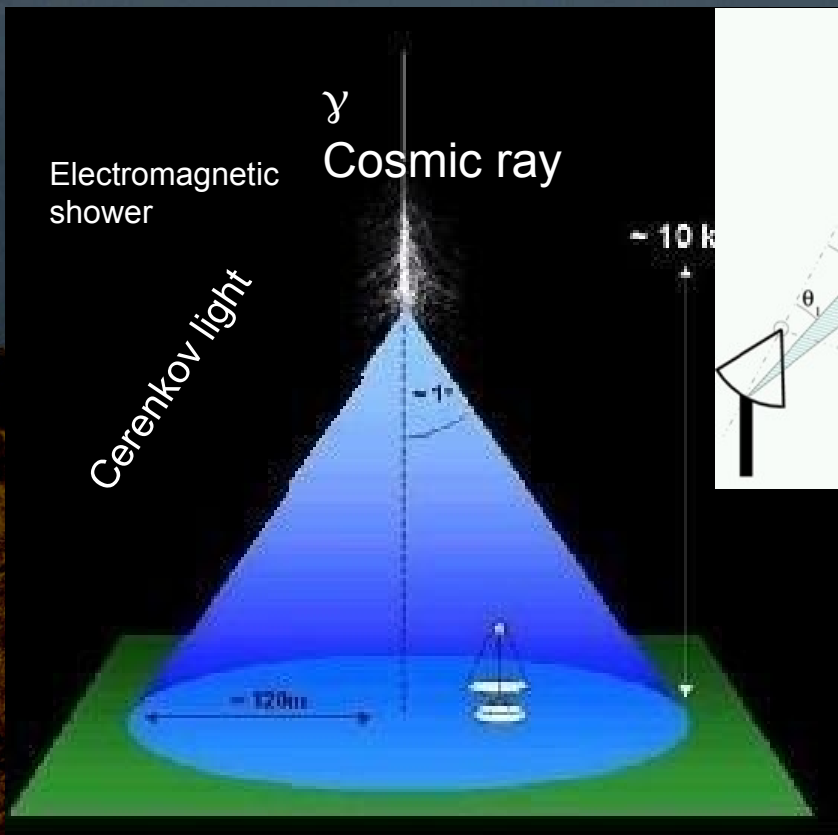 - High duty cycle
 - Poor rejection
  - Poor resolution

Long term survey instruments

Milagro Cross Section Schematic

4 r.l.
16r.l.
50 meters
80 meters
8 meters
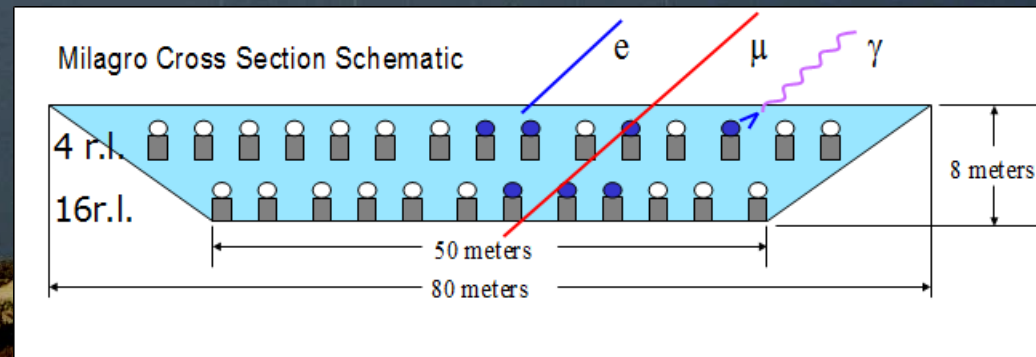
Atmospheric Cherenkov Telescopes

- 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

γ
Cosmic ray

Electromagnetic shower

Cerenkov light

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

muon

hadron

candidat γ
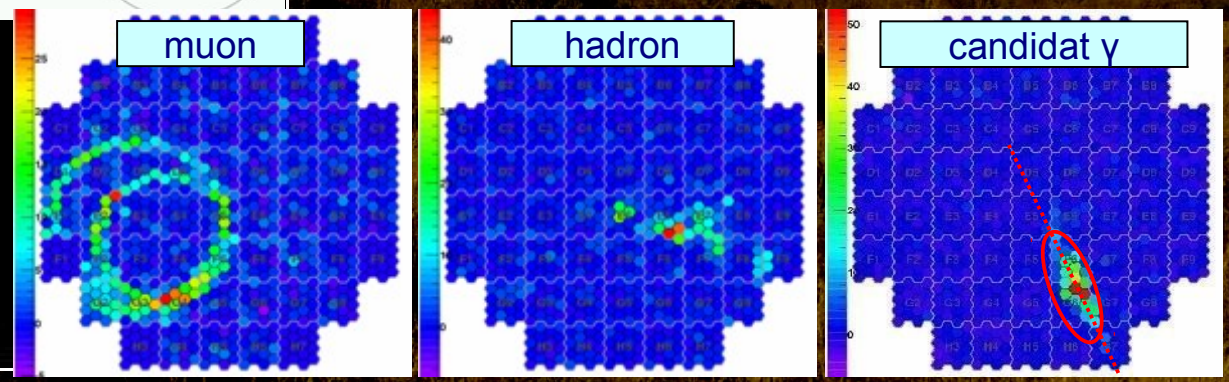
VHE γ-Ray world

HESS – II in Namibia

4×13 m Ø, $+ 1 \times 28$ m Ø (600 m^2) added in 2012

July 2012

• High Energy Stereoscopic System

☐ H.E.S.S. phase 1 :
- ☐ 4 telescopes: Ø 12 m, 107 m²
- ☐ 960 pixels/camera, FOV : 5°
- ☐ Observations : ~1000h/an
- ☐ Localisation accuracy : ~ 10"

☐ H.E.S.S. phase 2 :
- ☐ 5th telescope, Ø 28 m, 600 m²
- ☐ 2048 pixels, FOV : 3.5°
- ☐ Ponting in < 1 min for 50 % sky
- ☐ Extended energy range

HESS Galactic Plane Survey
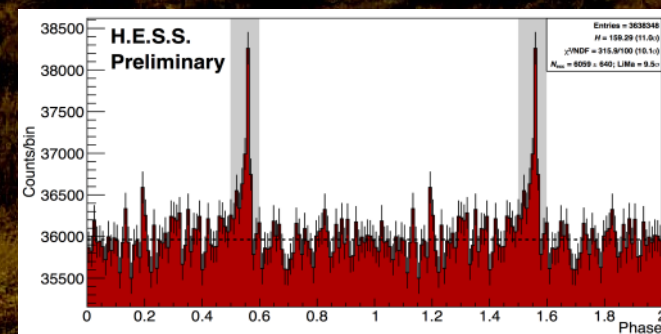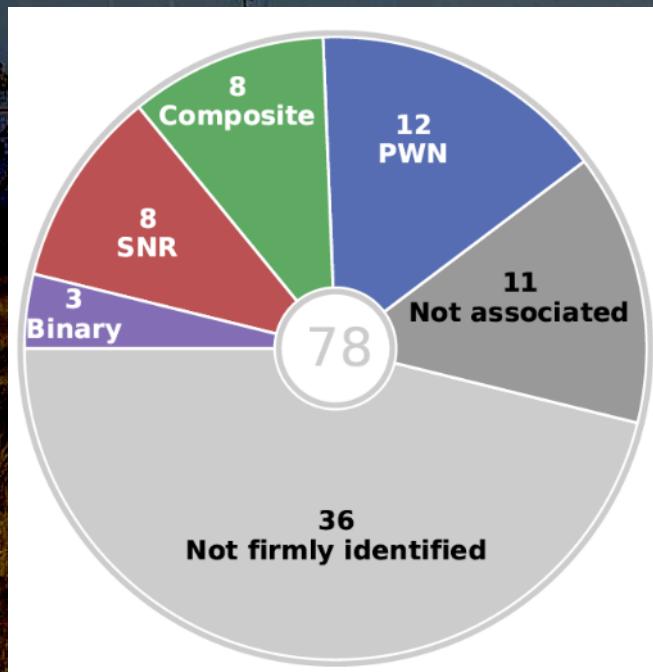
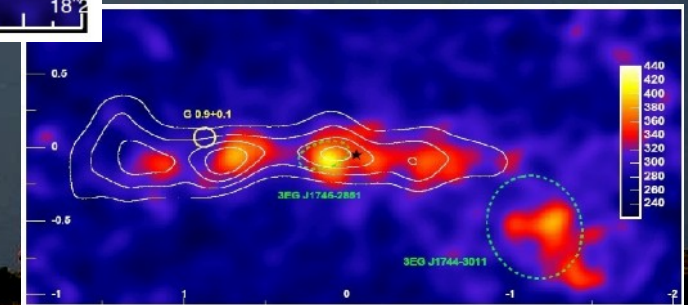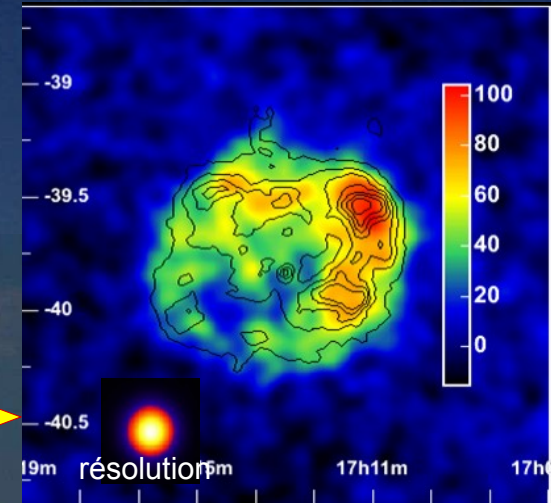☐ Major HESS project: 2700 h of data (2004 – 2010)
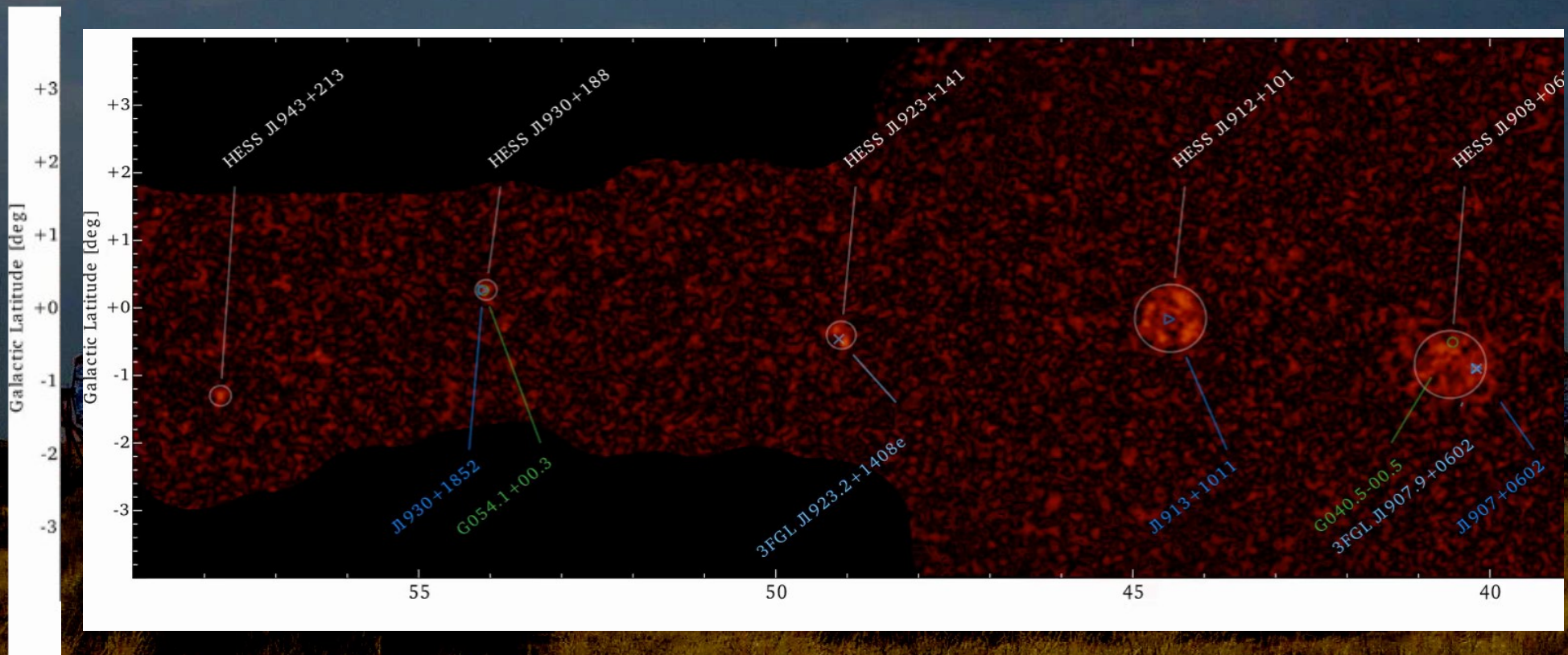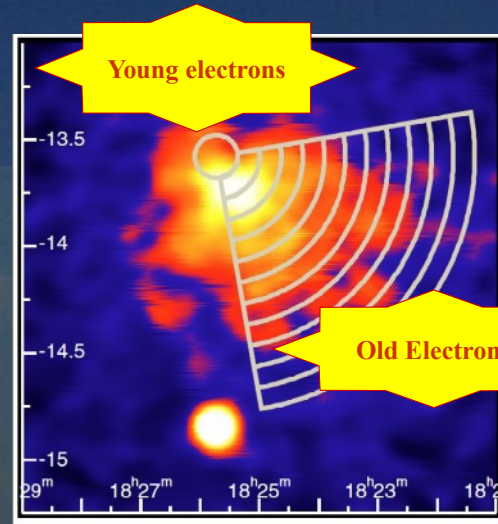

☐ 78 sources of different types (SNRs, PWNs, Binaries, ...)
☐ VHE Universe much richer than expected

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

- 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 ~10^{44} J (10^{16} × Hiroshima)

- Best candidates for galactic cosmic rays
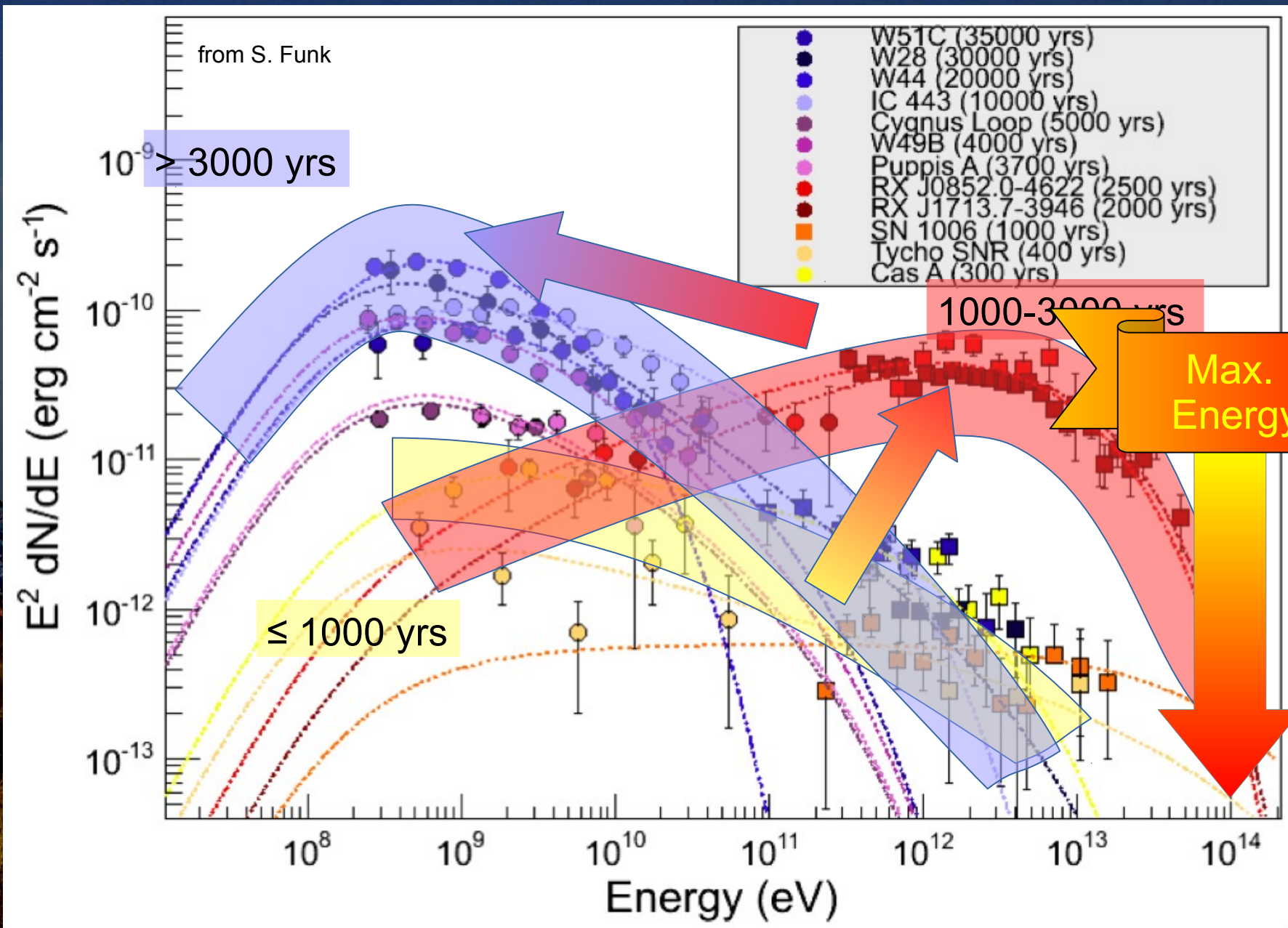 - Matching rate 1 SNR/Galaxy/century
  - Conversion efficiency ~10%

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
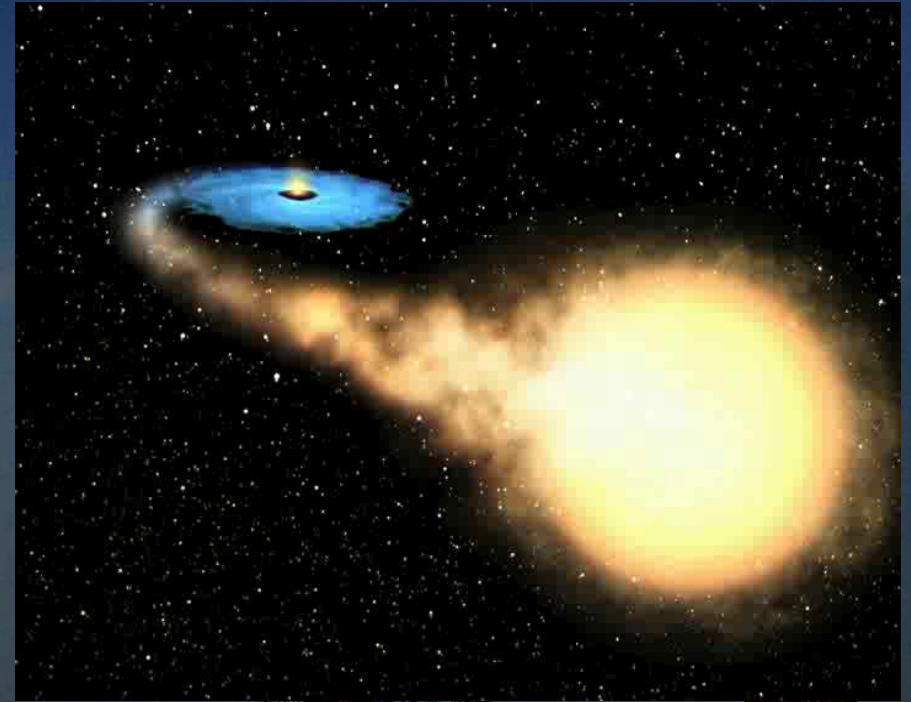
□ Maximum acceleration energy around 100 TeV

X rays   γ rays
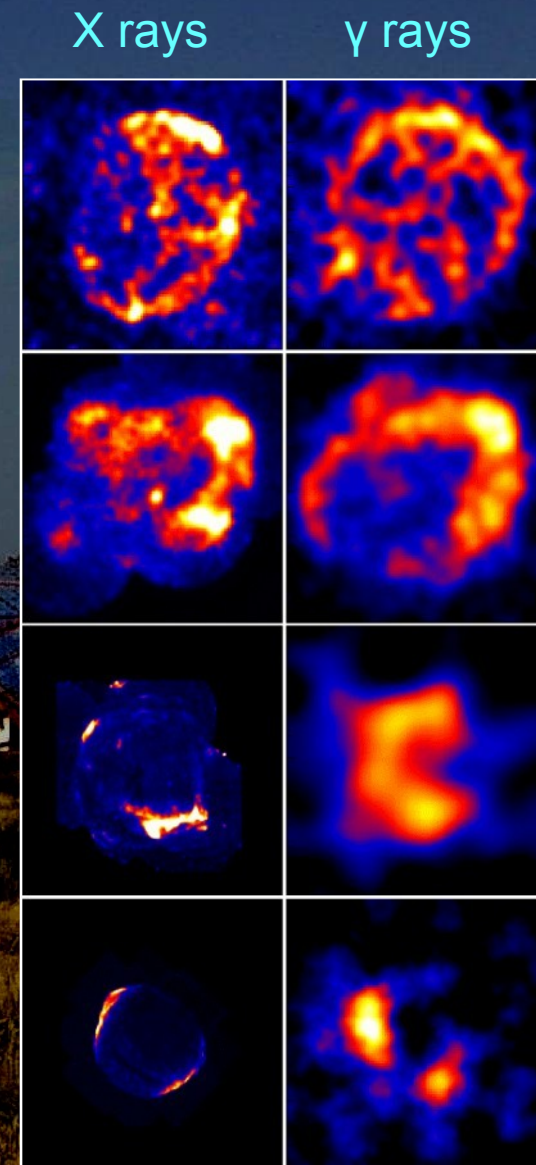
Supernova Remnant Evolution

Binary Systems

- ❑ 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
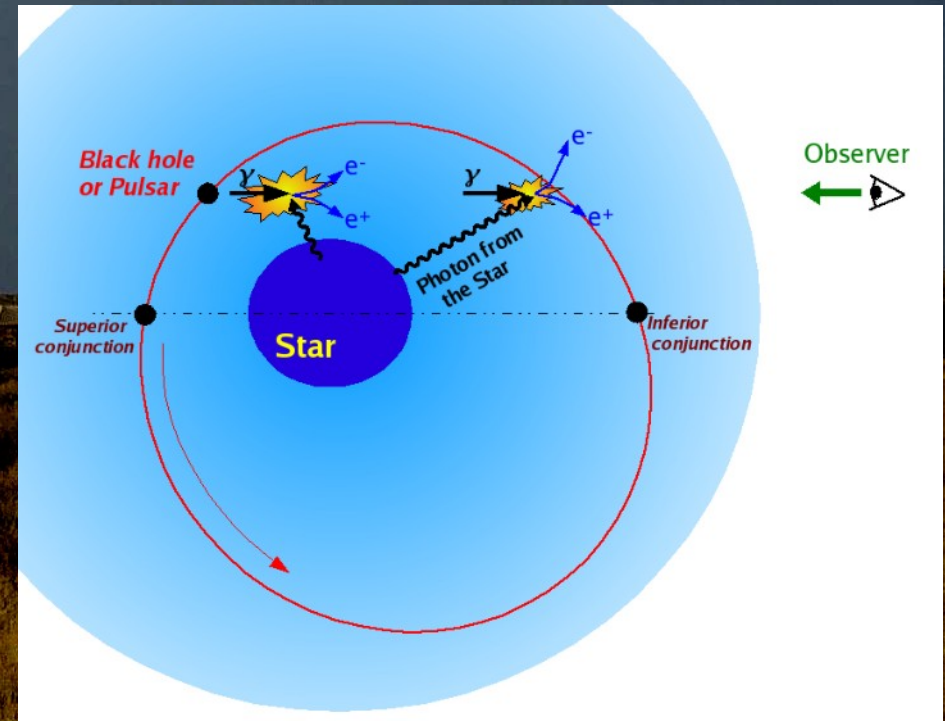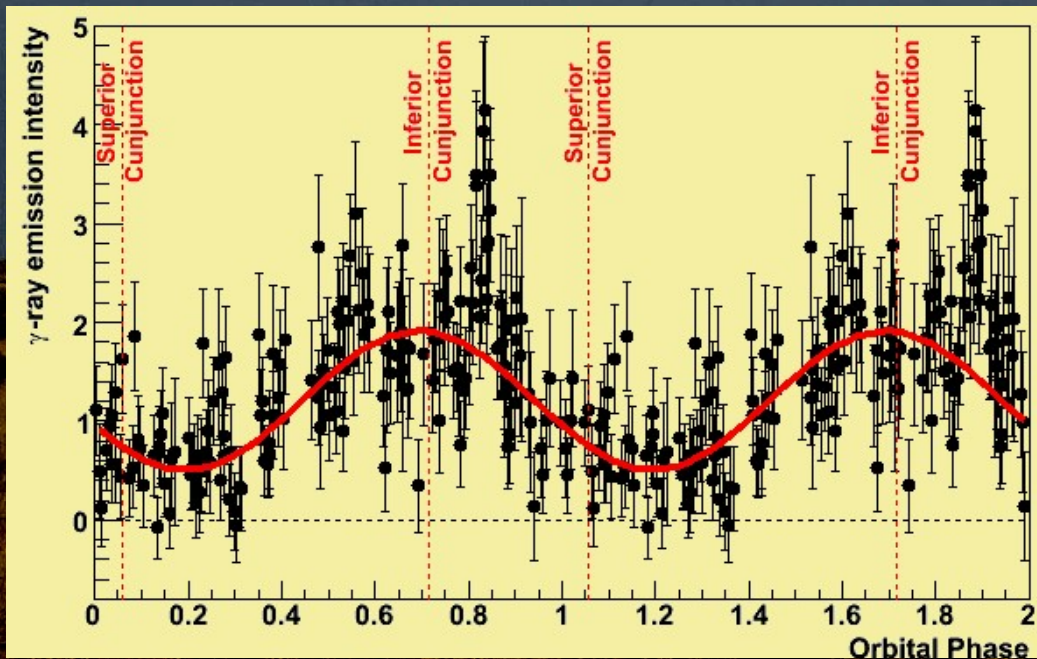
Active Galactic Nuclei

❑ Supermassive black hole (10^6-10^9 M$_\odot$) surrounded by accretion disk

❑ Giant ultra-relativistic jets of plasma (size ~Mpc)
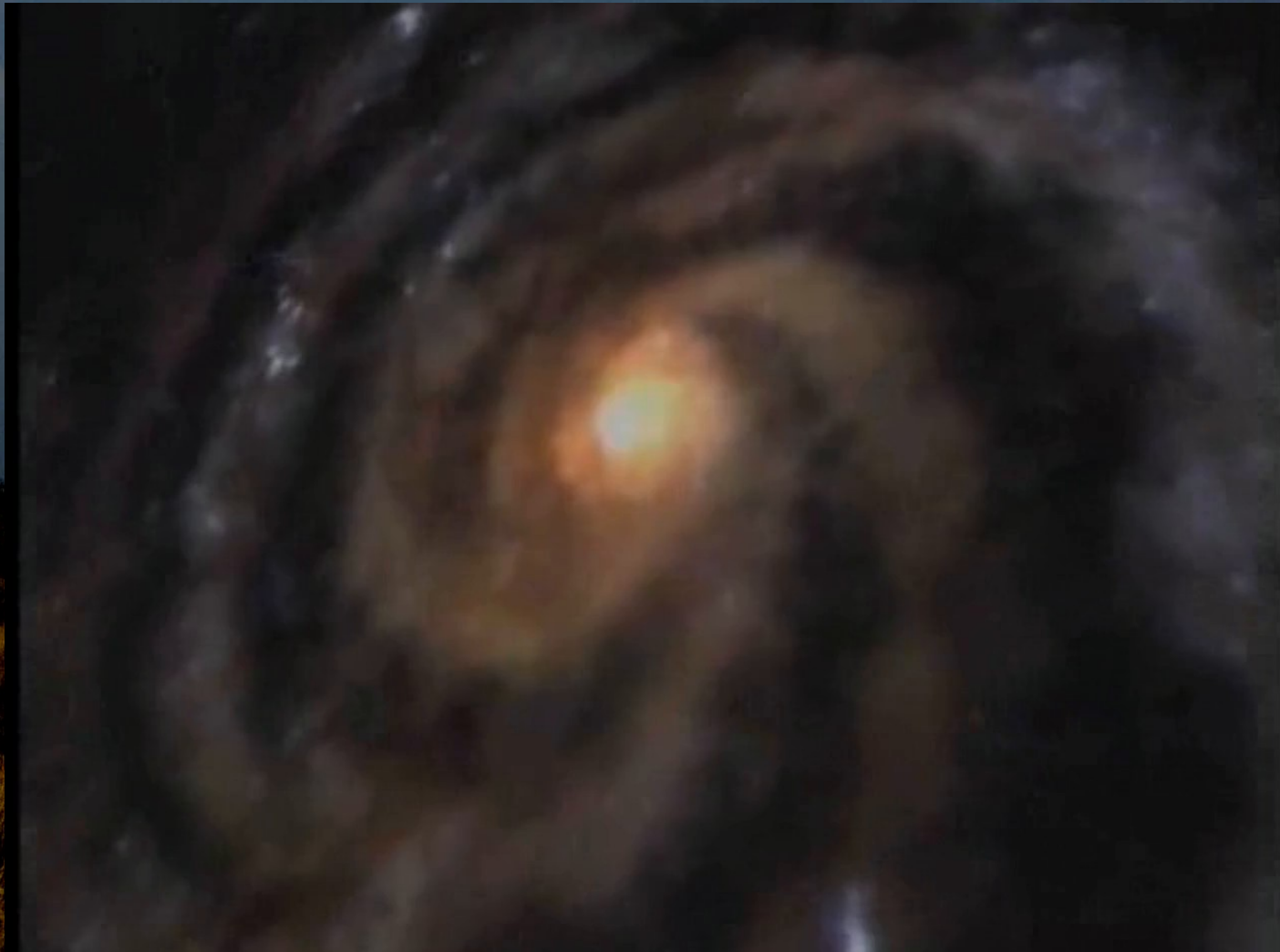
Artist's view (ESA/NASA)

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)
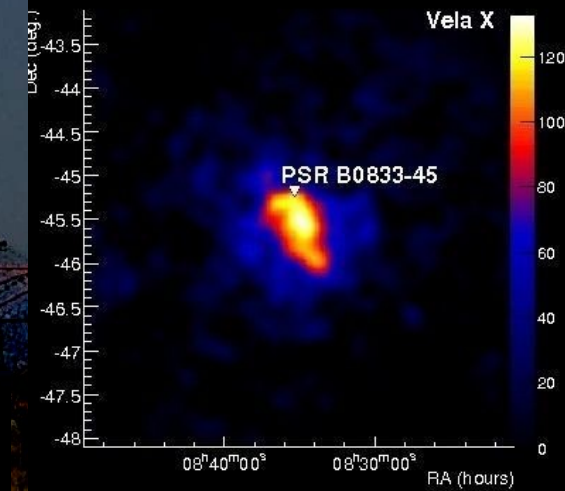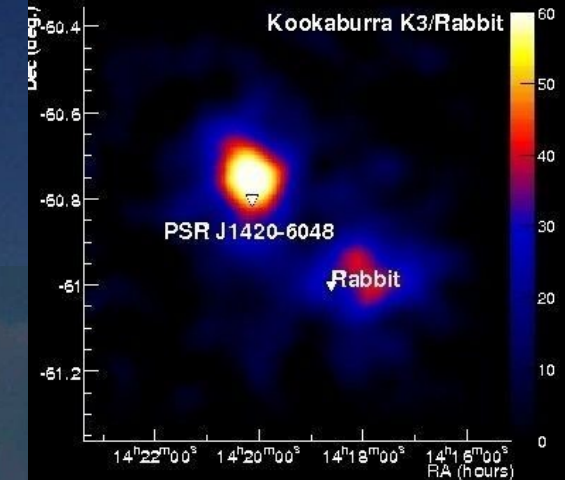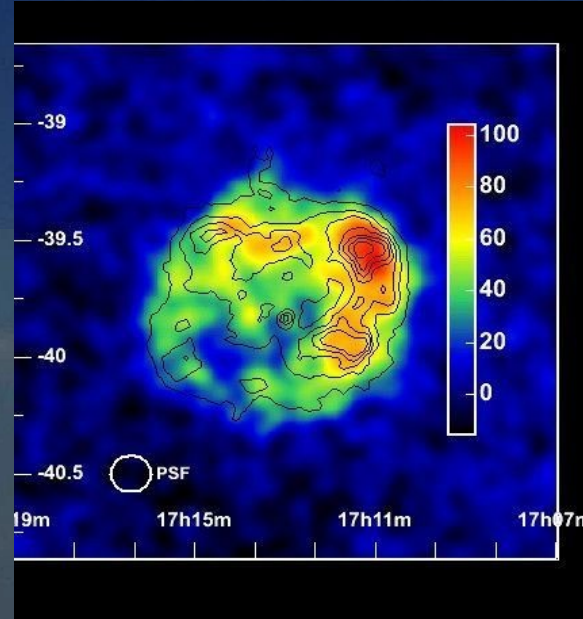

H.E.S.S.
arXiv:0706.0797

HESS
28th July 2006

MAGIC: Mrk 501

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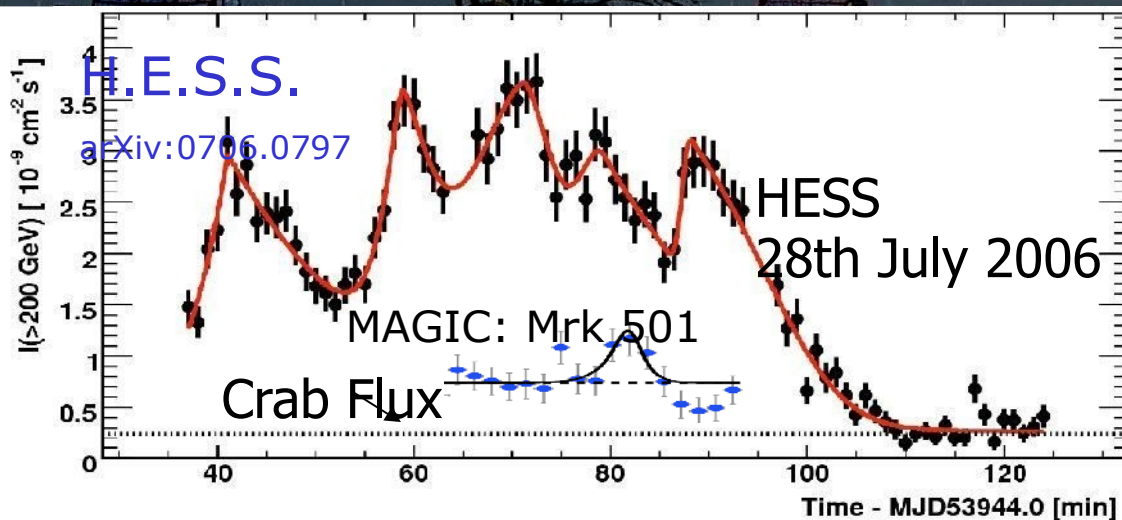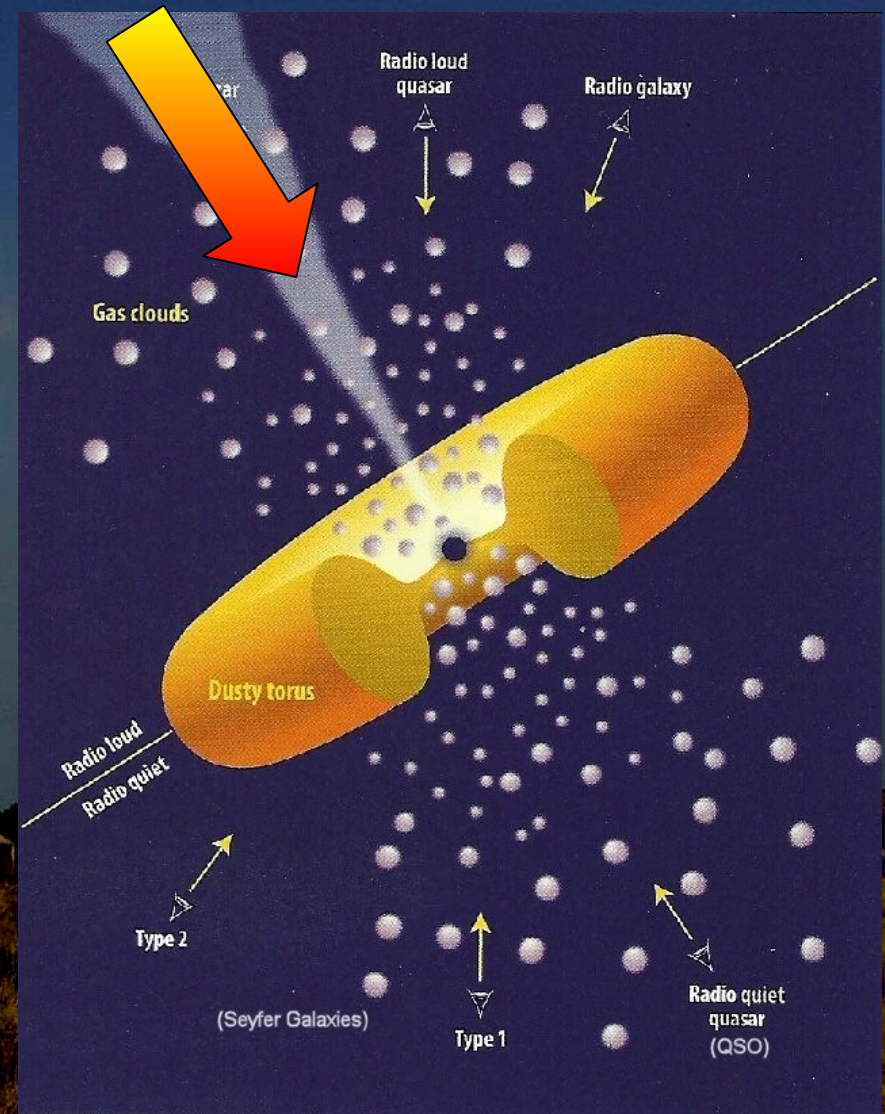
$$c' = c \left(1 \pm \xi \frac{E}{E_P} \pm \zeta^2 \frac{E^2}{E_P^2} \right)$$

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,
  □ ....
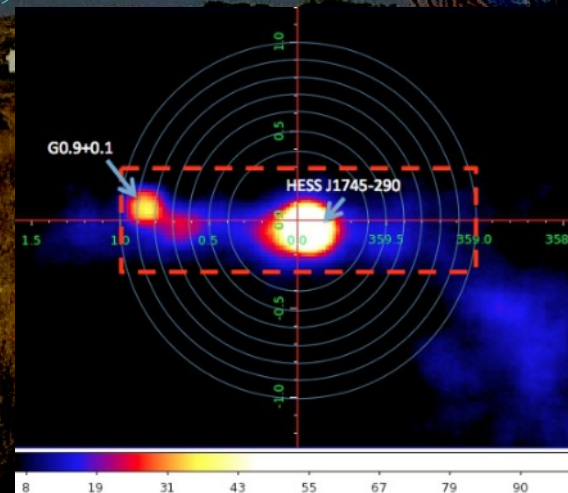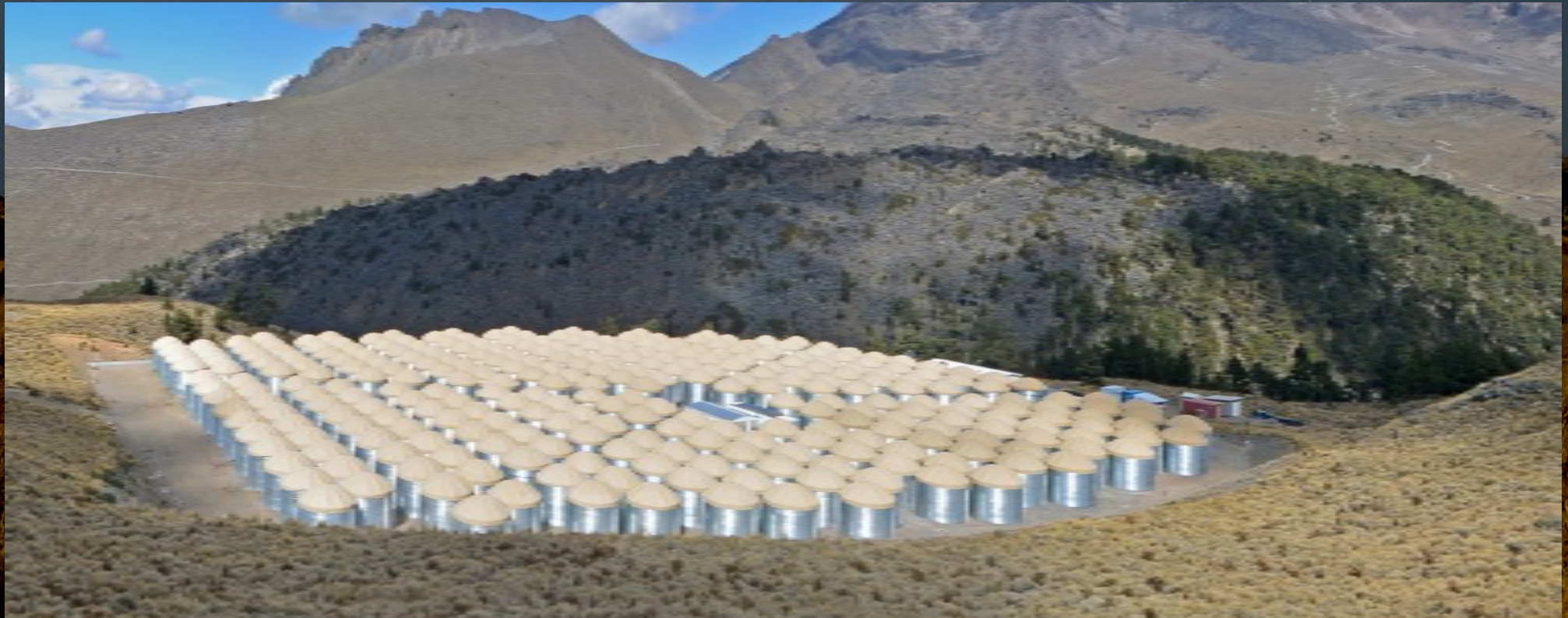
Unveiling the sources of cosmic rays!

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
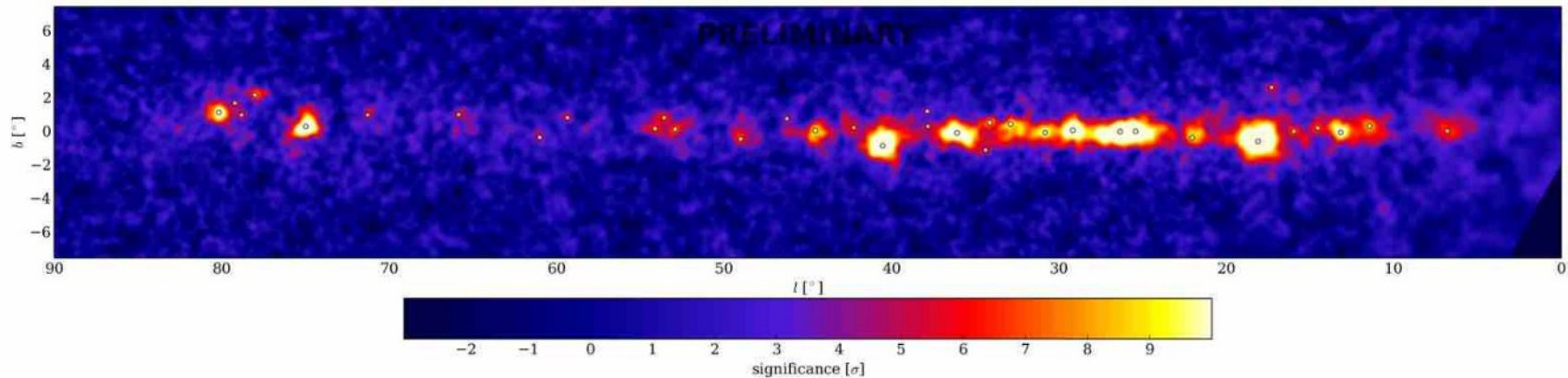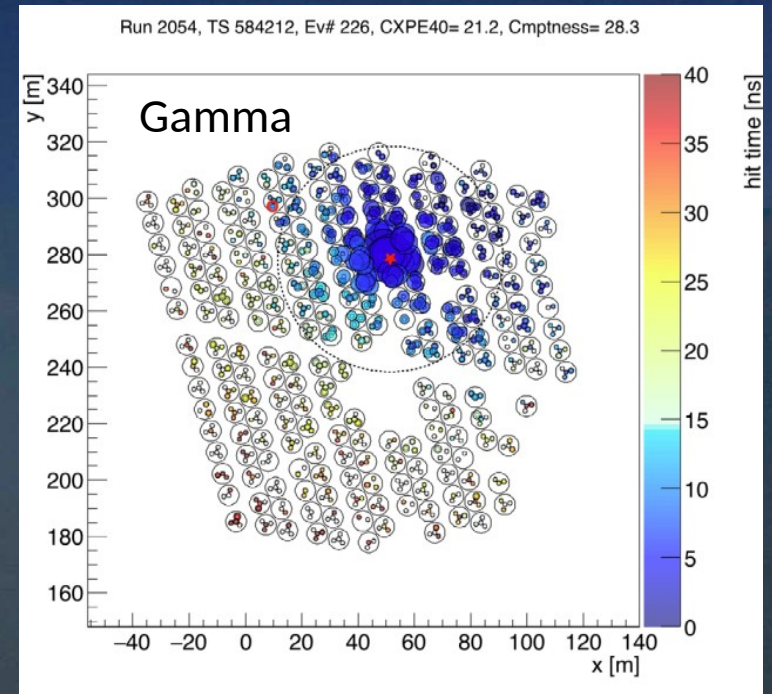- Sierra Negra, Mexico, alt: 4100 m   lat: +19°

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

Run 2054, TS 584212, Ev# 226, CXPE40= 21.2, Cmptness= 28.3

Gamma

PRELIMINARY

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