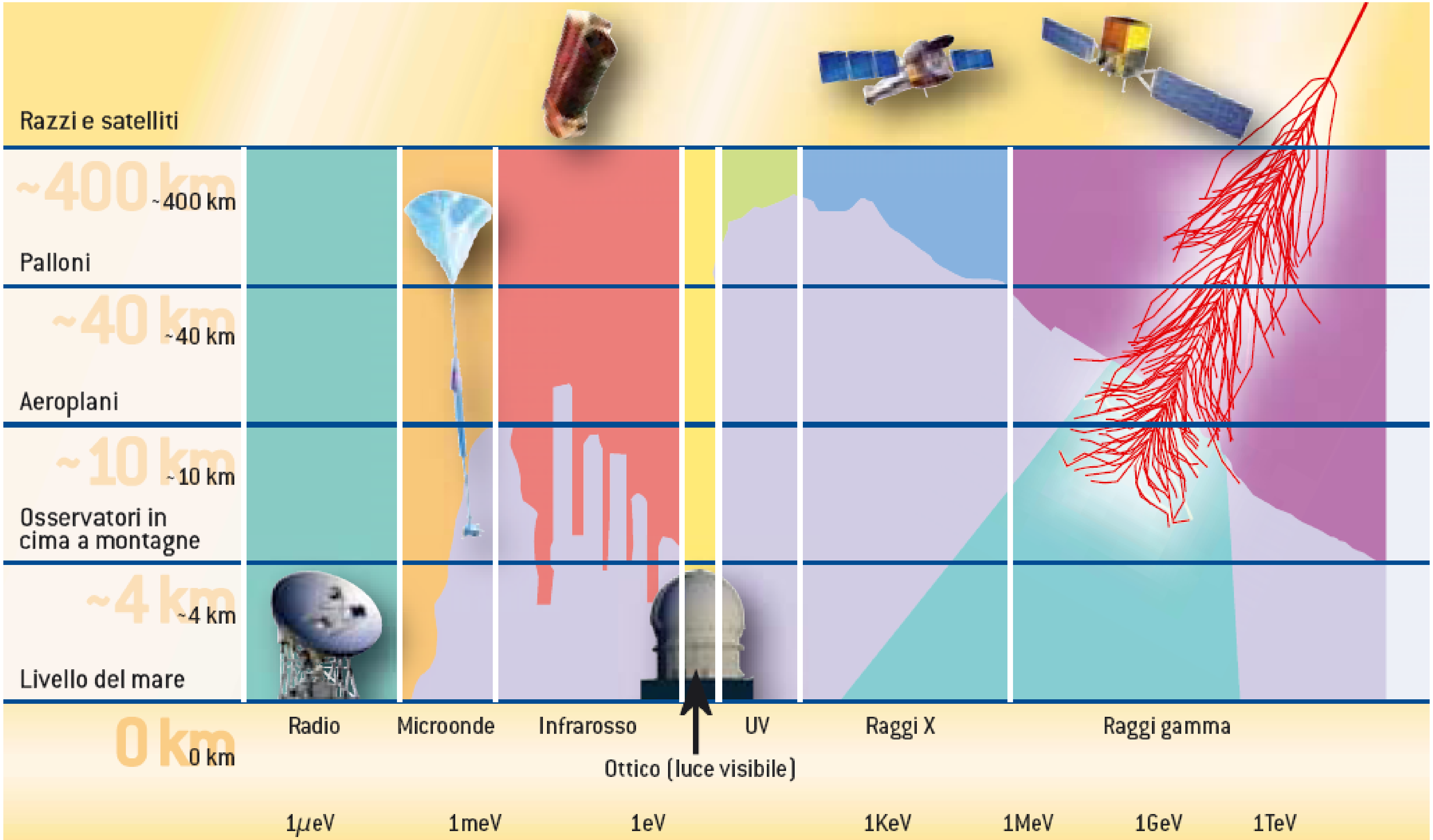
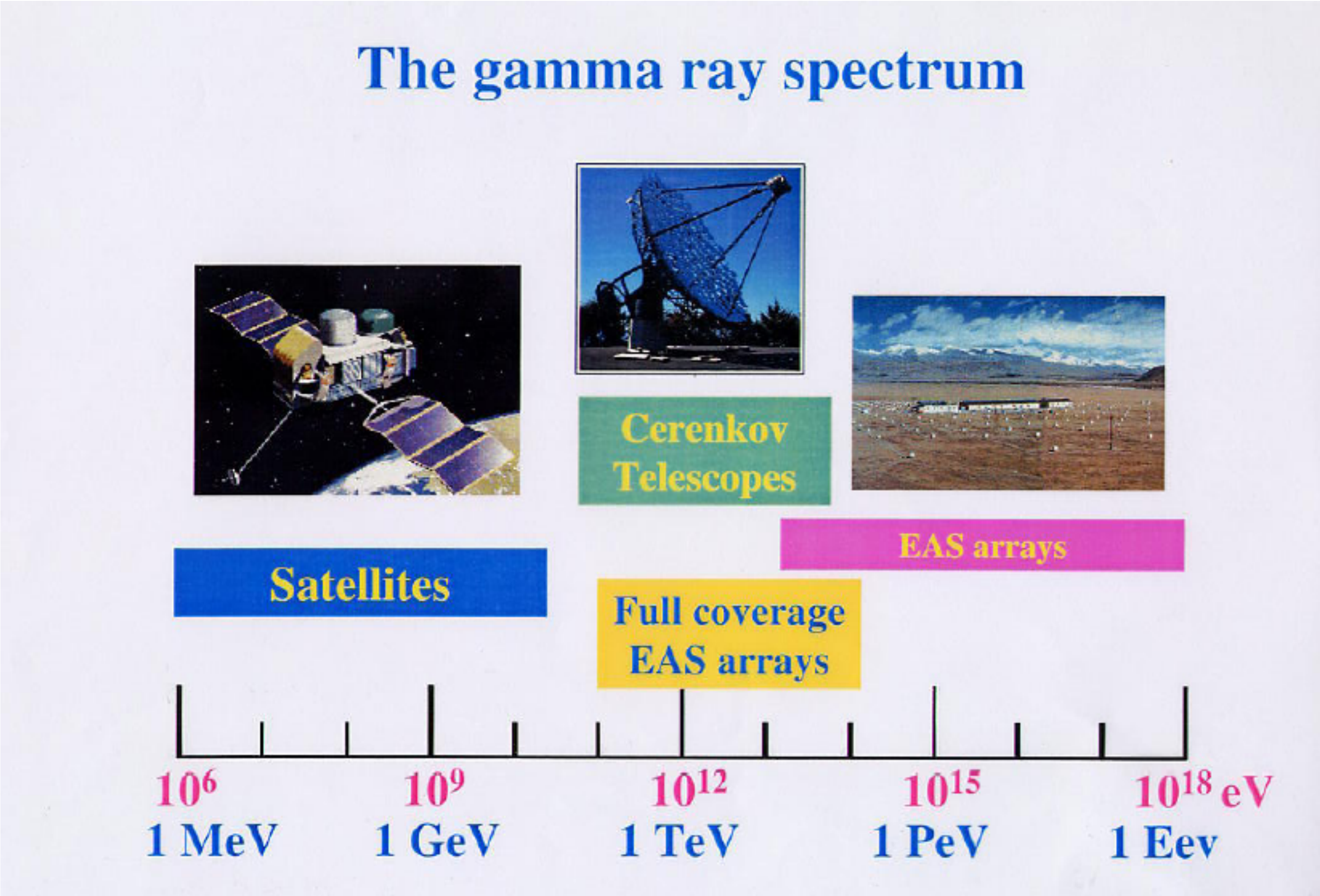
Astrofisica Nucleare e Subnucleare

TeV Astrophysics

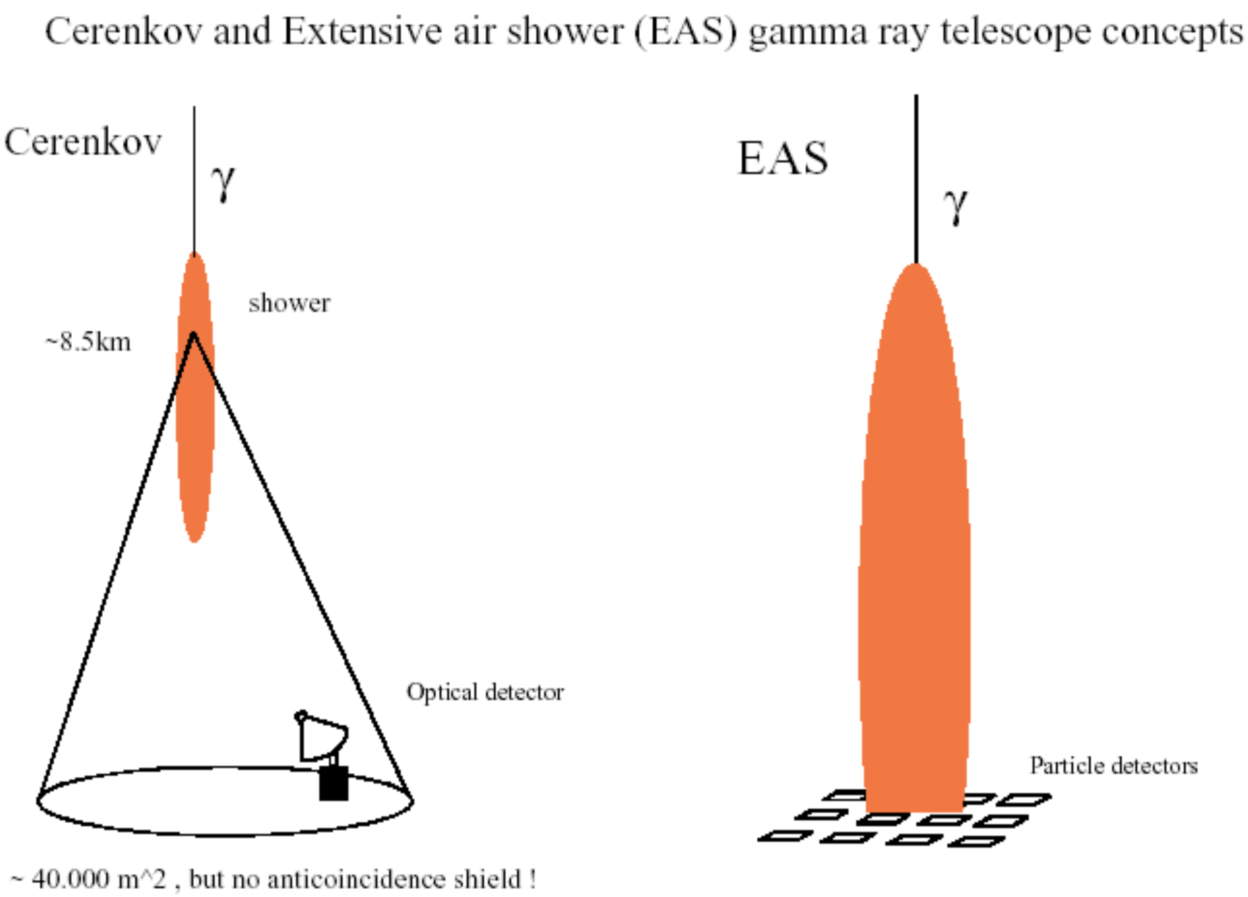
The opacity of the atmosphere



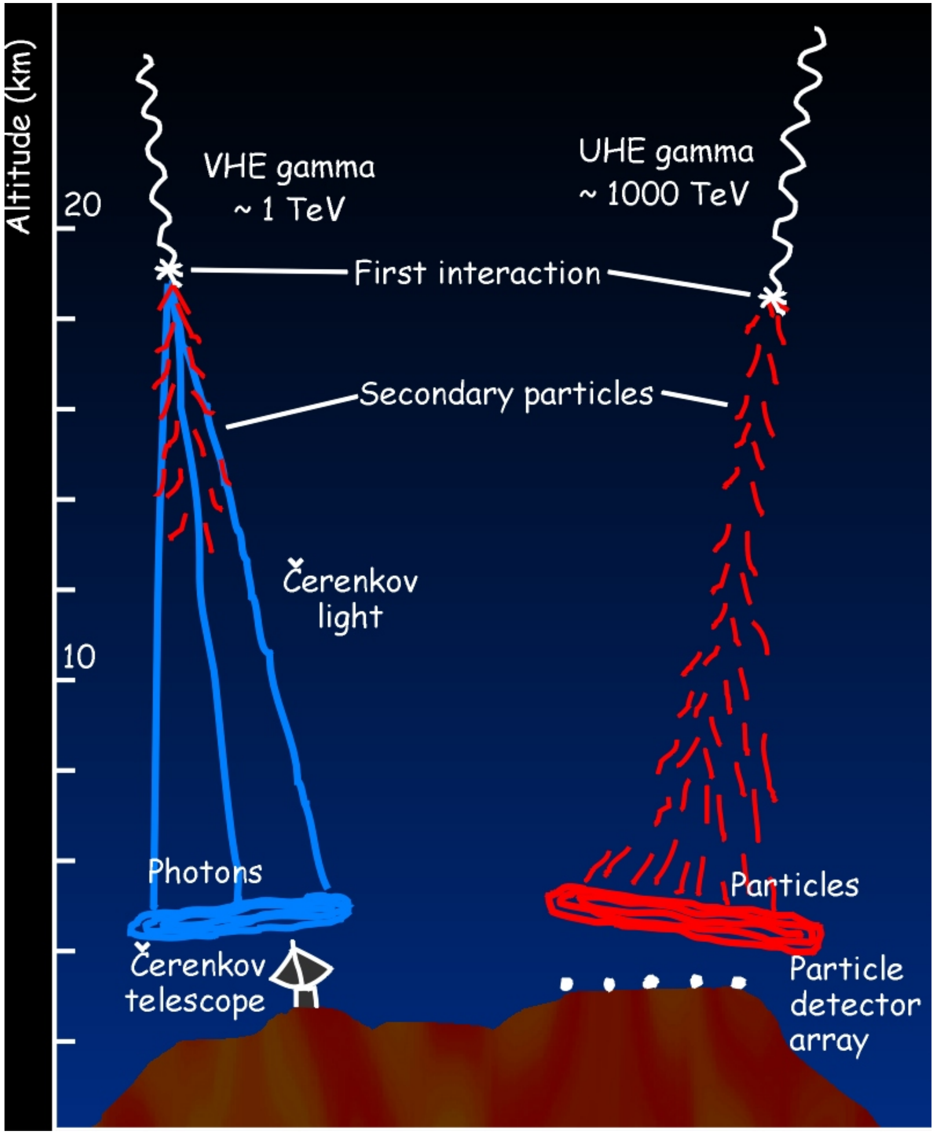
TeV detectors



TeV detectors



IACT & EAS experiments



- Cherenkov experiments consist of almost-optical telescopes devoted to detect Cherenkov light.
- EAS (Extensive Air Shower) experiments are huge arrays or carpets of particle detectors.
- Cherenkov experiments have lower energy thresholds, but also a lower duty-cycle as well as a smaller field of view.

Complementary Capabilities

Parameter	Ground-based		Space-based
	ACT	EAS	Pair
angular resolution	good	fair	good
duty cycle	low	high	high
area	large	large	small
field of view	small	large	large & can repoint
energy resolution	good	fair	good w/ smaller systematic uncertainties

The next generation of ground-based and space-based facilities are well matched!

EM Air Showers

Air shower development

- Pair production $I = I_0 e^{-x/\lambda}$

  λ = mean free path

- Bremsstrahlung $E = E_0 e^{-x/\chi_0}$

  χ_0 = radiation length

In the ultra-relativistic limit $\lambda \sim \chi_0 = 36.5 \text{ g/cm}^2$ in air

$R = \chi_0 \ln 2 \Rightarrow$ After a distance nR :

$N_{e,\gamma} = 2^n \qquad E_{e,\gamma} \sim E_{pr} / 2^n$

EM Air Showers

The process continues until the electrons energy is $E > E_c$

E_c= critical energy = 83 MeV in air

Number of particles at the shower maximum:

$N_{max} = 2^n = E_{pr} / E_c$

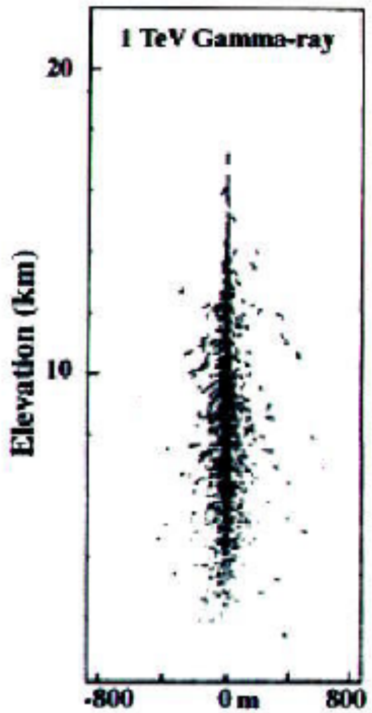
Depth of the maximum:

$n_{max} = \ln (E_{pr} / E_c) / \ln 2$

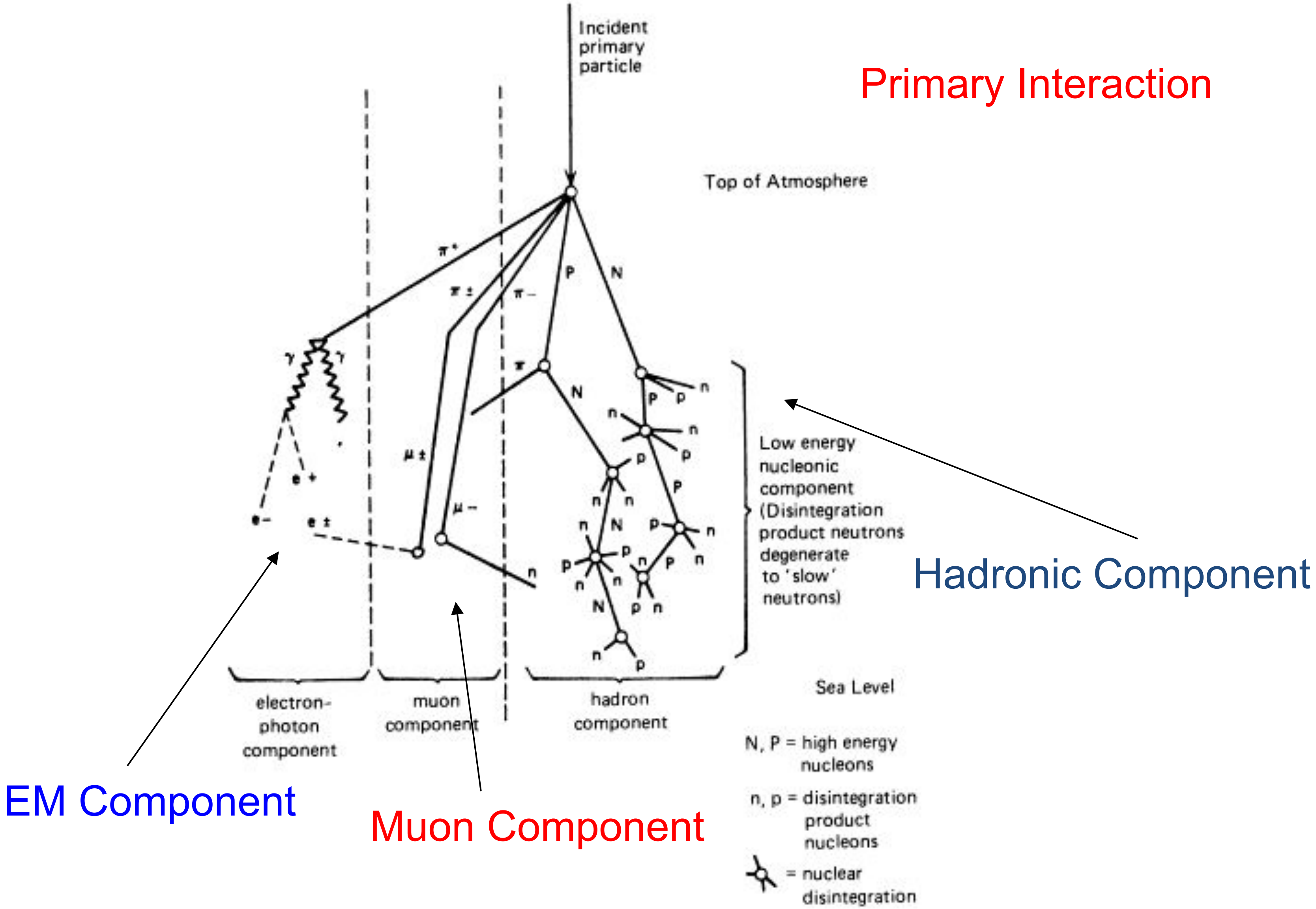
$\Rightarrow X_{max} = n R = n \chi_0 \ln 2 = \chi_0 \ln (E_{pr} / E_c)$

Example: $E_{pr} = 1$ TeV

$\Rightarrow X_{max} = 340$ g / cm² ~ 8 Km



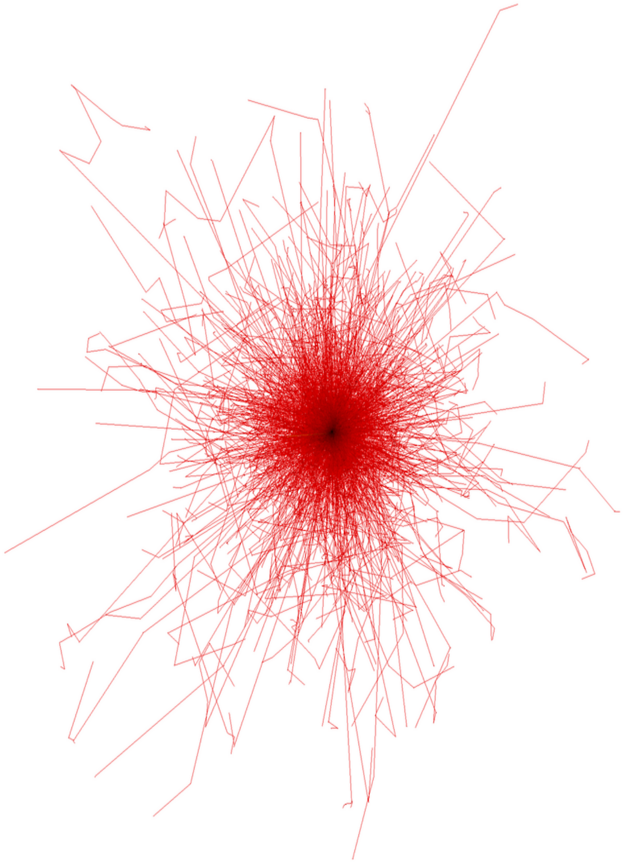
CR interactions

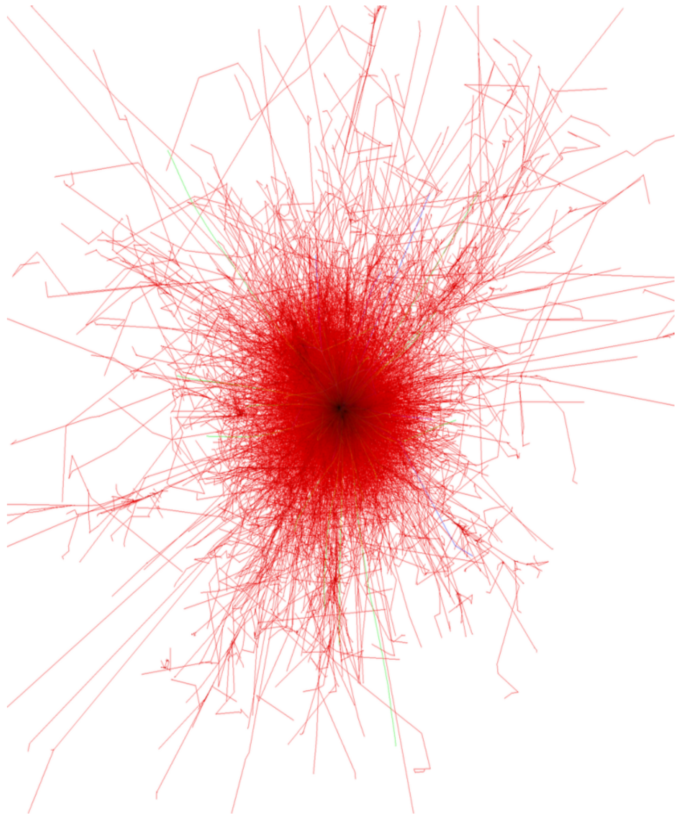


The importance of MC

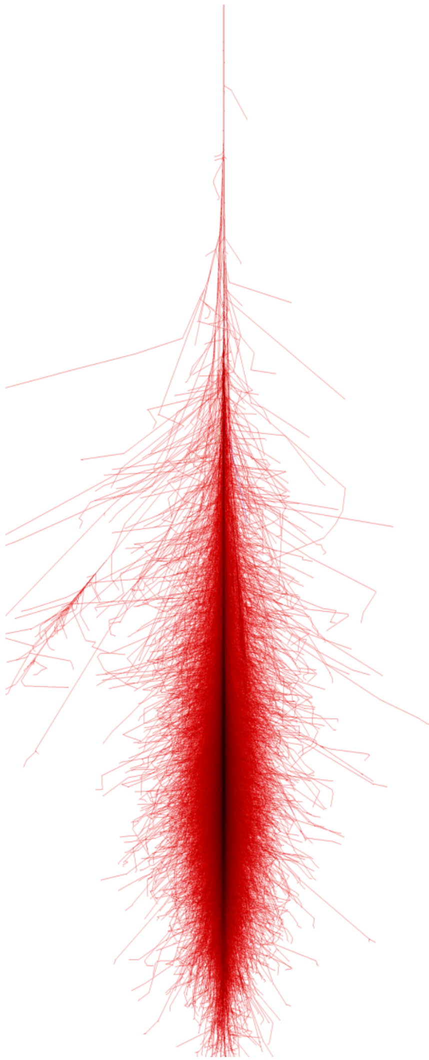
- CORSIKA (COsmic Ray SImulations for KAscade) is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. Protons, light nuclei up to iron, photons, and many other particles may be treated as primaries.
- The particles are tracked through the atmosphere until they undergo reactions with the air nuclei or - in the case of instable secondaries - decay.
- The hadronic interactions at high energies may be described by six reaction models alternatively: The VENUS, QGSJET, and DPMJET models are based on the Gribov-Regge theory, while SIBYLL is a minijet model. HDPM is inspired by findings of the Dual Parton Model and tries to reproduce relevant kinematical distributions being measured at colliders. The neXus model extends far above a simple combination of QGSJET and VENUS routines.
- Hadronic interactions at lower energies are described either by the GHEISHA interaction routines, by a link to FLUKA, or by the UrQMD model.
- In particle decays all decay branches down to the 1 % level are taken into account.
- For electromagnetic interactions a taylor made version of the shower program EGS4 or the analytical NKG formulas may be used.
- Options for the generation of Cherenkov radiation and neutrinos exist.
- CORSIKA may be used up to and beyond the highest energies of 100 EeV.
- http://www-ik.fzk.de/corsika/ → https://www.iap.kit.edu/corsika/

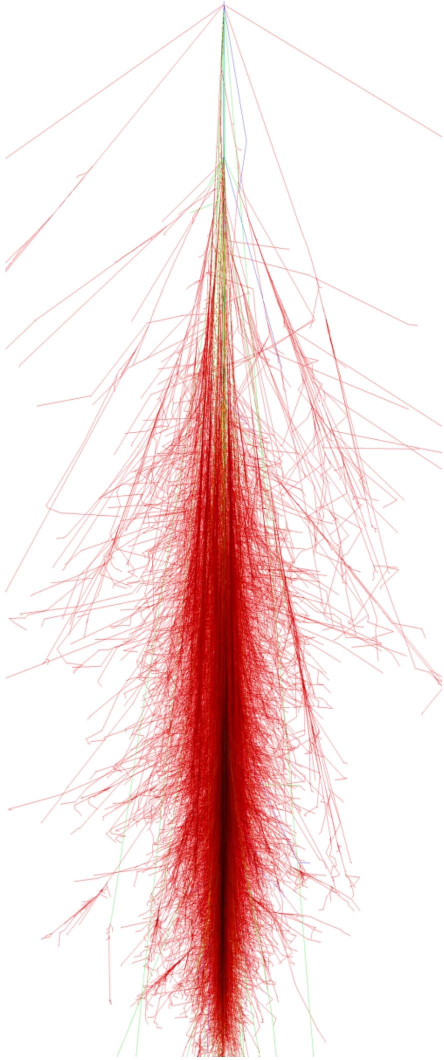
Shower Images



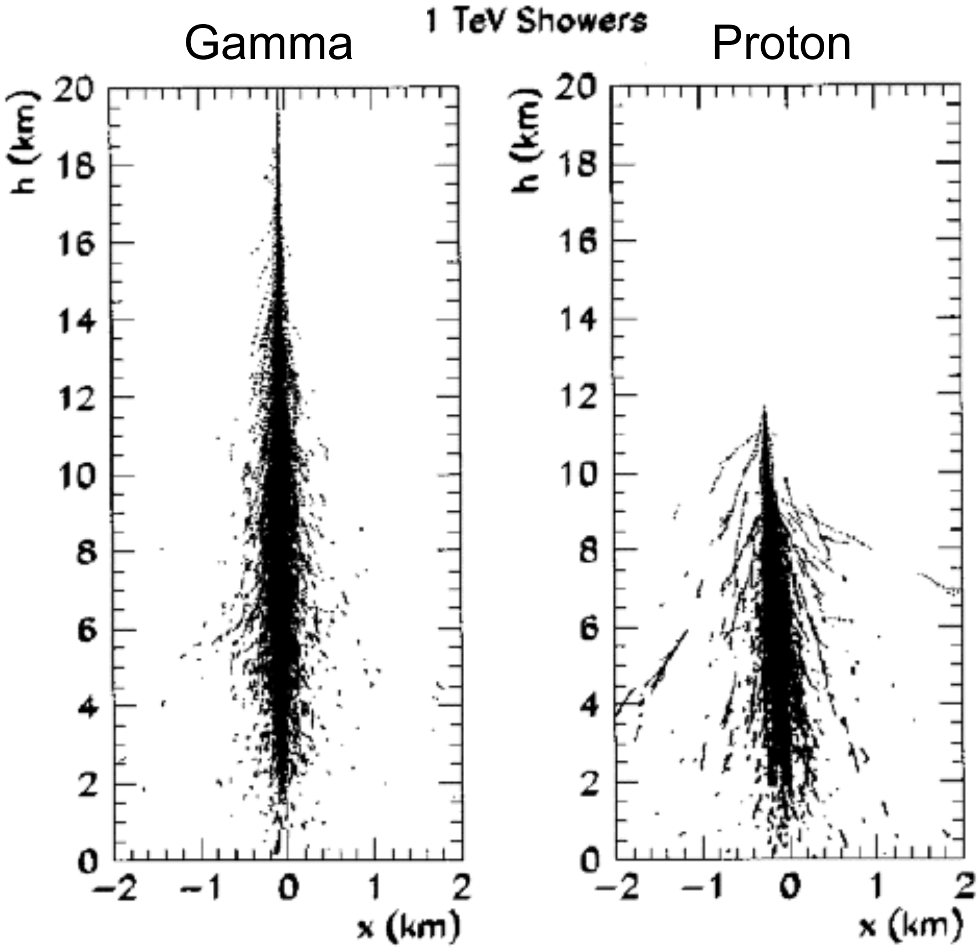


Shower Images



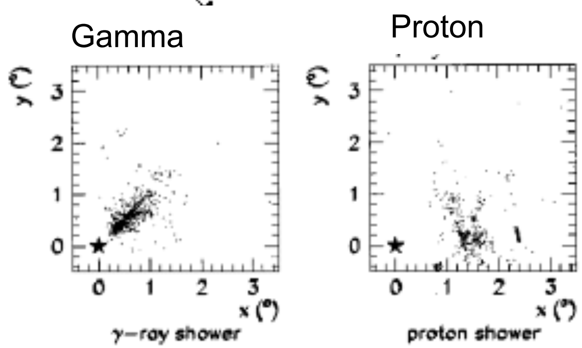


Development of vertical 1-TeV proton and γ-ray shower

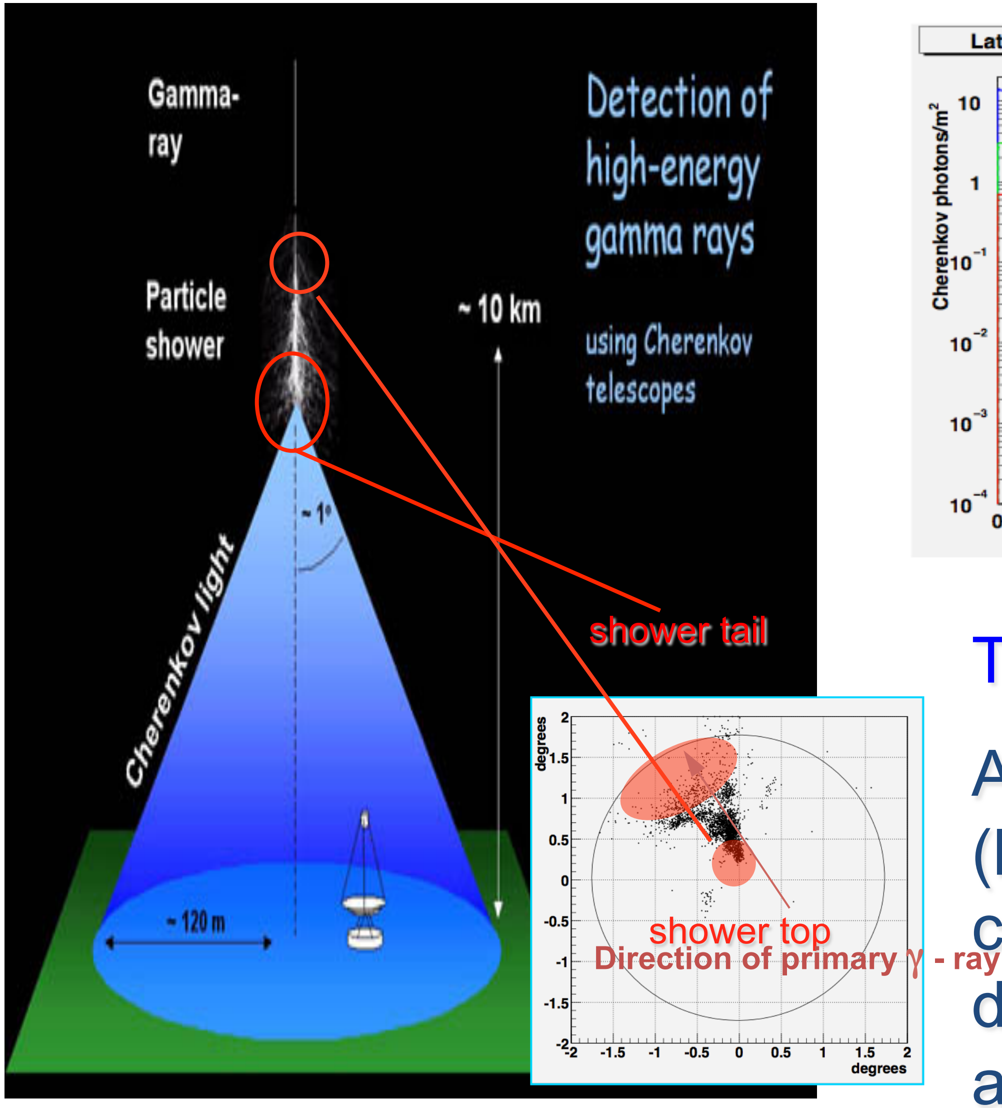


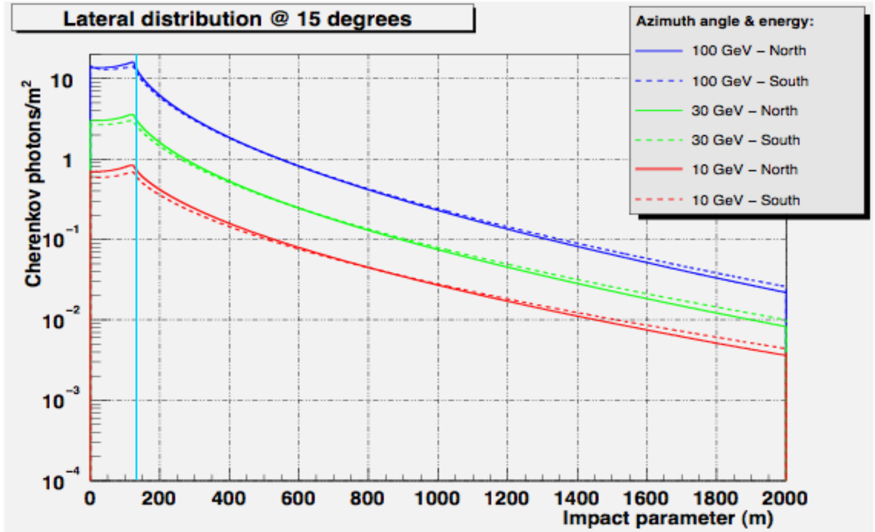
Positions in the atmosphere of all shower electrons above the Cerenkov threshold

Resulting Cerenkov images in the focal plane of a 10-m reflecting mirror .



Imaging Atmospheric Cherenkov Telescopes

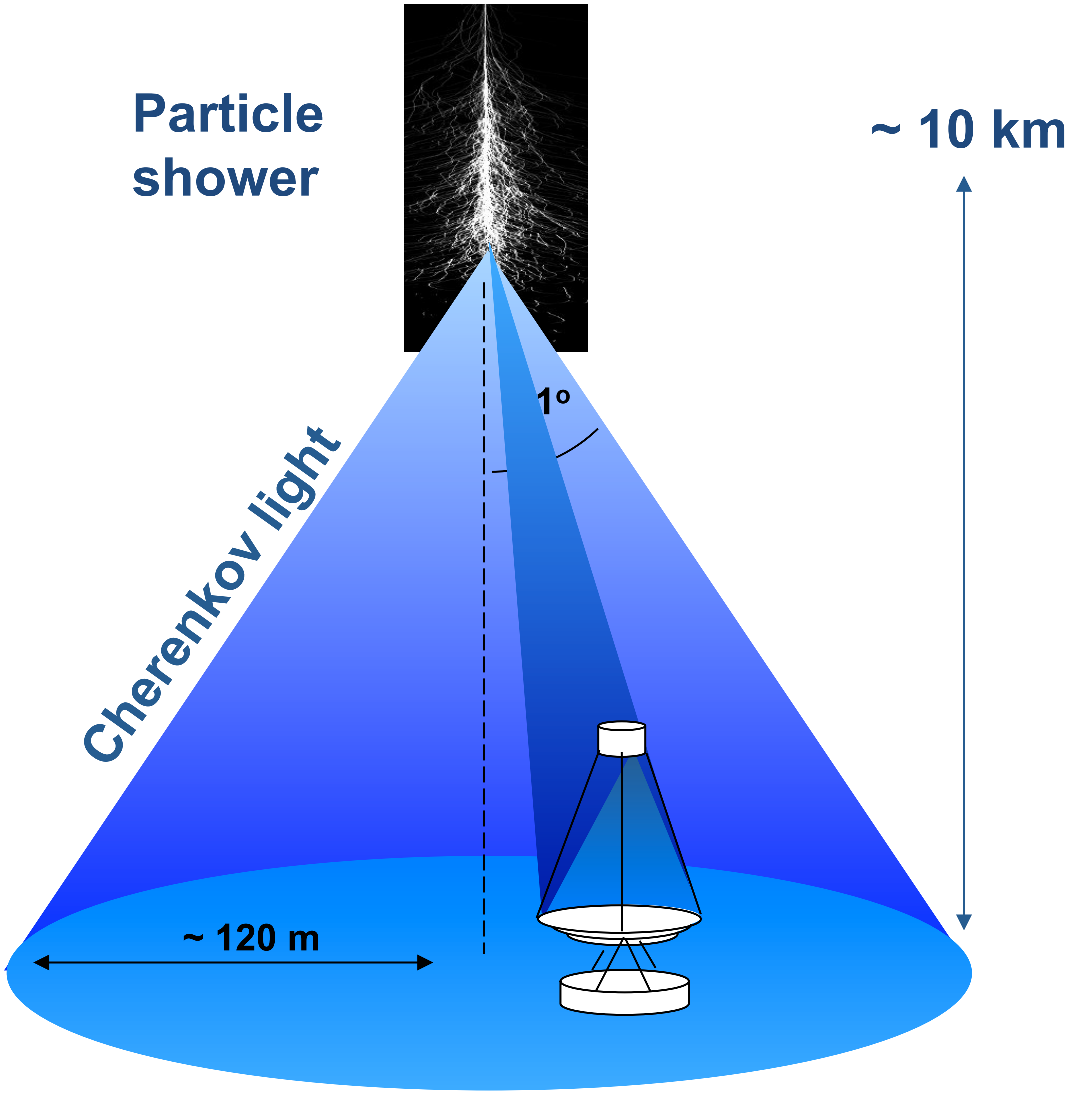




The principle:

A telescope placed inside the (huge) Cherenkov light pool can obtain an image of the development of the shower above the bkg fluctuations

Observation tecnique



Detection of TeV gamma rays

using Cherenkov telescopes

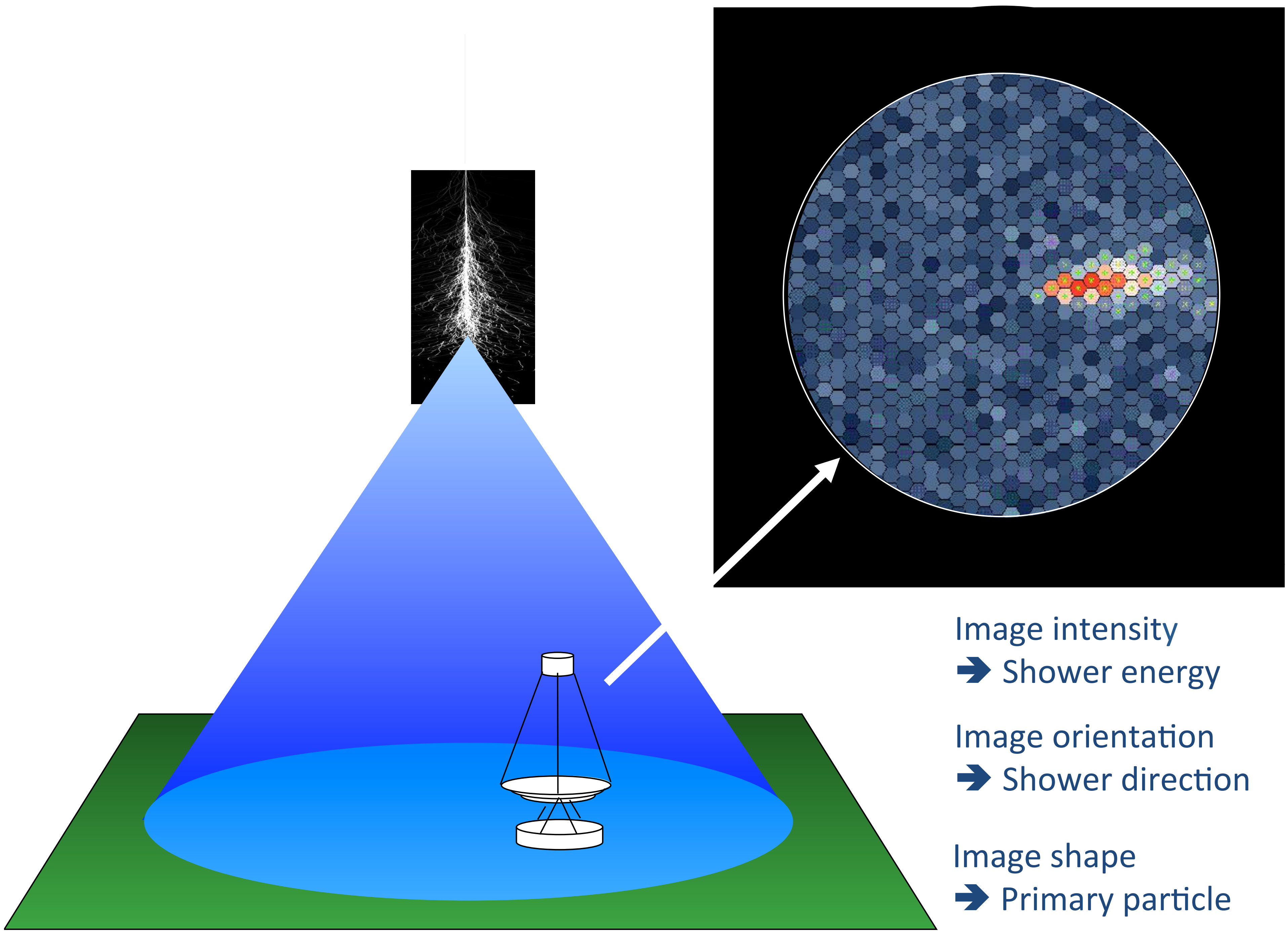
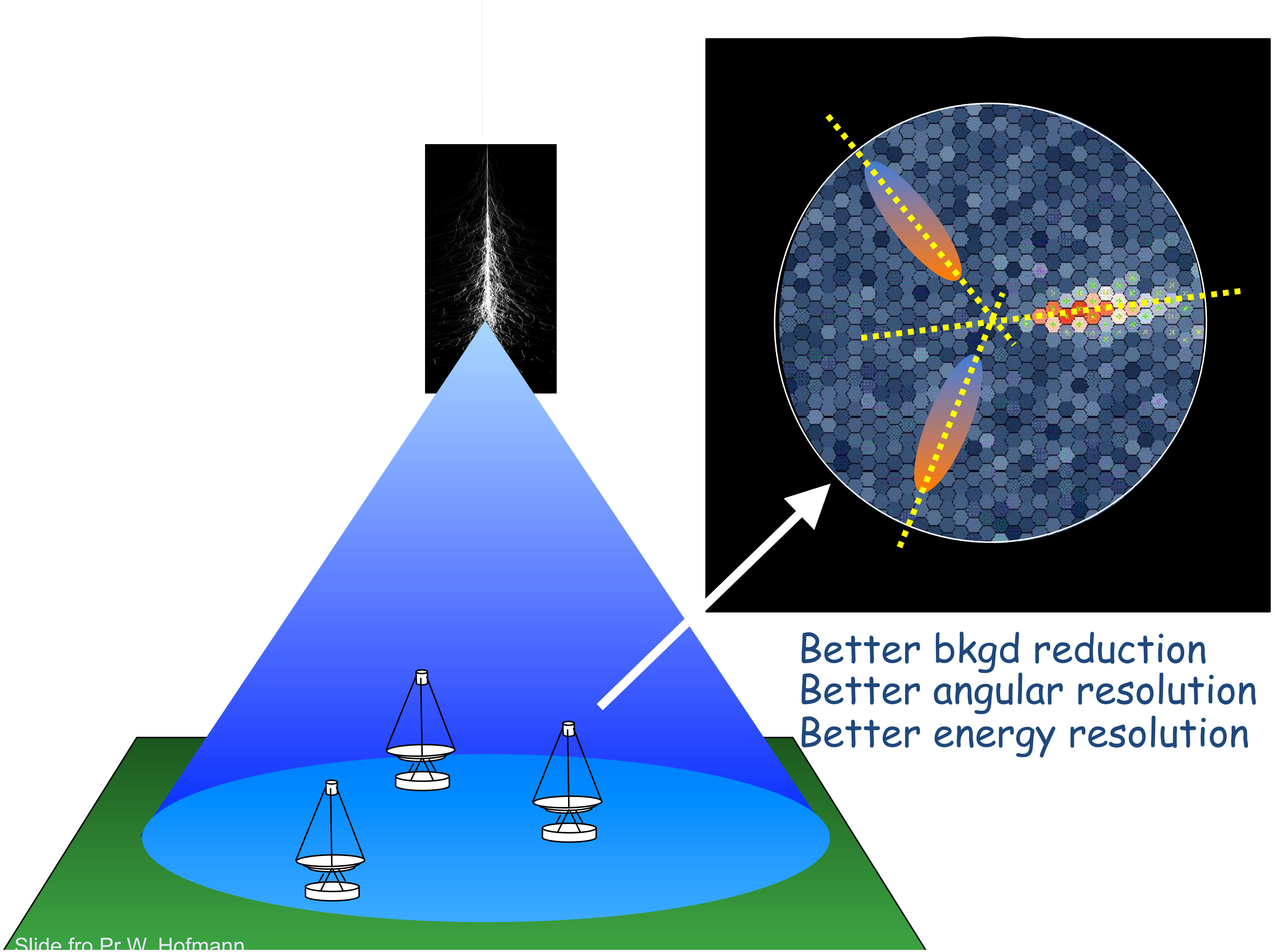
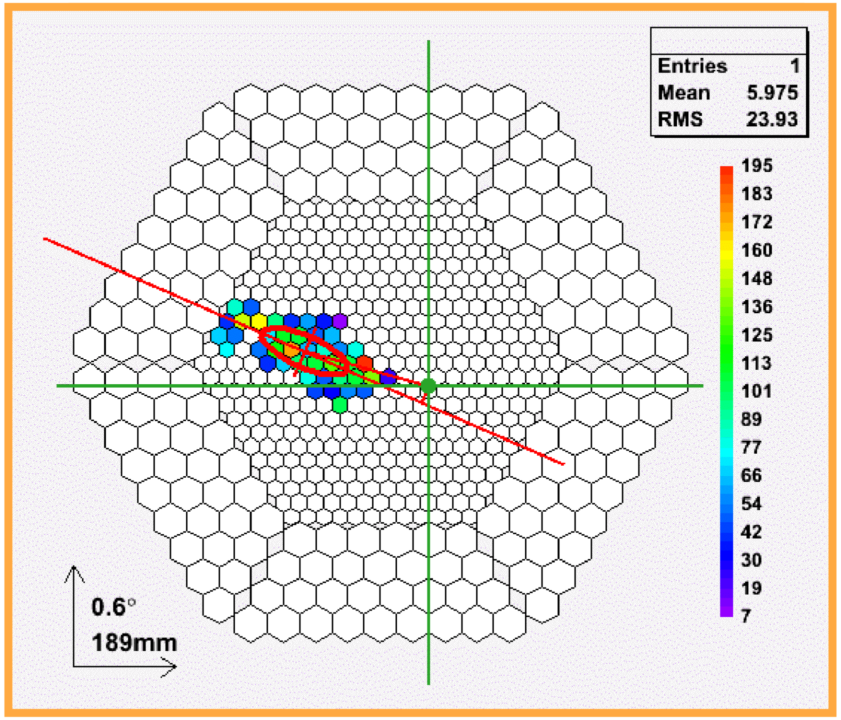


Image intensity
➔ Shower energy
Image orientation
➔ Shower direction
Image shape
➔ Primary particle

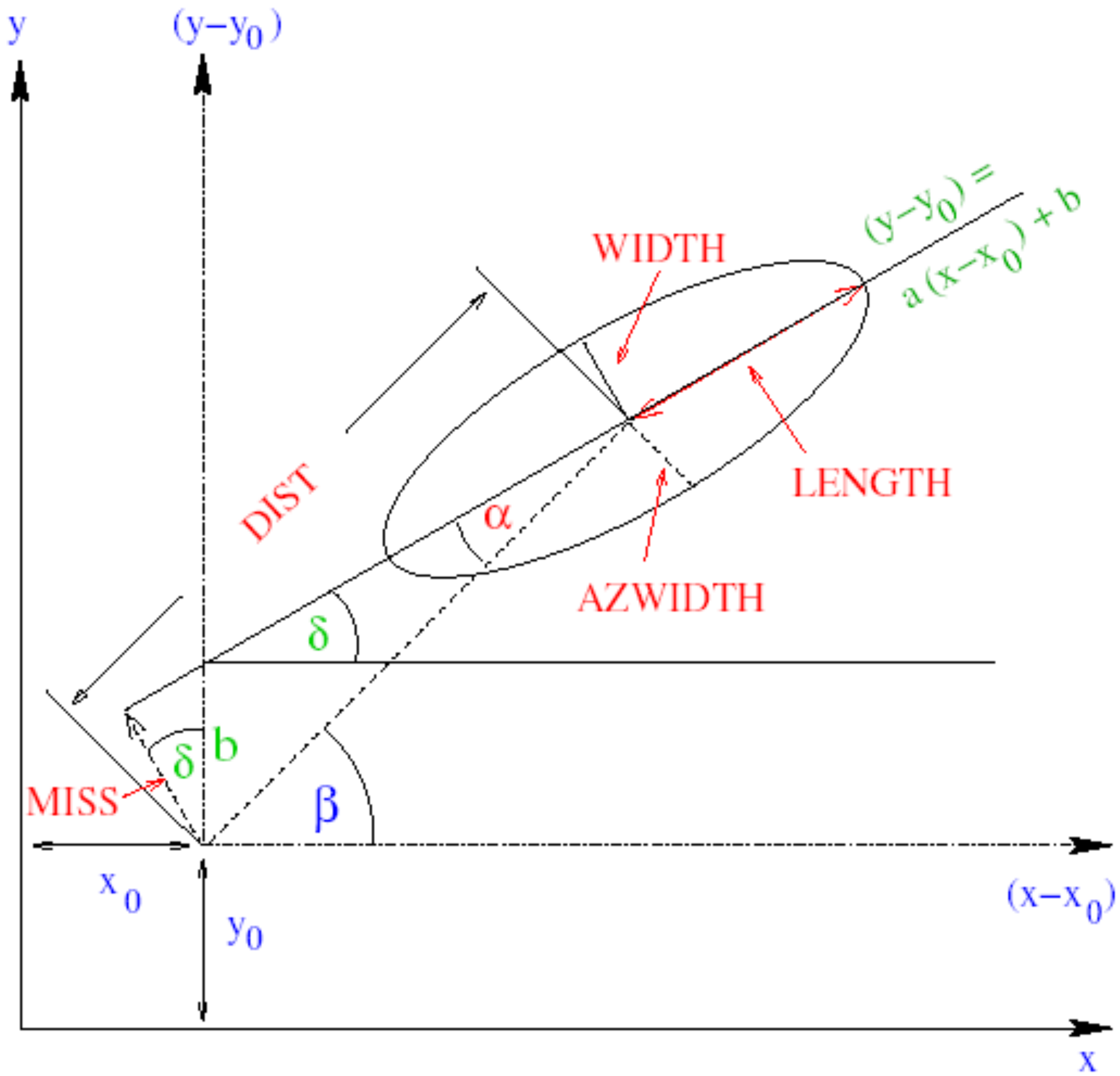

Better bkgd reduction
Better angular resolution
Better energy resolution
Slide fro Pr W. Hofmann

IACT image reconstruction

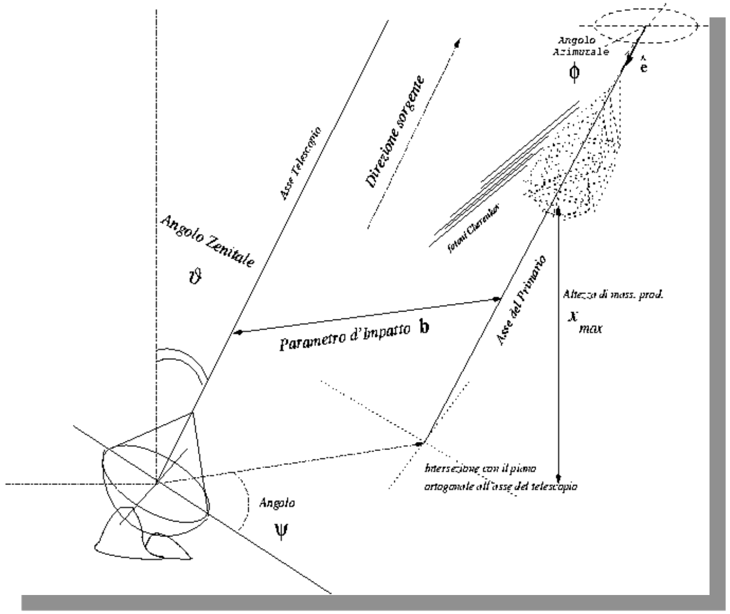
- Primary γ parameters reconstruction by particle shower image analysis
- Different primary particles give different image shapes
- Possible γ-hadron separation
- Reconstructed parameters of primary γ: energy, direction, arrival time
- Signal estimation
- Spectrum calculation
- Lightcurve



Hillas parameters

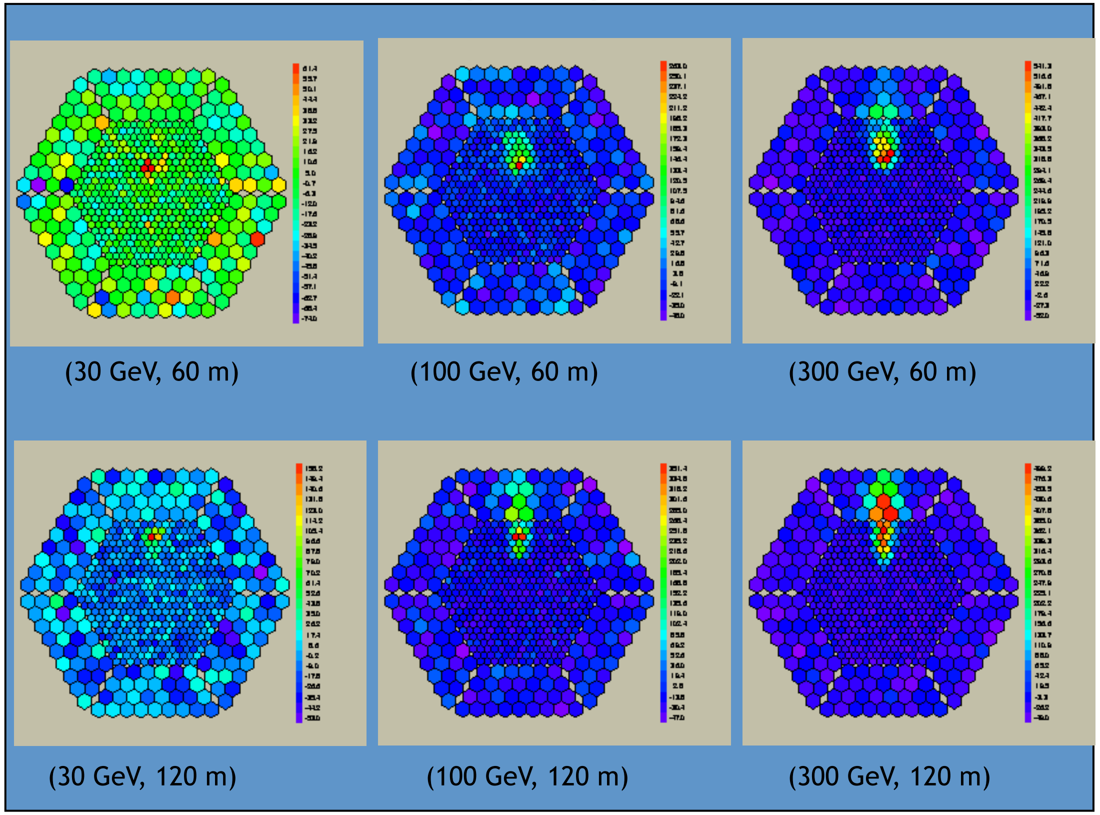


Imaging Atmospheric Cherenkov Telescopes

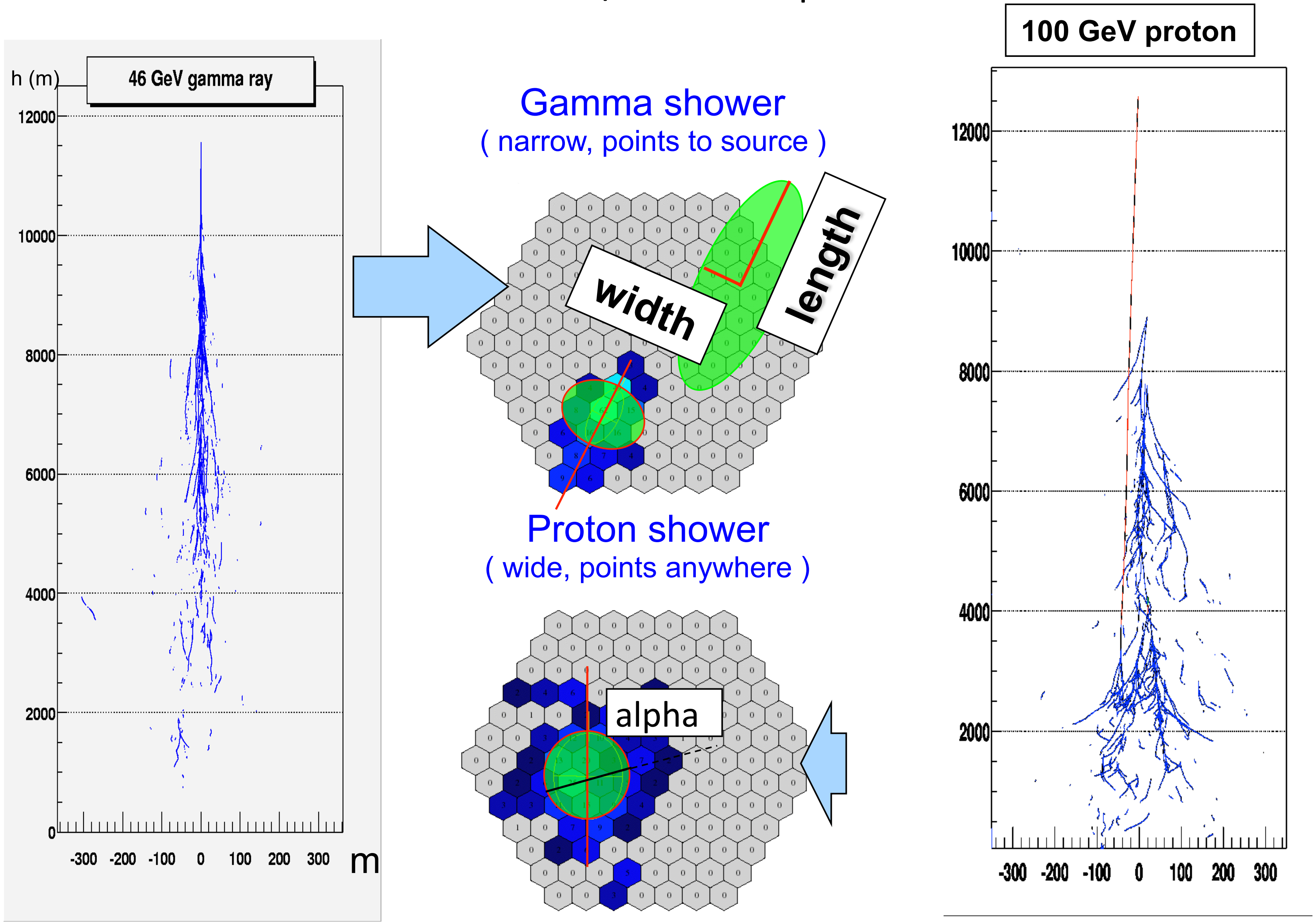


Geometric relations between a shower and the Cherenkov Telescope optics

Typical γ shower images simulated with different energy and different impact parameter

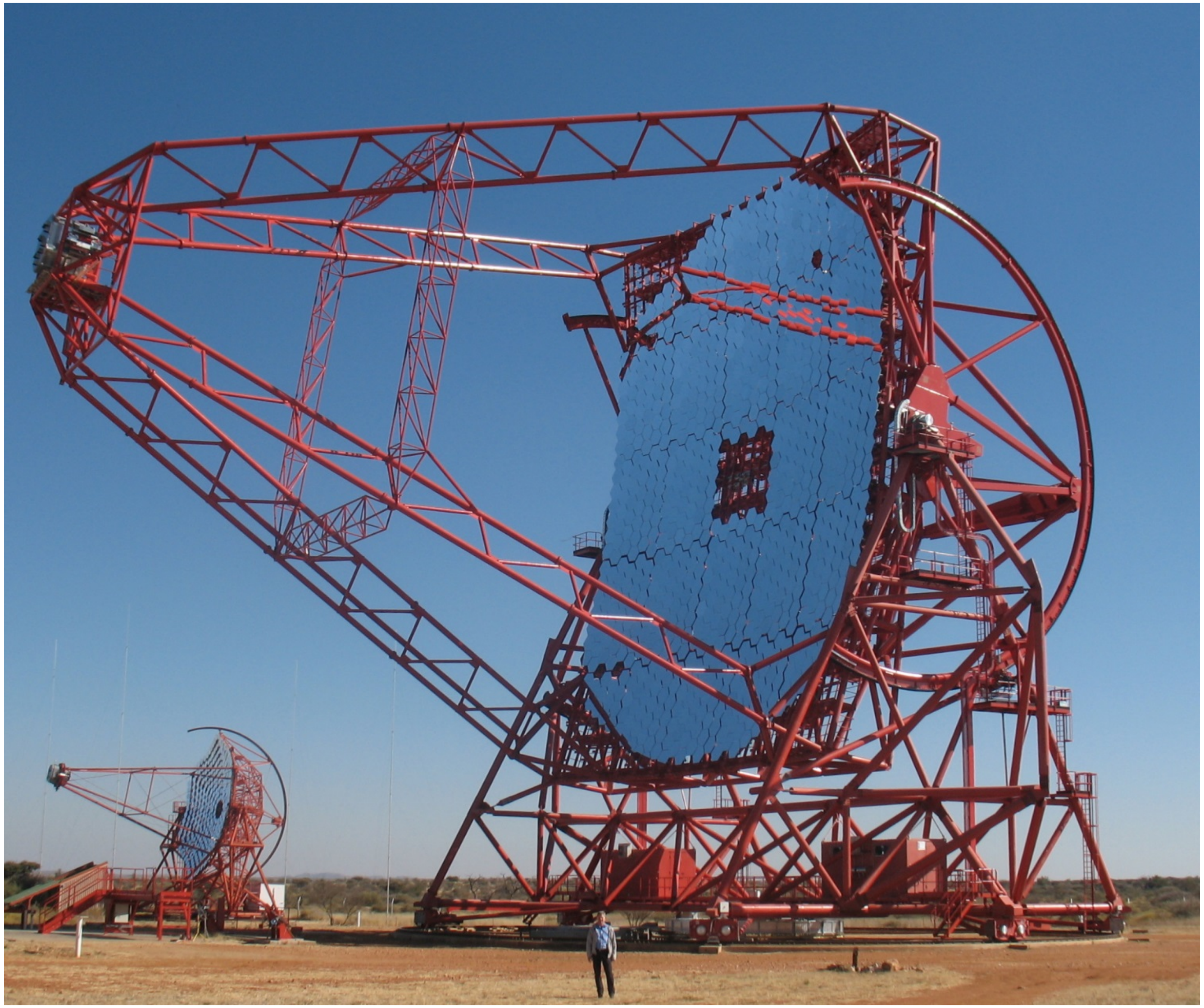


Gamma / hadron separation



HESS

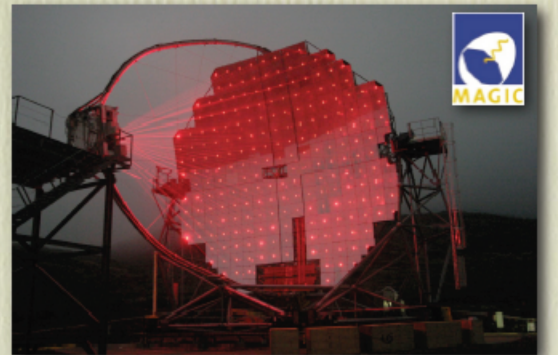
HESS-II



The MAGIC Telescope

Major Atmospheric Gamma Imaging Cherenkov telescope

Located at the Roque de los Muchachos on La Palma, Canary Islands (Spain) at ~2200 m *asl*



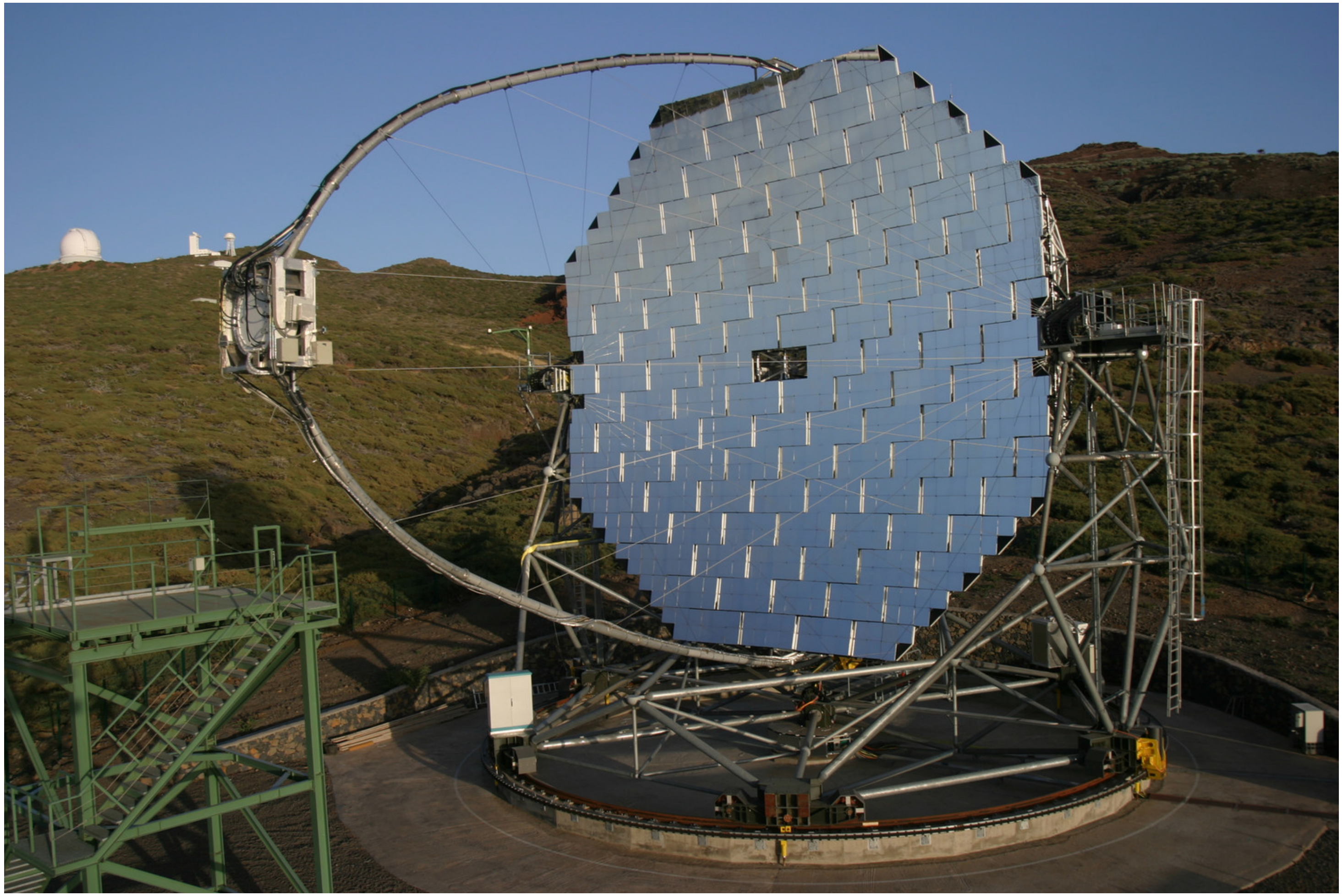
Largest imaging Cherenkov telescope for γ-ray astronomy

Designed for:

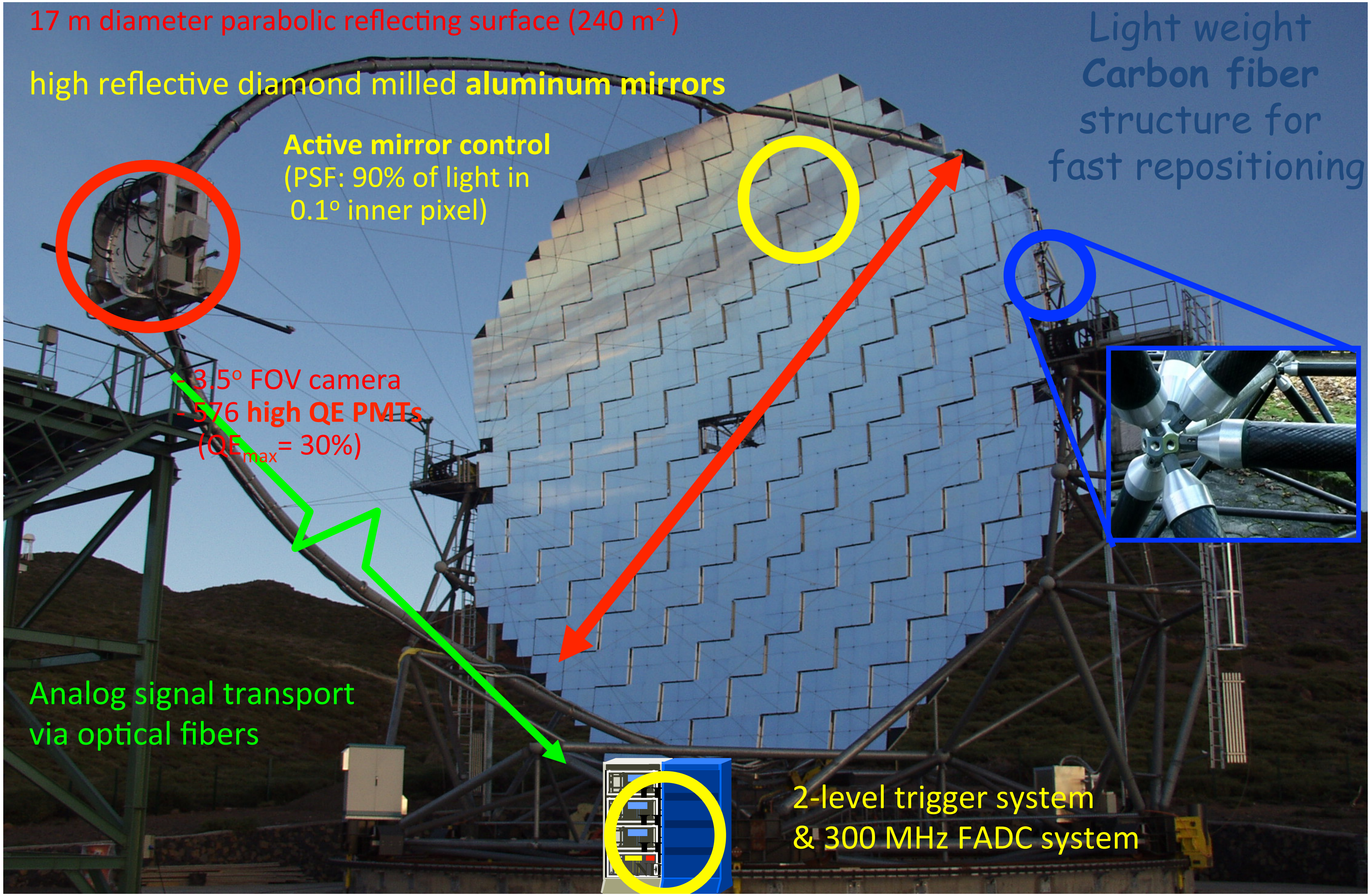
- Low energy threshold $E_{th} \approx 50$ GeV
- Fast repositioning in < 30 s

Construction 2001-2003
Inauguration 10/10/2003
Commissioning 2004
Cycle I 2005-2006

MAGIC



Key technological elements for MAGIC



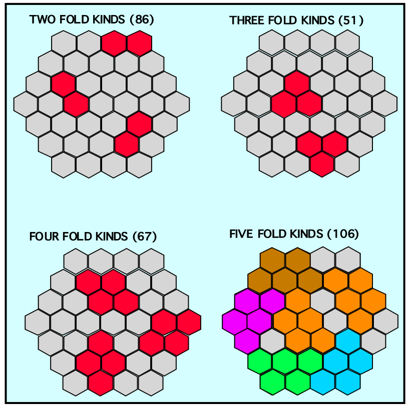
The trigger architecture

The trigger is split into two stages: level 1 (L1) and level 2 (L2). The L1 is a fast coincidence device (2-5 ns) with simple patterns (n-next-neighbor logic) while L2 is slower (50-150 ns) but can do a more sophisticated patter recognition.

Discriminators
L0

Choose the **number of photoelectrons** per pixel you want to use in the trigger

Level 1
L1

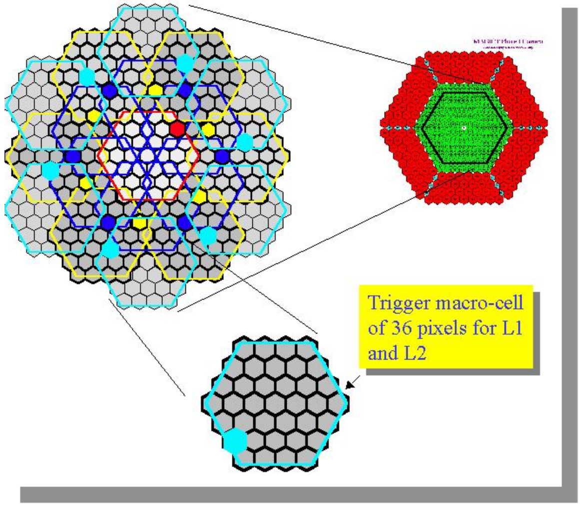


Make a **tight time coincidence** on simple pattern of compact images and **enable L2**

Level 2
L2

Make an **advanced pattern recognition** to use topological constraint:
•pixel counting in a given region of the detector
•mask hot spots like bright stars
•rough center of gravity of the image…etc…..

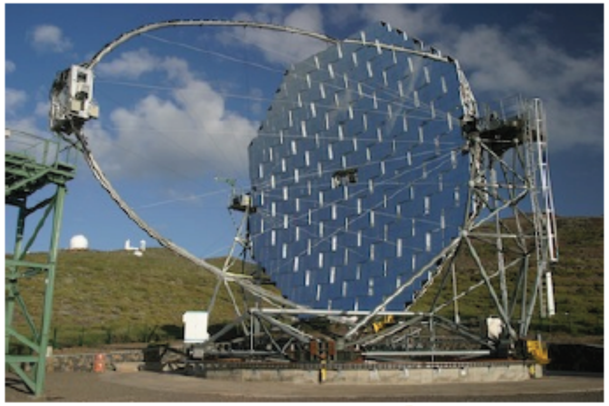
To FADC



MAGIC telescopes

MAGIC – II

+ The telescope(s)



Design

- Solar power-plant design
- 17-m diameter
- F/D=1
- ~500kg camera
- Signal digitization off-telescope
- 64 tons total moving weight
- Fast-movement (GRBs): 20 sec ptp

Performance

- Energy threshold ~50 GeV (~ 25 GeV with a special trigger)
- FOV 3.5deg
- Energy Resolution ~16% (E>300 GeV)
- Angular Resolution ~0.07deg (E>300 GeV)
- Sensitivity (5 σ in 50 hours) ~0.8% Crab Nebula flux (> 250 GeV)

Colin, ICRC 2009

Several "firsts"

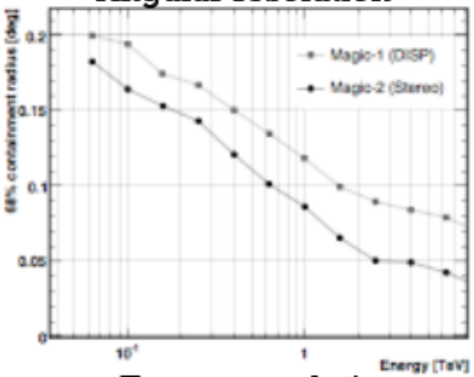
- Worldwide largest mirror dish.
- Lightweight CFRP tubes for structure
- Diamond milled light weight all-aluminum sandwich mirrors
- Active mirror control
- Low gain hemispherical PMTs with diffuse lacquer coating
- Transmission over 160 m by optical
- 2 GHz FADCs

MD, ICAPTT 2008

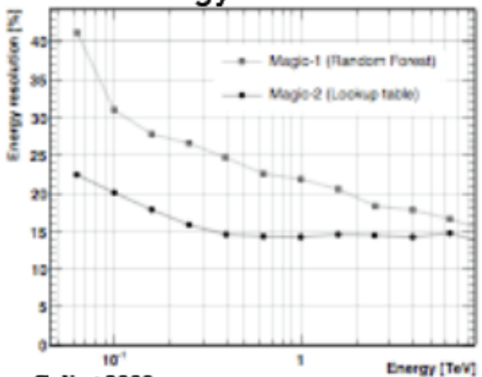
MAGIC – II

+ Improvements

Angular resolution

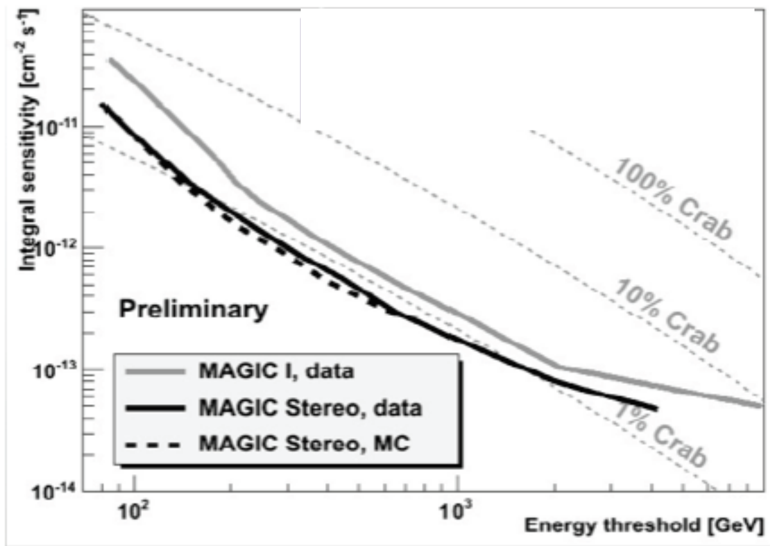


Energy resolution



Colin+2009

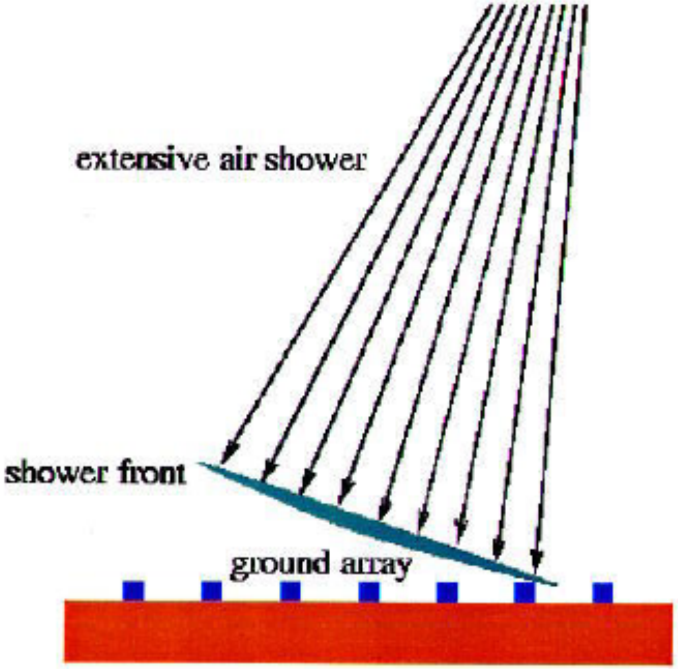
- Extended sources and morphology now possible
- **Sensitivity improved of 100%** over most of the energy range
- Better performance specially at low energy (<100 GeV)



VERITAS

TeV detectors

Air Shower Arrays



Reconstruction of the γ direction with the particles arrival times

Large field of view: ~ π sr

Duty cycle ~ 100%

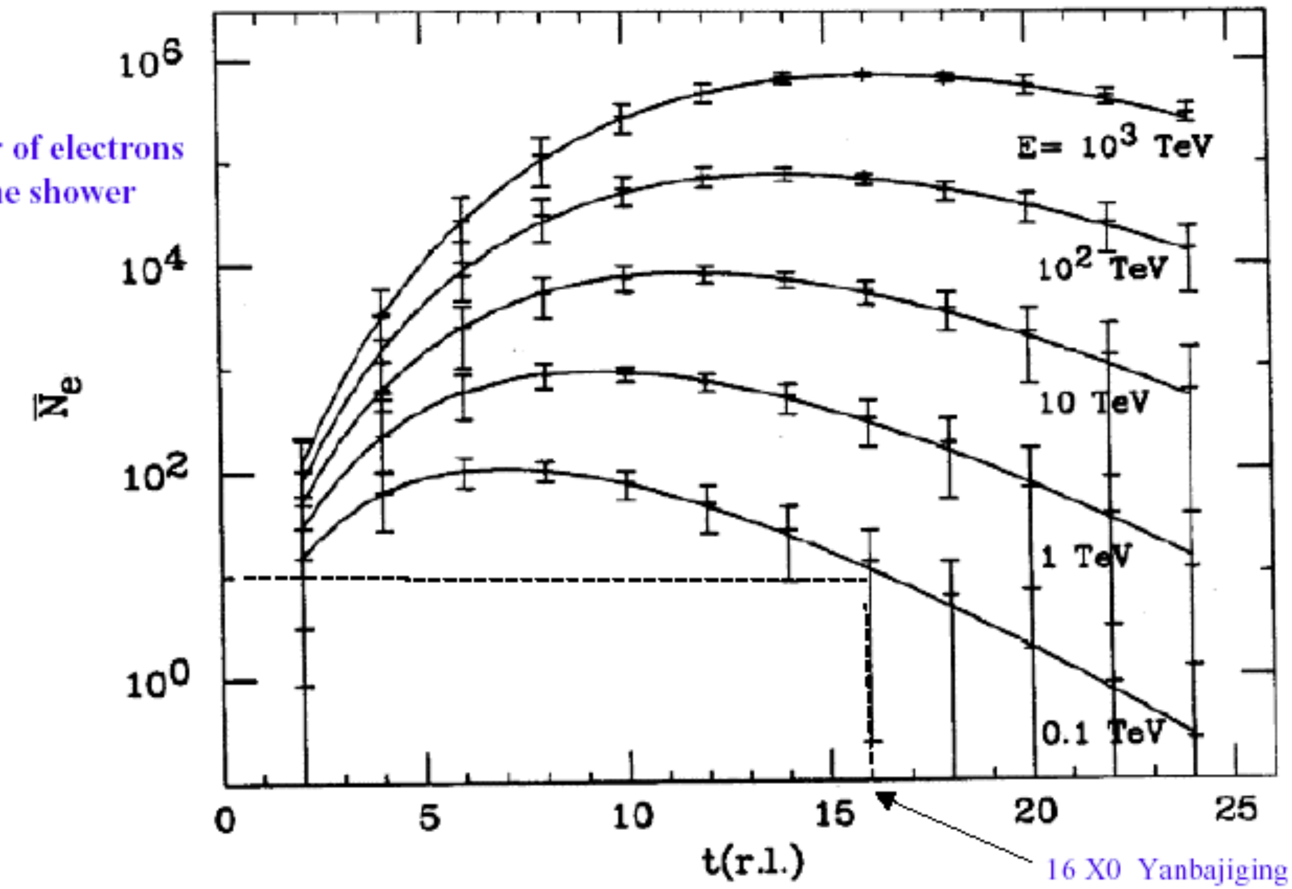
Gamma-hadrons discrimination:

μ-poor showers

TeV detectors

Longitudinal development of the electron component of photon initiated shower
(with electron threshold energy of 5 MeV and fluctuations superimposed)

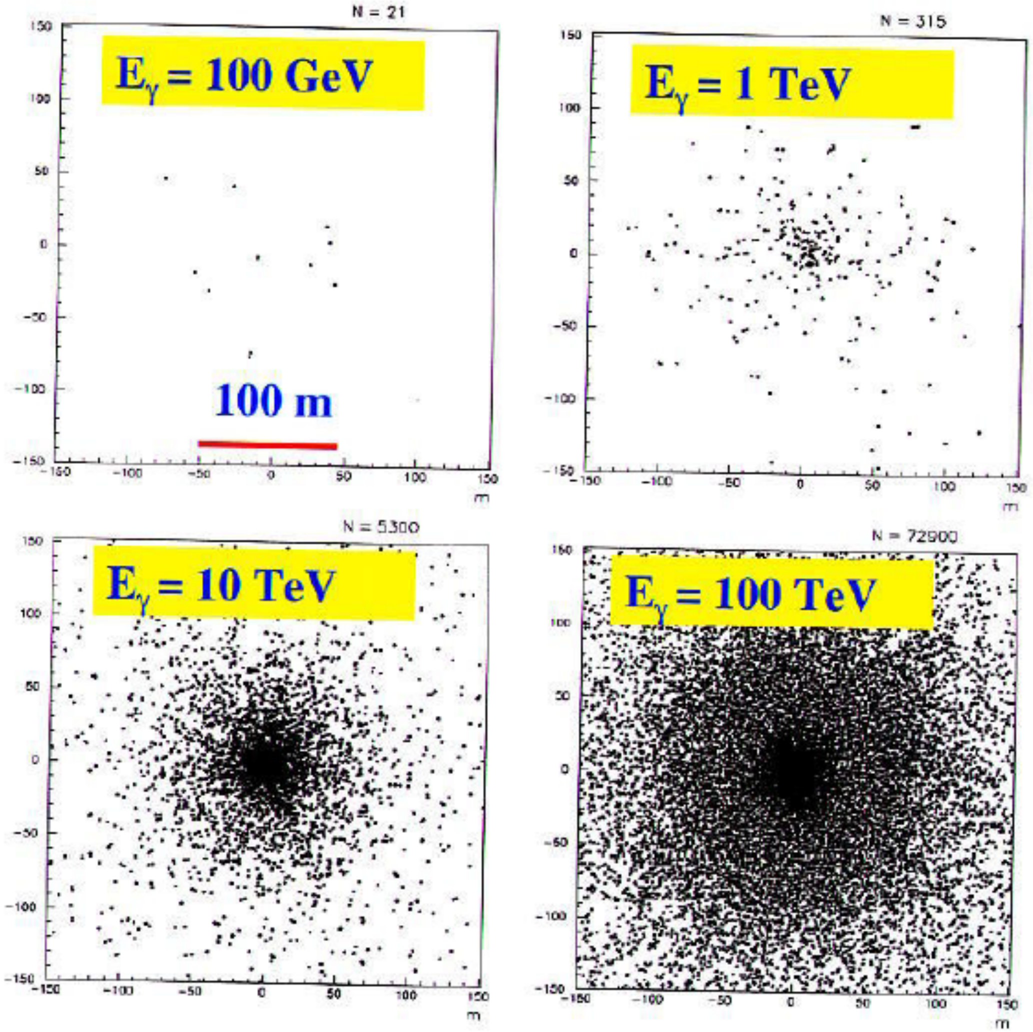
Number of electrons in the shower



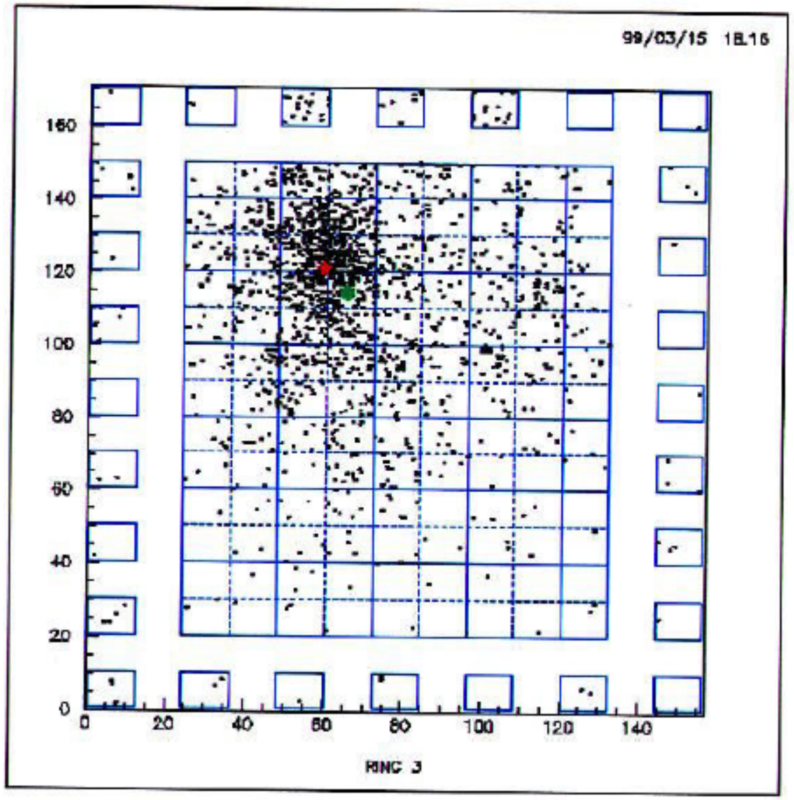
16 X0 Yanbajiging

TeV detectors

EAS
at
4300 m



TeV detectors



Montecarlo simulation of a 10 TeV air shower

EAS technique

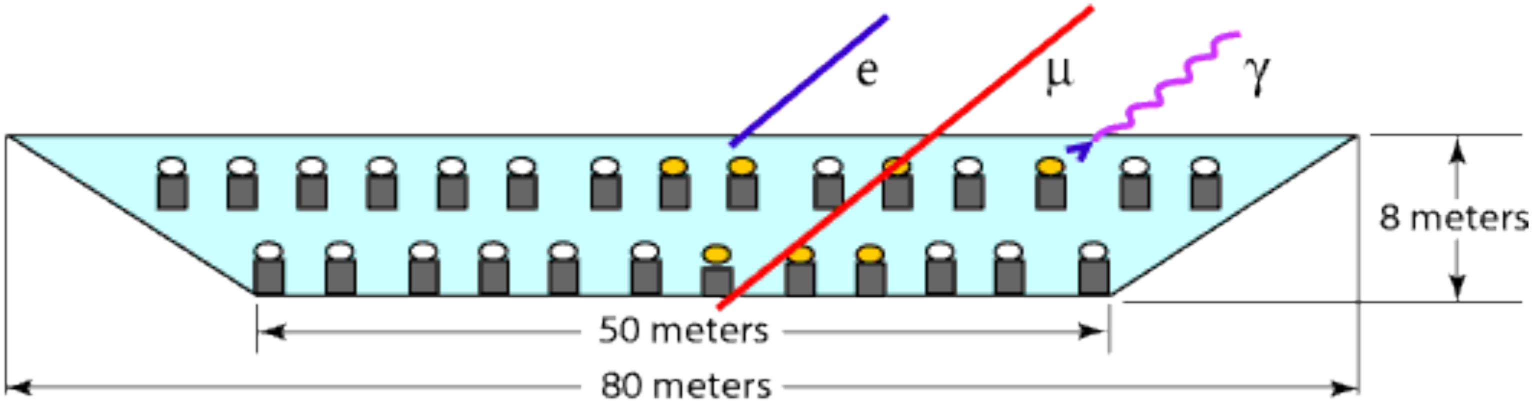
Charged particles produce Cherenkov photons in water

~1400 times more Cherenkov photons than in air per unit length track of charged particle

Cherenkov cone in water ~41° (in air: less than 1°)

Uniform sky view with an array of PMTs

Direction reconstruction through PMTs signal times



Wide Angle Telescopes

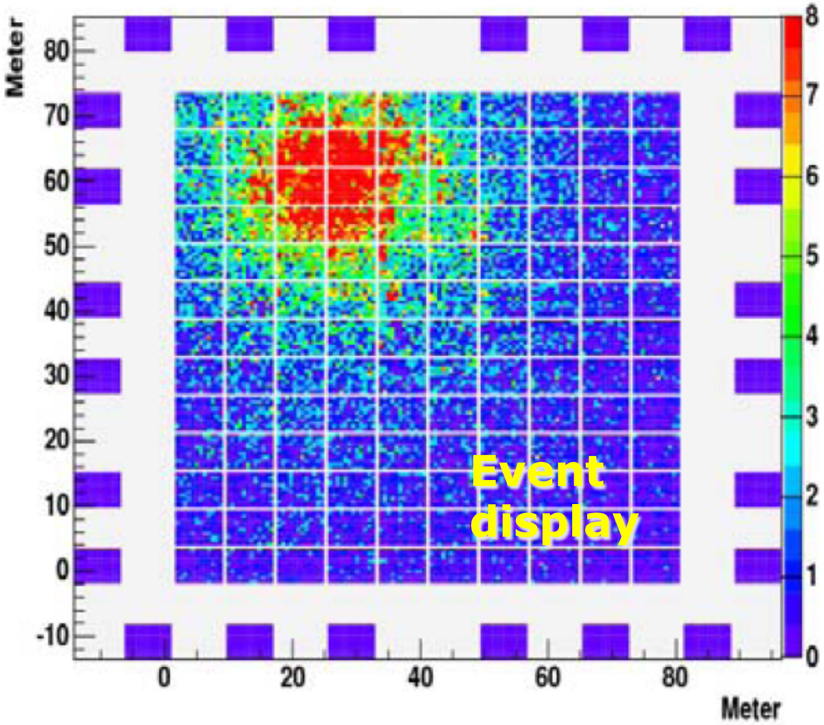
Tibet AS-γ– Air Shower Array
ARGO – Carpet array with RPC
MILAGRO – Water Cherenkov

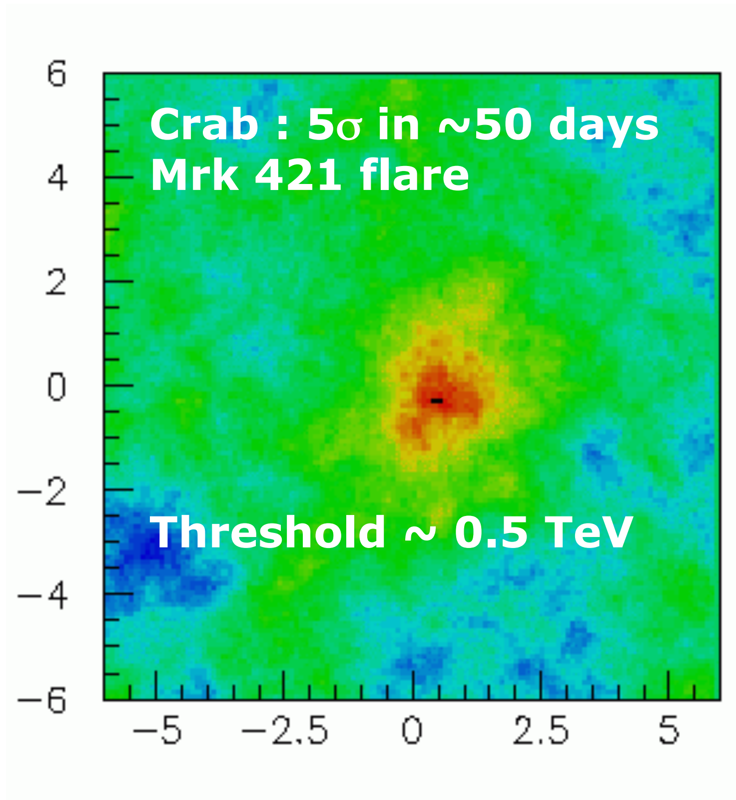
Advantage: Wide Angle 0.5π~1π
Non-bias observation

Cons: Moderate sensitivity
~5σ/yr$^{1/2}$ for Crab

ARGO-YBJ (RPC):

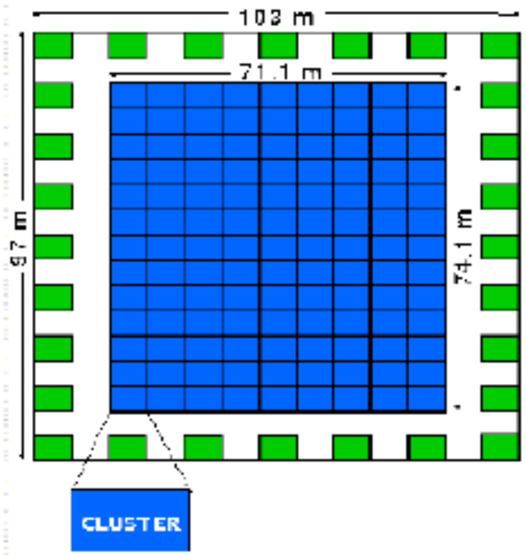

ARGO 实验厅


Meter
Meter
Event display


Crab : 5σ in ~50 days
Mrk 421 flare
Threshold ~ 0.5 TeV

ARGO

Area 5.200 m² (full coverage)
(10.000 m² with guard ring)
Field of view ~ 1 sr
E = 50 GeV - 50 TeV
Location: Tibet 4300m alt.



17400 Pads 56 by 60 cm² each of Resistive Plate Chamber (RPC).
Each pad subdivided in pick-up strips 6 cm wide for the space pattern inside the pad.
The CLUSTER is made of 12 RPCs Pads

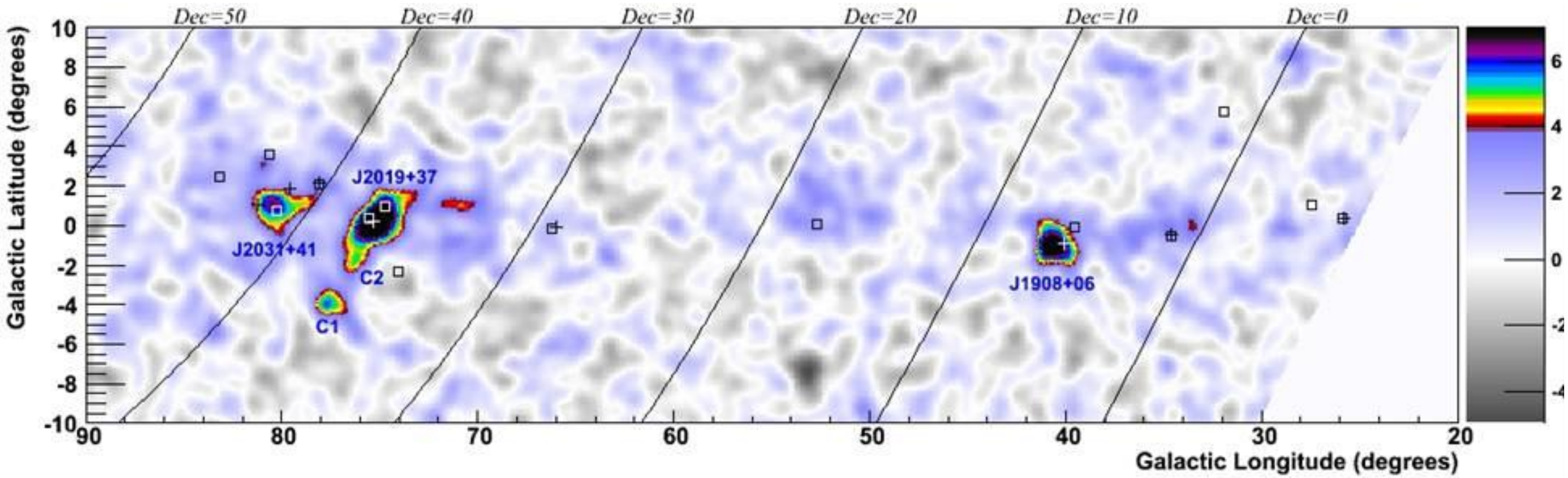
TIBET air shower array

Our air shower array consists of 697 scintillation counters which are placed at a lattice with 7.5 m spacing and 36 scintillation counters which are placed at a lattice with 15 m spacing. Each counter has a plate of plastic scintillator, 0.5 m^2 in area and 3 cm in thickness, equipped with a 2-inch-in-diameter photomultiplier tube (PMT). The time and charge information of each PMT hit by an air shower event is recorded to determine its direction and energy. The detection threshold energy is approximately 3 TeV, which is the lowest one achieved by an air shower array in the world.

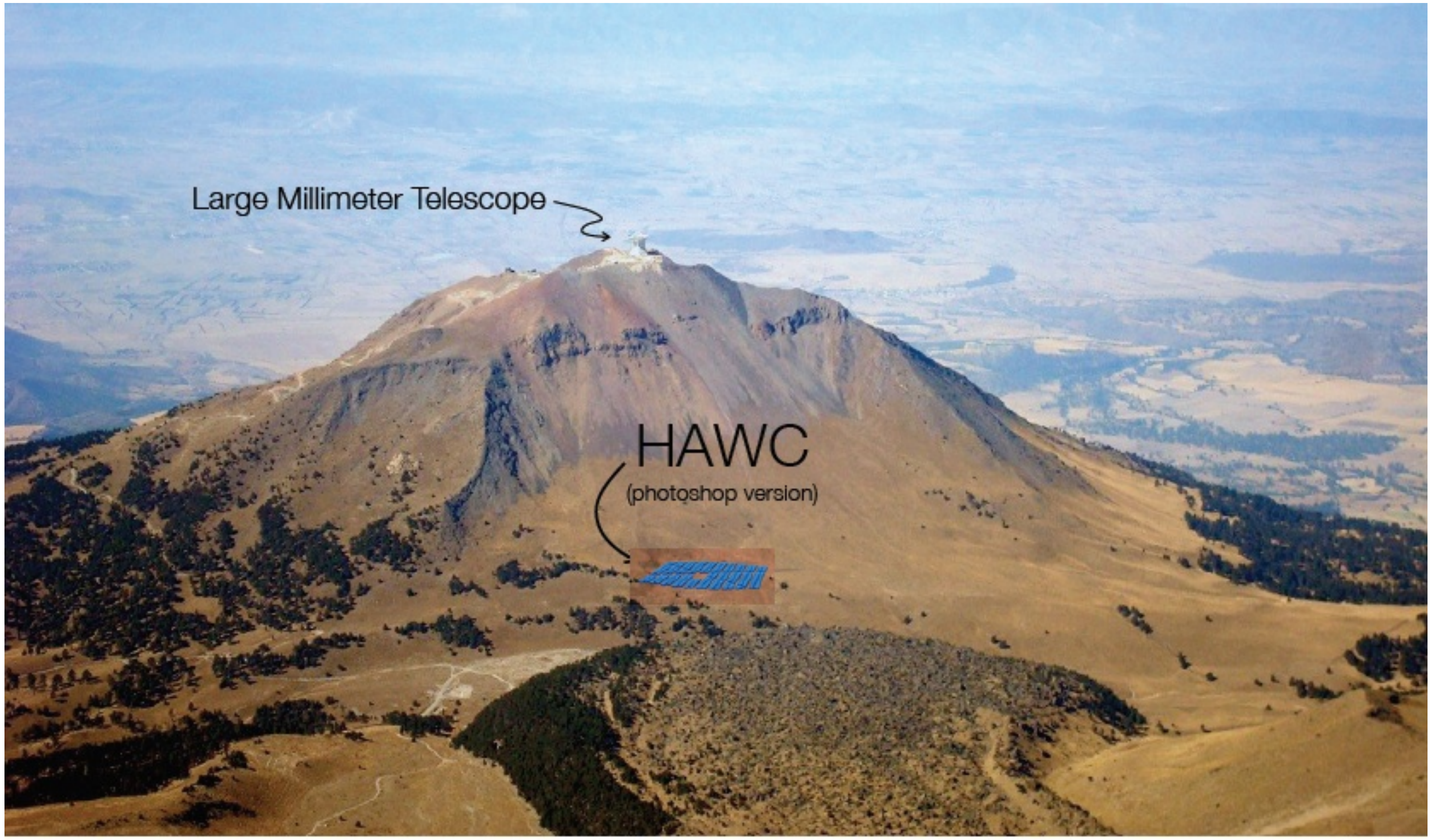
MILAGRO

Cherenkov in water, Arizona

Crab:
~5σ in 100 days
Median energy ~20 TeV



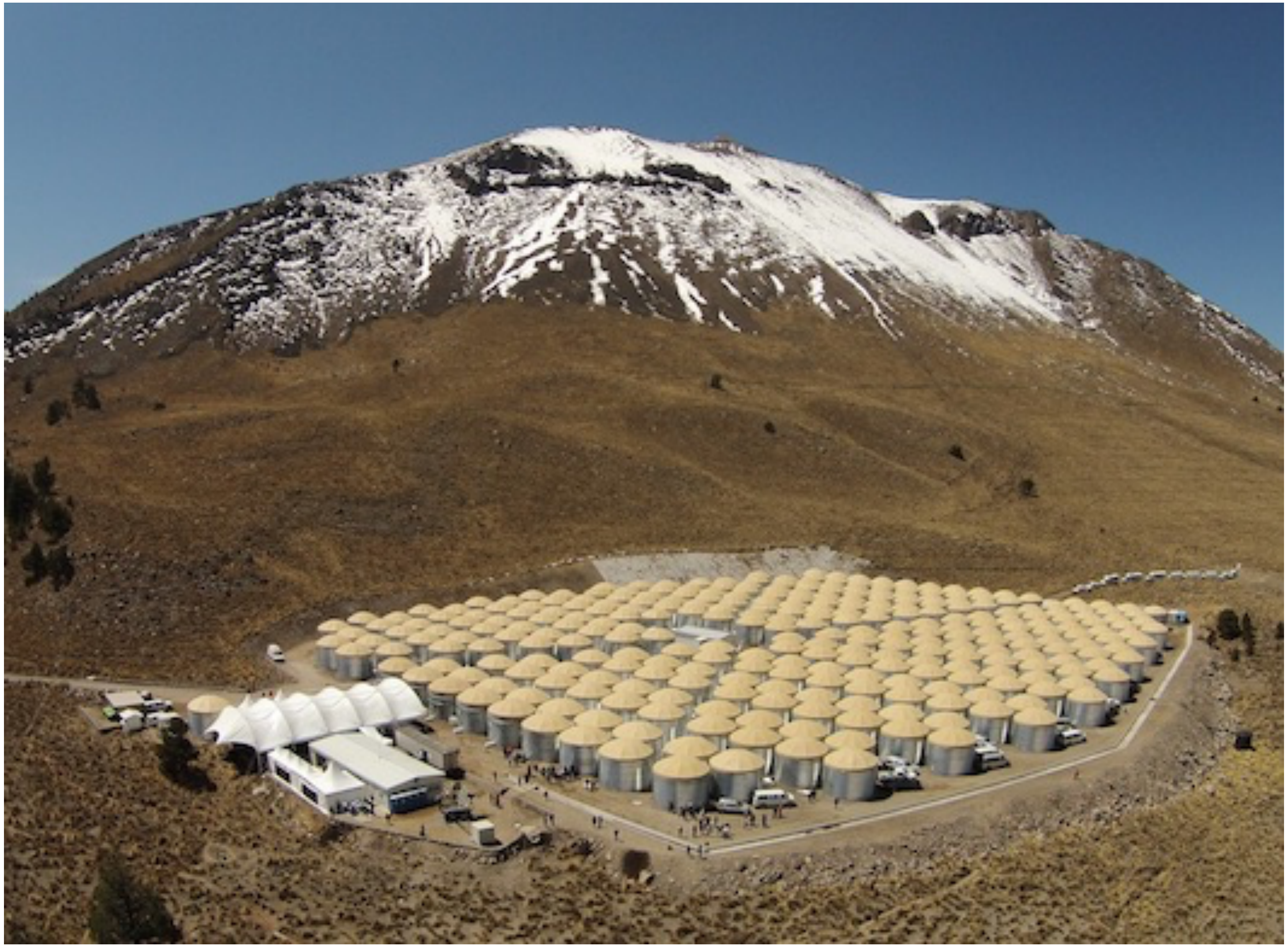
HAWC



HAWC

Pico de Orizaba, altitude 4100 m, latitude 18º 59’ N
Two hours drive from Puebla, four from México City
Site of Large Millimeter Telescope (existing infrastructure)

HAWC

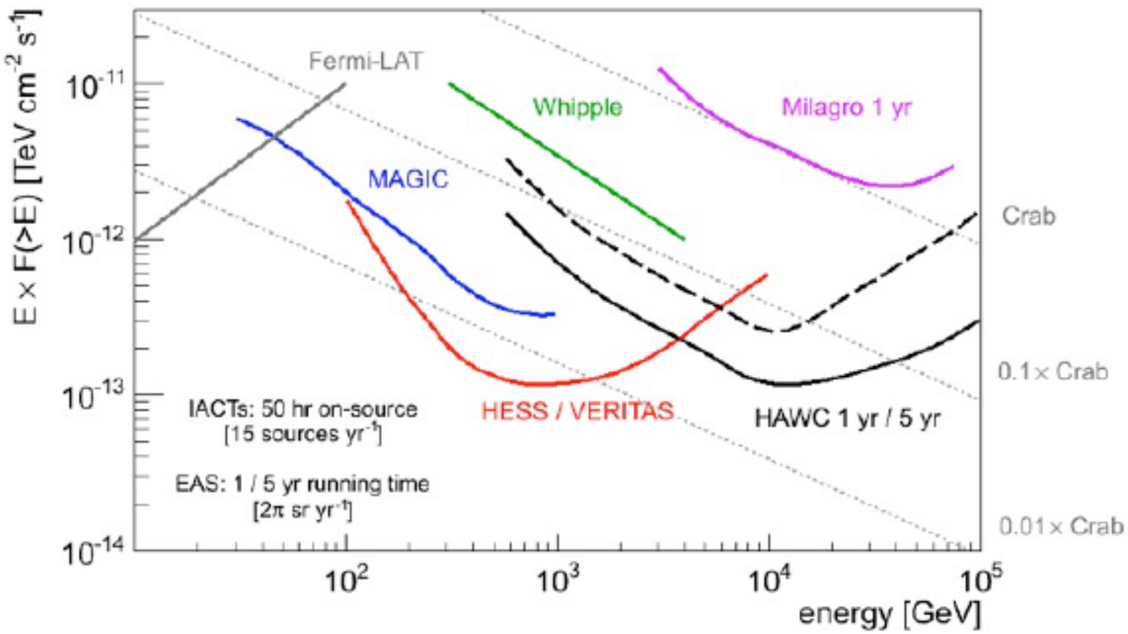


HAWC

Sensitivity to Point Sources

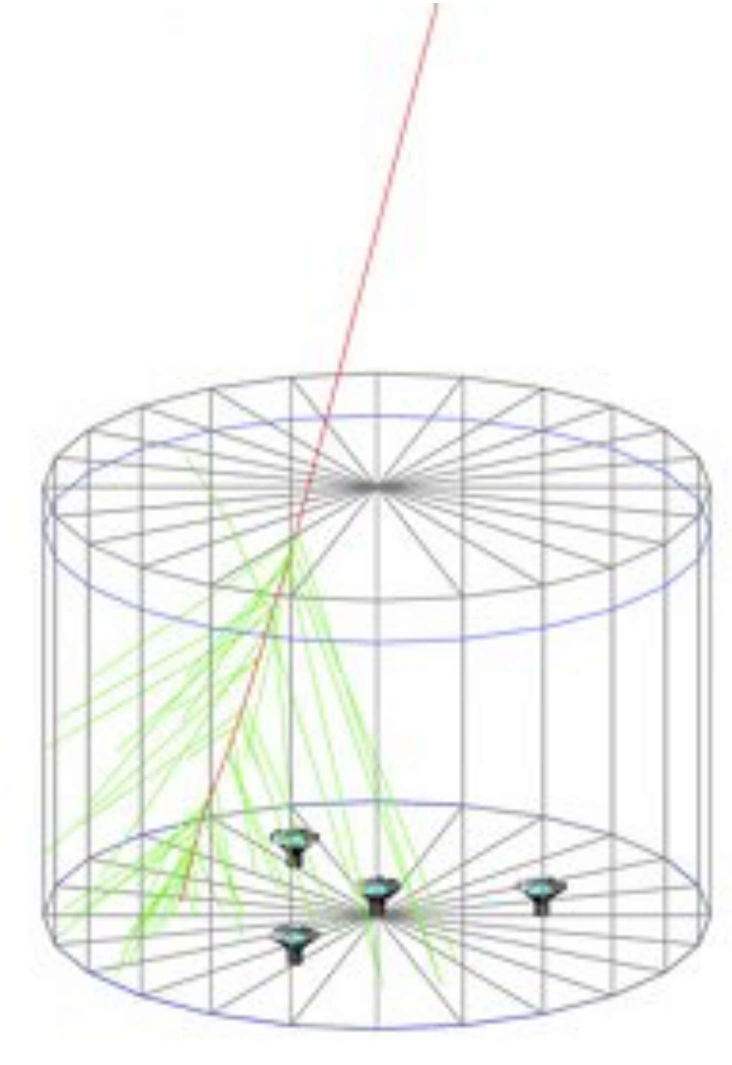
- Long integration times lead to excellent sensitivity at highest energies (> few TeV)

- 5σ sensitivity to:
  10 Crab in 3 min
  1 Crab in 5 hr
  0.1 Crab in ⅓ year

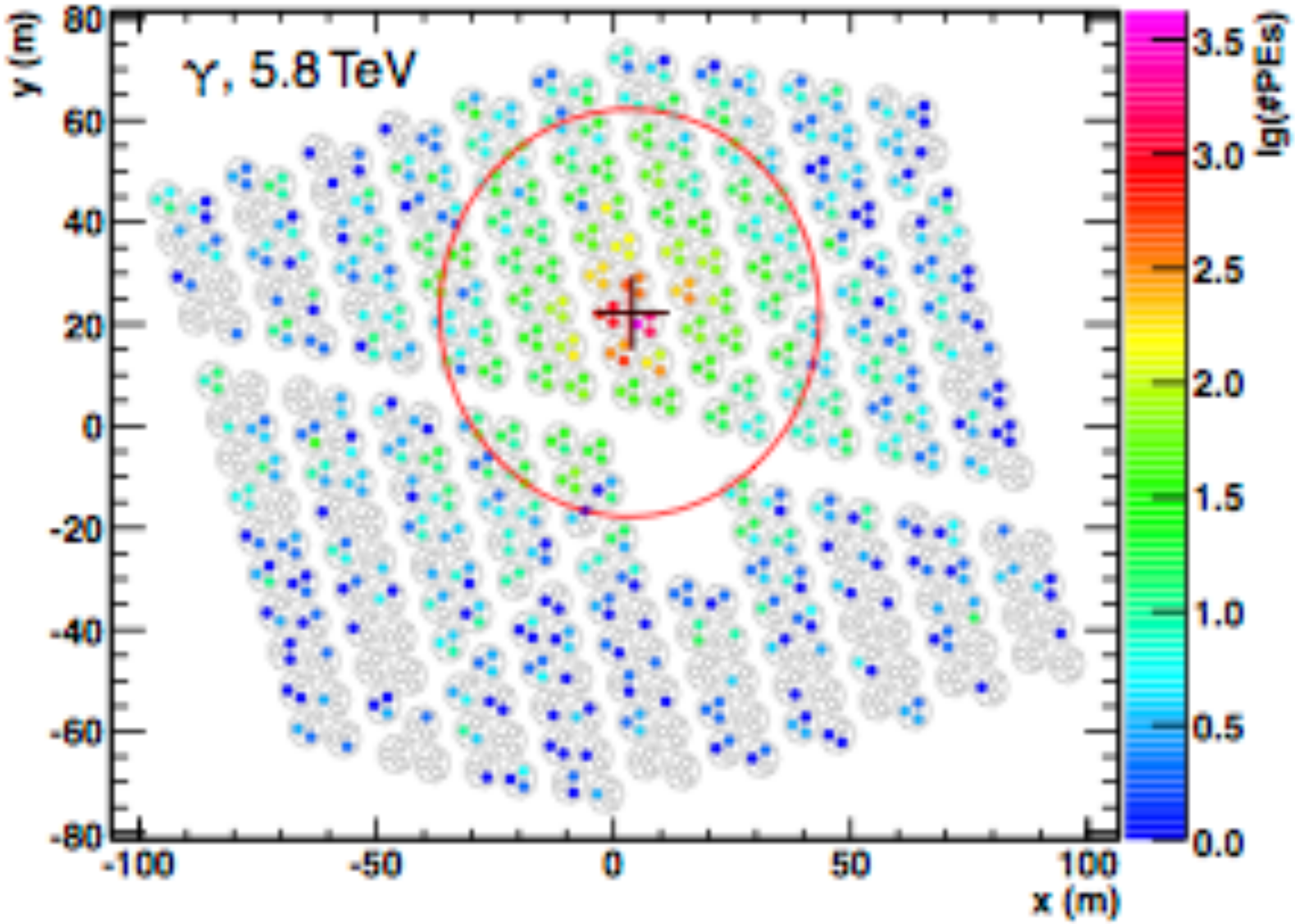


- Around 15x the sensitivity of Milagro

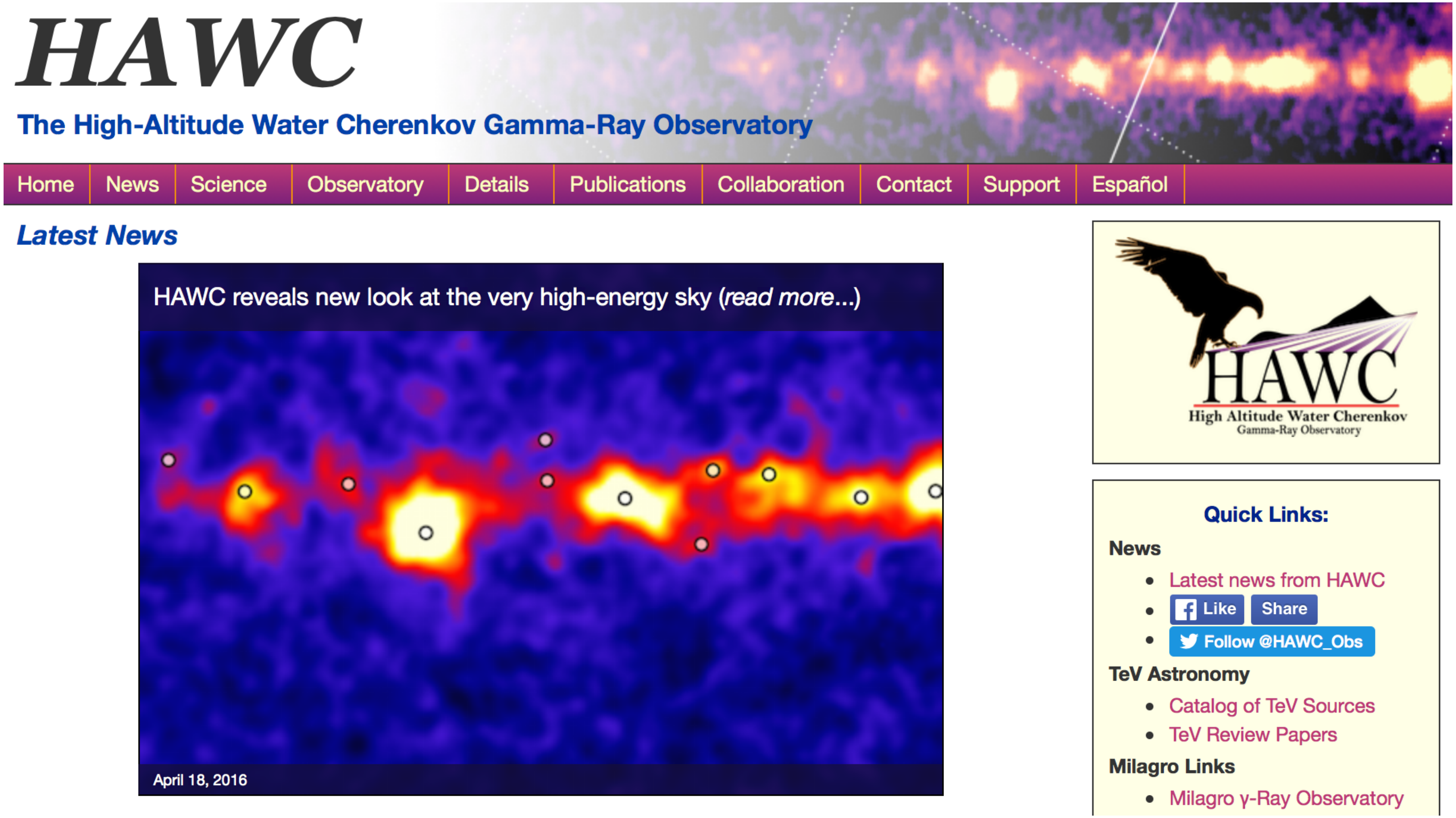
HAWC



HAWC

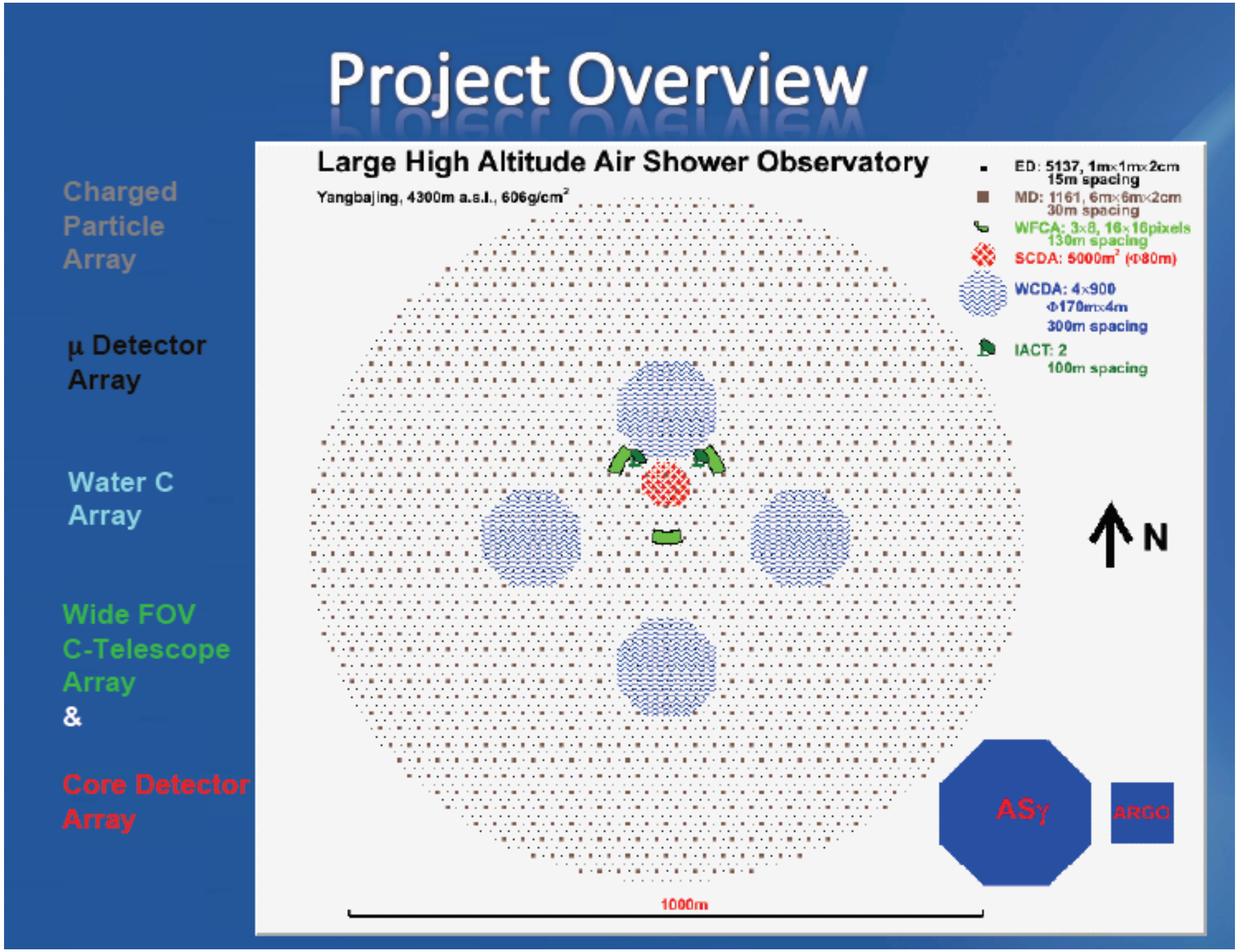

γ, 5.8 TeV
y (m)
x (m)
lg(#PEs)
80
60
40
20
0
-20
-40
-60
-80
-100
-50
0
50
100
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0

HAWC



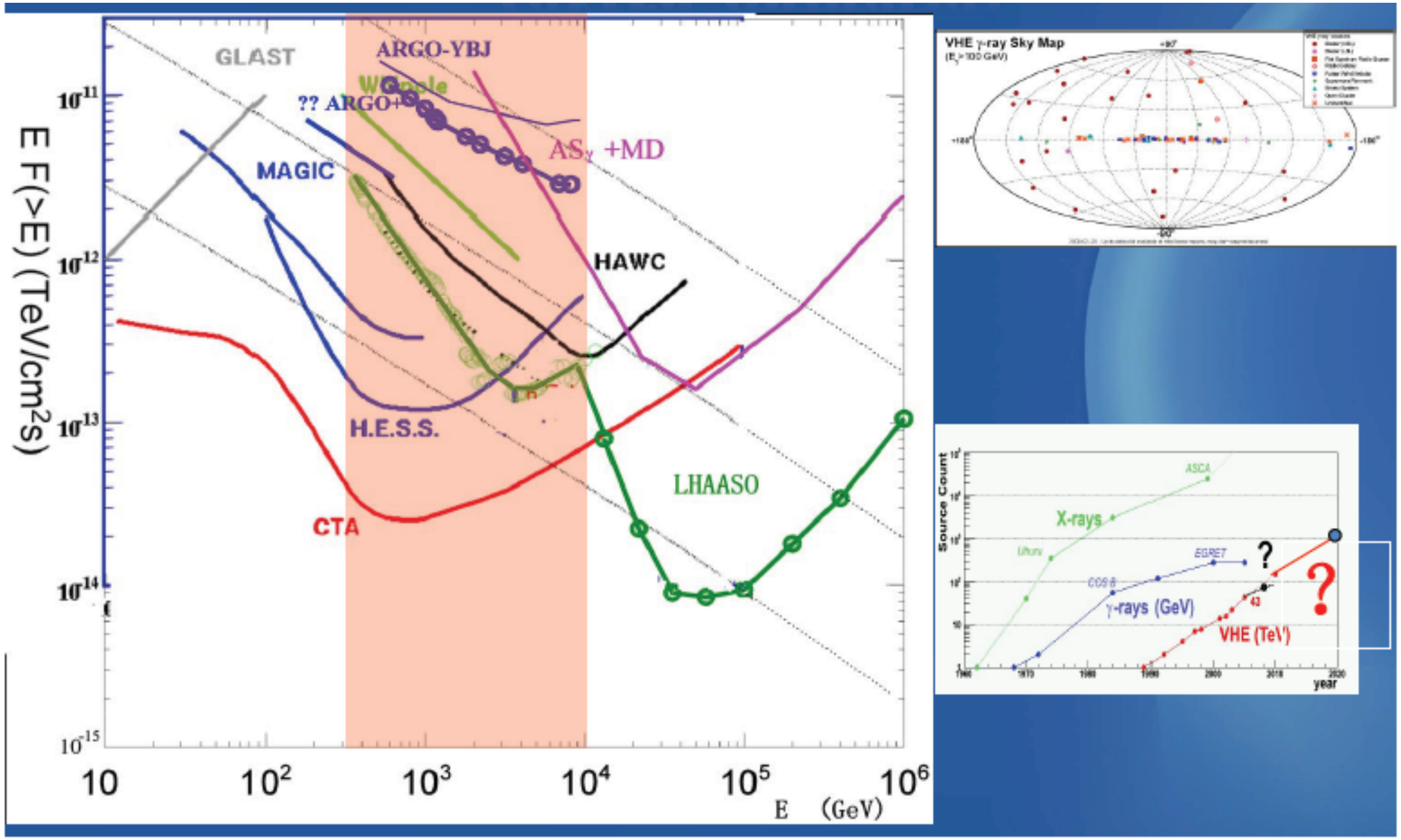
http://www.hawc-observatory.org

LHAASO



Project Overview
Charged Particle Array
μ Detector Array
Water C Array
Wide FOV C-Telescope Array
&
Core Detector Array
Large High Altitude Air Shower Observatory
Yangbajing, 4300m a.s.l., 606g/cm²
ED: 5137, 1m×1m×2cm
15m spacing
MD: 1161, 6m×6m×2cm
30m spacing
WFCA: 3×8, 16×16pixels
130m spacing
SCDA: 5000m² (Φ80m)
WCDA: 4×900
Φ170m×4m
300m spacing
IACT: 2
100m spacing
N
ASγ
ARGO
1000m

LHAASO


GLAST
ARGO-YBJ
?? ARGO+
Whipple
MAGIC
ASγ +MD
HAWC
H.E.S.S.
CTA
LHAASO
E F(>E) (TeV/cm²s)
E (GeV)
VHE γ-ray Sky Map
Source Count
ASCA
X-rays
Uhuru
EGRET
COS B
γ-rays (GeV)
VHE (TeV)
year

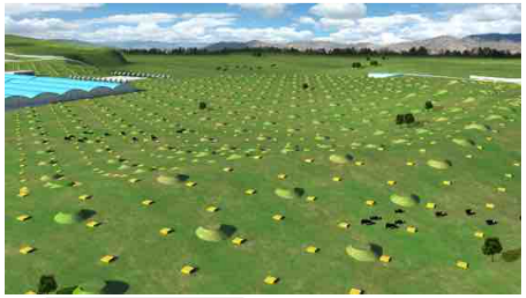
The LHAASO experiment

The Large High Altitude Air Shower Observatory (LHAASO) project is a new generation all-sky instrument to investigate the '*cosmic ray connection*' through a combined study of cosmic rays and gamma-rays in the wide energy range 10^{11} -- 10^{17} eV.

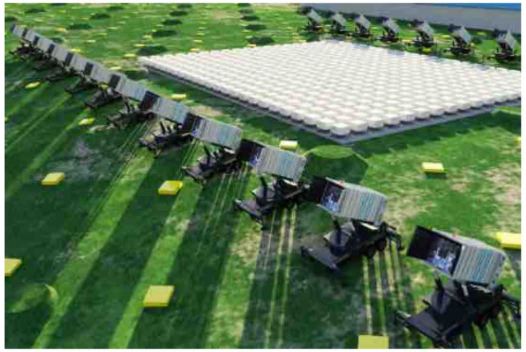
The first phase of LHAASO will consist of the following major components:

- 1 km^2 array (LHAASO-KM2A), including 5635 scintillator detectors, with 15 m spacing, for electromagnetic particle detection.
- An overlapping 1 km^2 array of 1221, 36 m^2 underground water Cherenkov tanks, with 30 m spacing, for muon detection (total sensitive area 40,000 m^2).
- A close-packed, surface water Cherenkov detector facility with a total area of 90,000 m^2 (LHAASO-WCDA), four times that of HAWC.
- 24 wide field-of-view air Cherenkov (and fluorescence) telescopes (LHAASO-WFCTA).
- 452 close-packed burst detectors, located near the centre of the array, for detection of high energy secondary particles in the shower core region (LHAASO-SCDA).

LHAASO main components



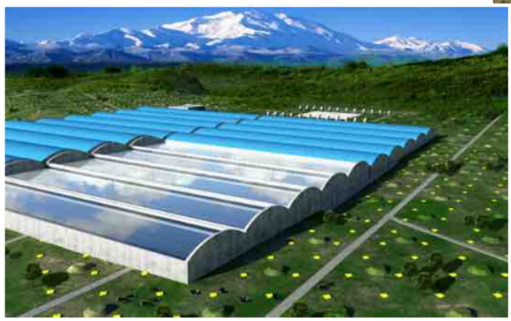
1 KM2A:
5635 EDs
1221 MDs



WFCTA:
24 telescopes
1024 pixels each

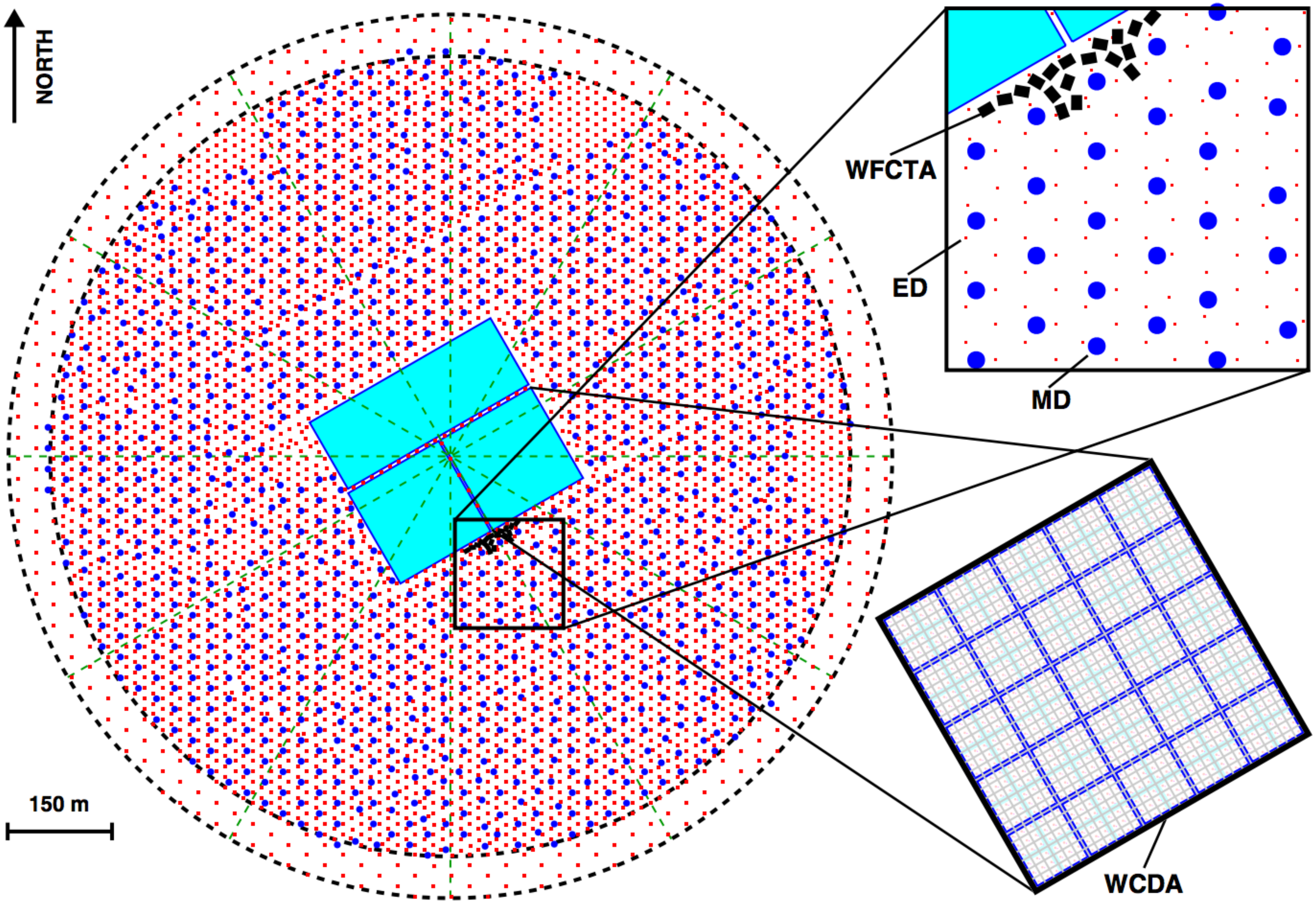
Coverage area: 1.3 km^2

WCDA:
3600 cells
90,000 m^2



SCDA:
452 detectors

LHAASO

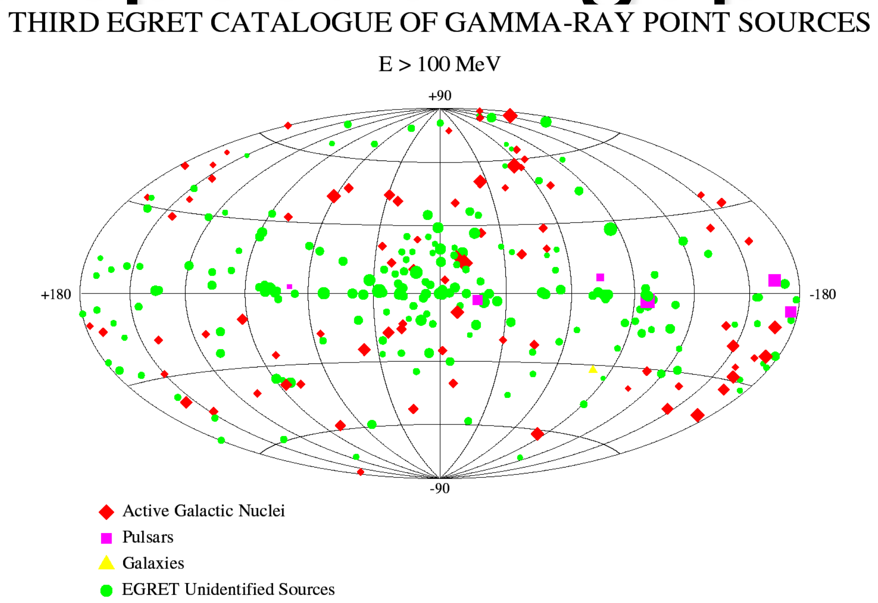


Astrofisica Nucleare e Subnucleare

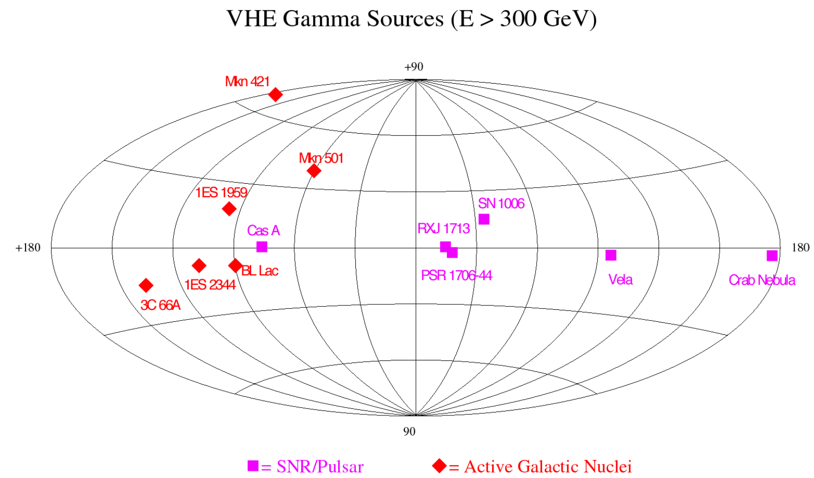
VHE Gamma Astrophysics

The unexplored spectrum gap

- Satellites give a nice crowded picture of energies up to 10 GeV.



- **Ground based experiments show very few sources with energies > ~300 GeV.**



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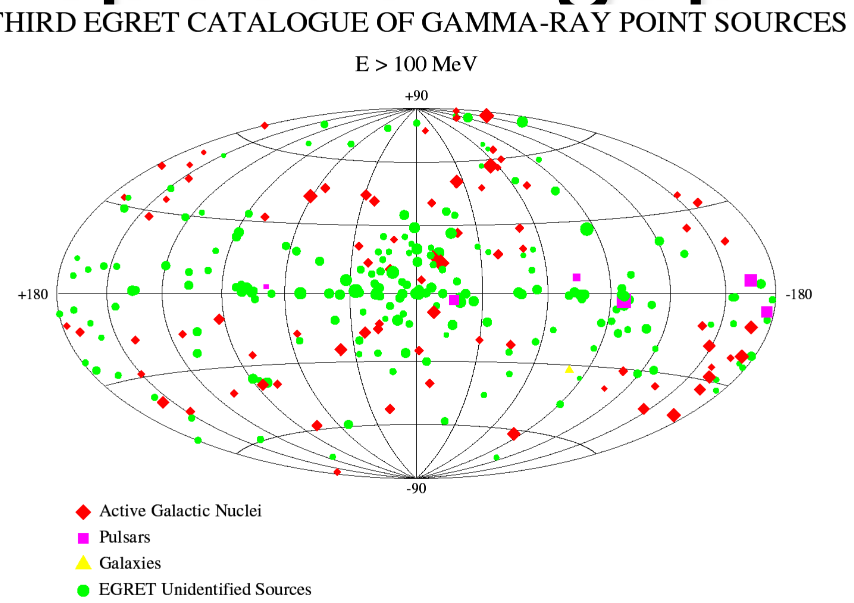

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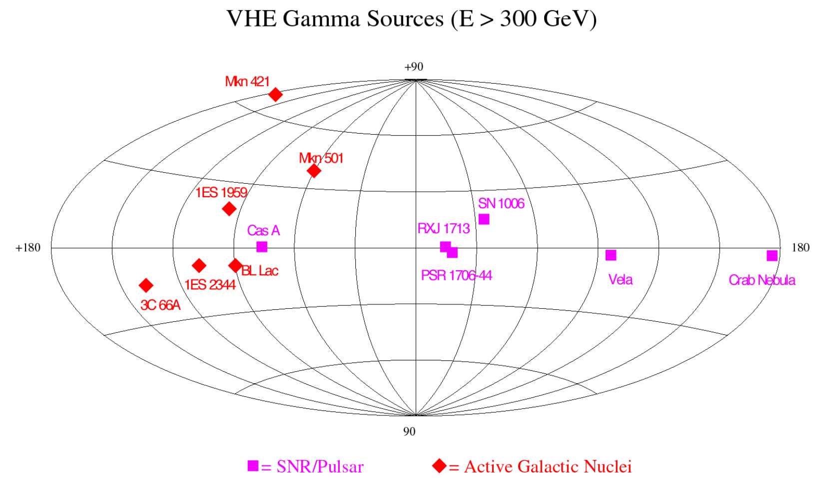
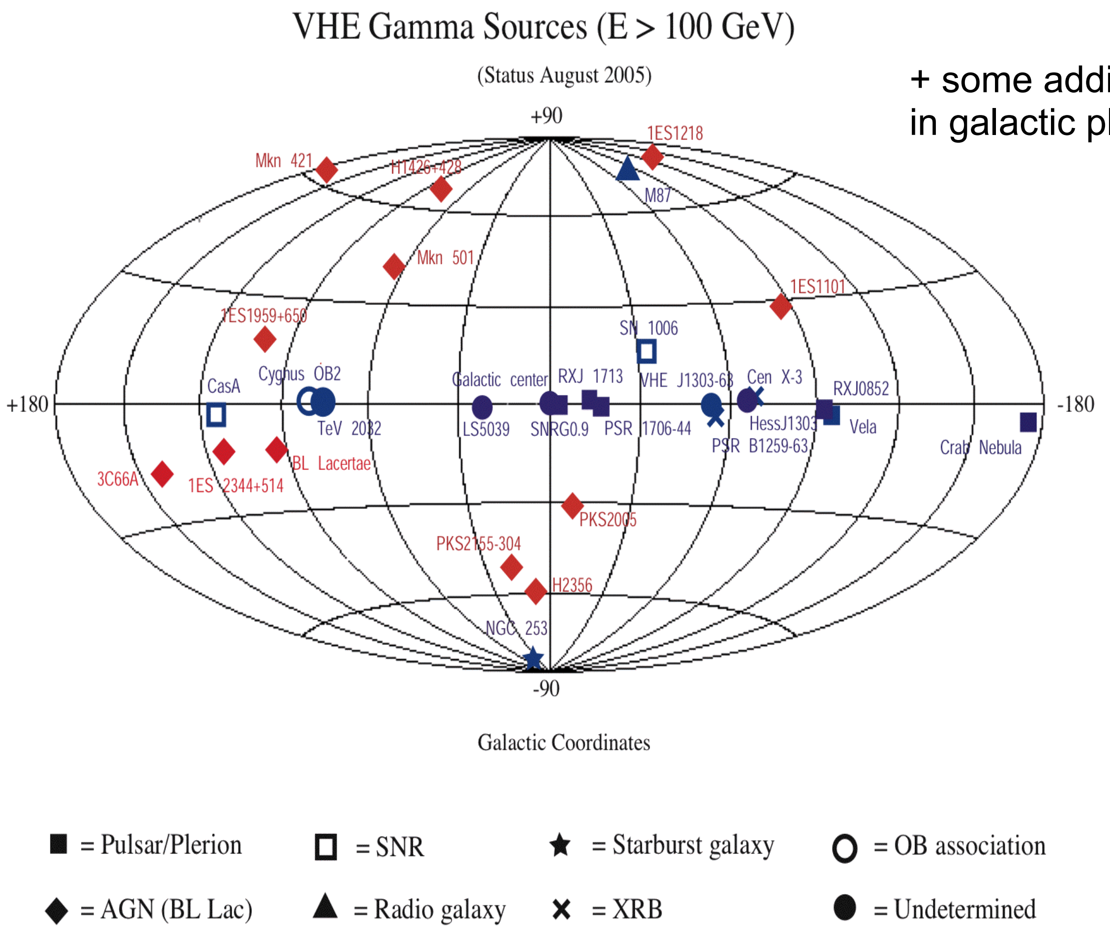


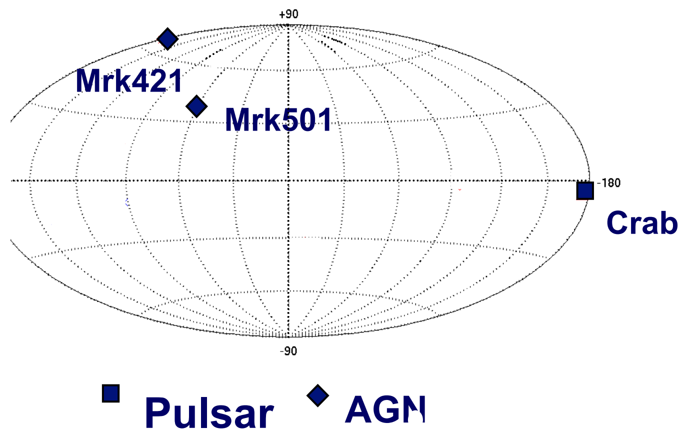
The VHE γ ray sky

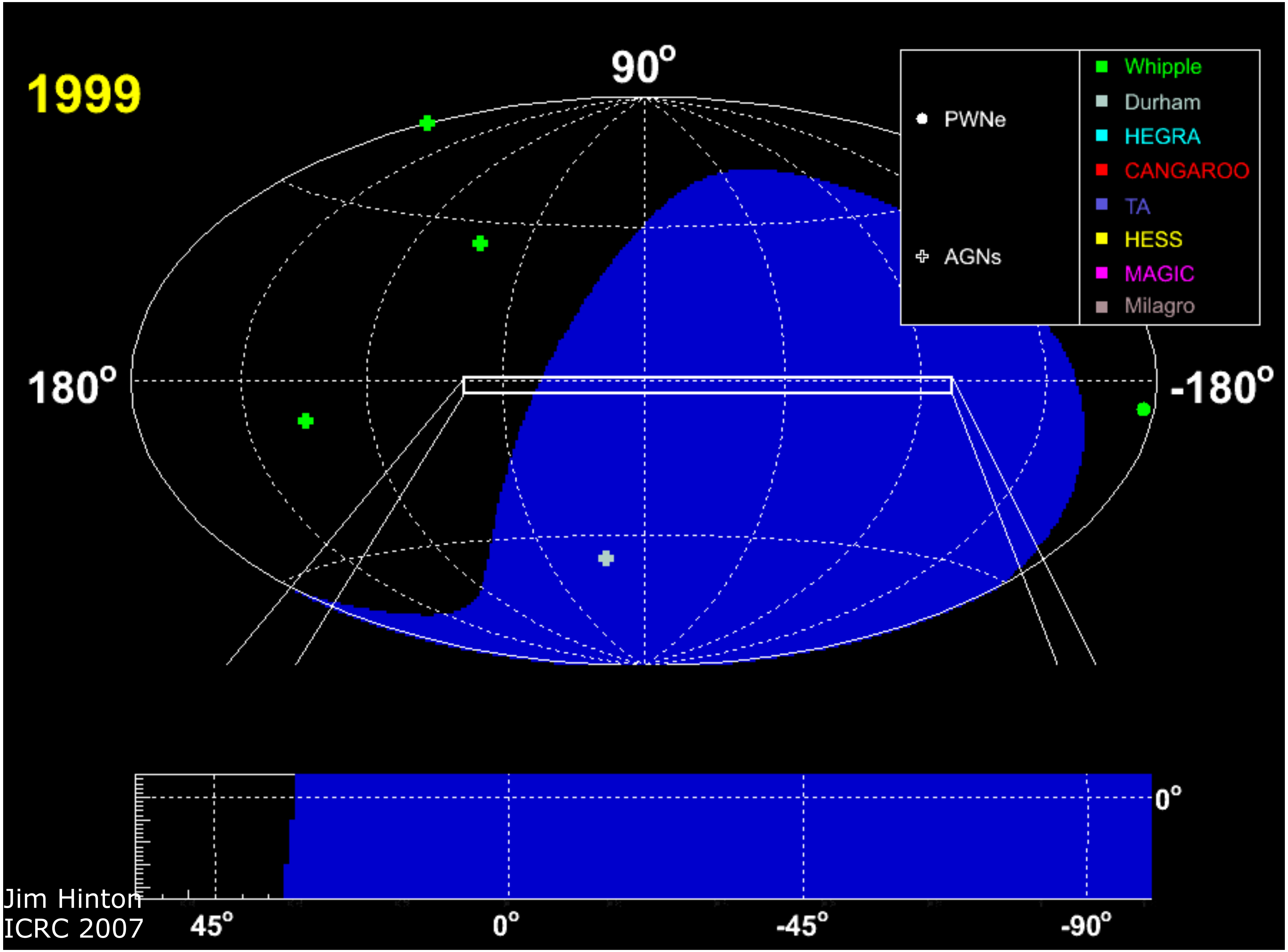
2005



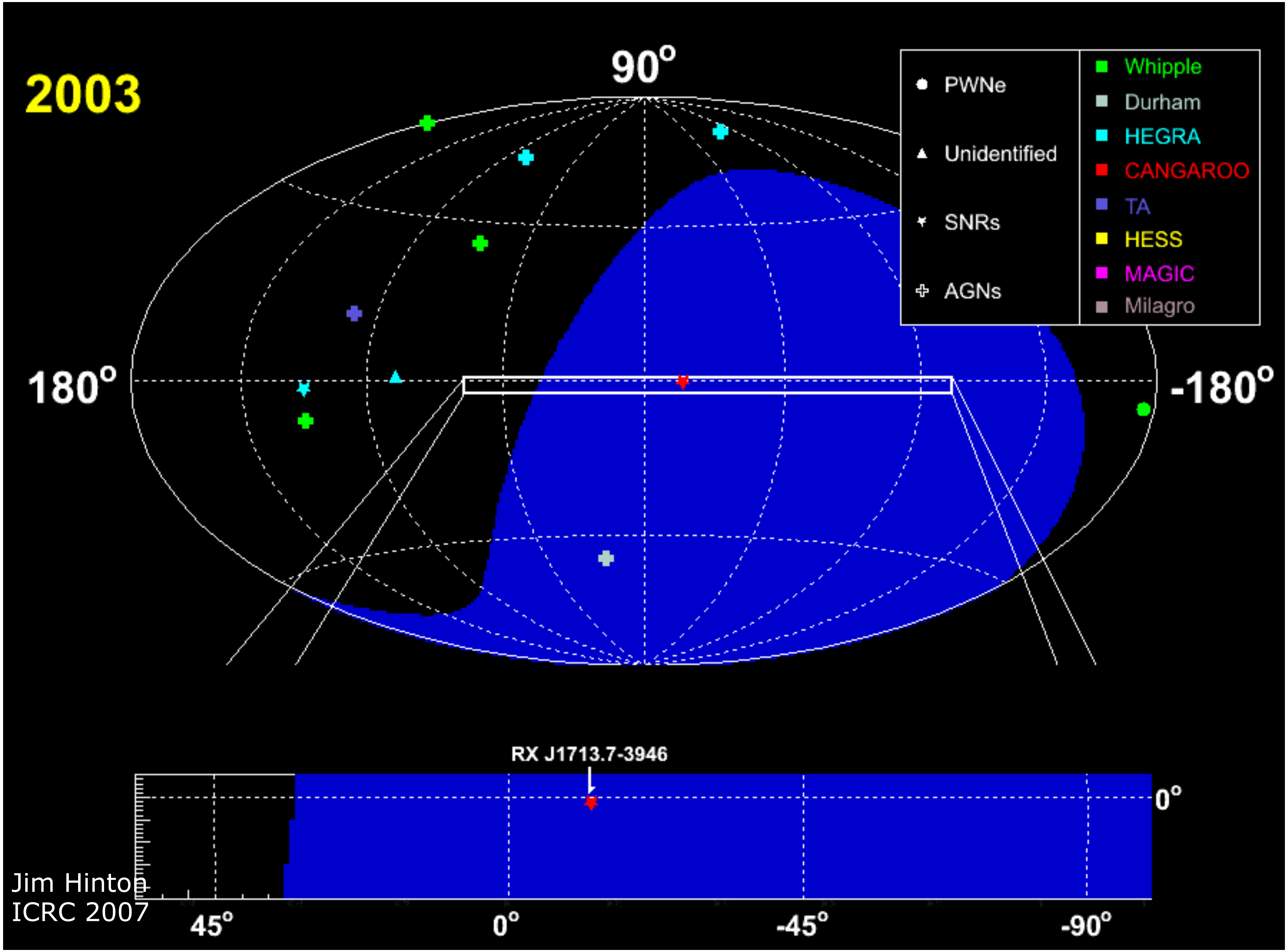
+ some additional sources in galactic plane.

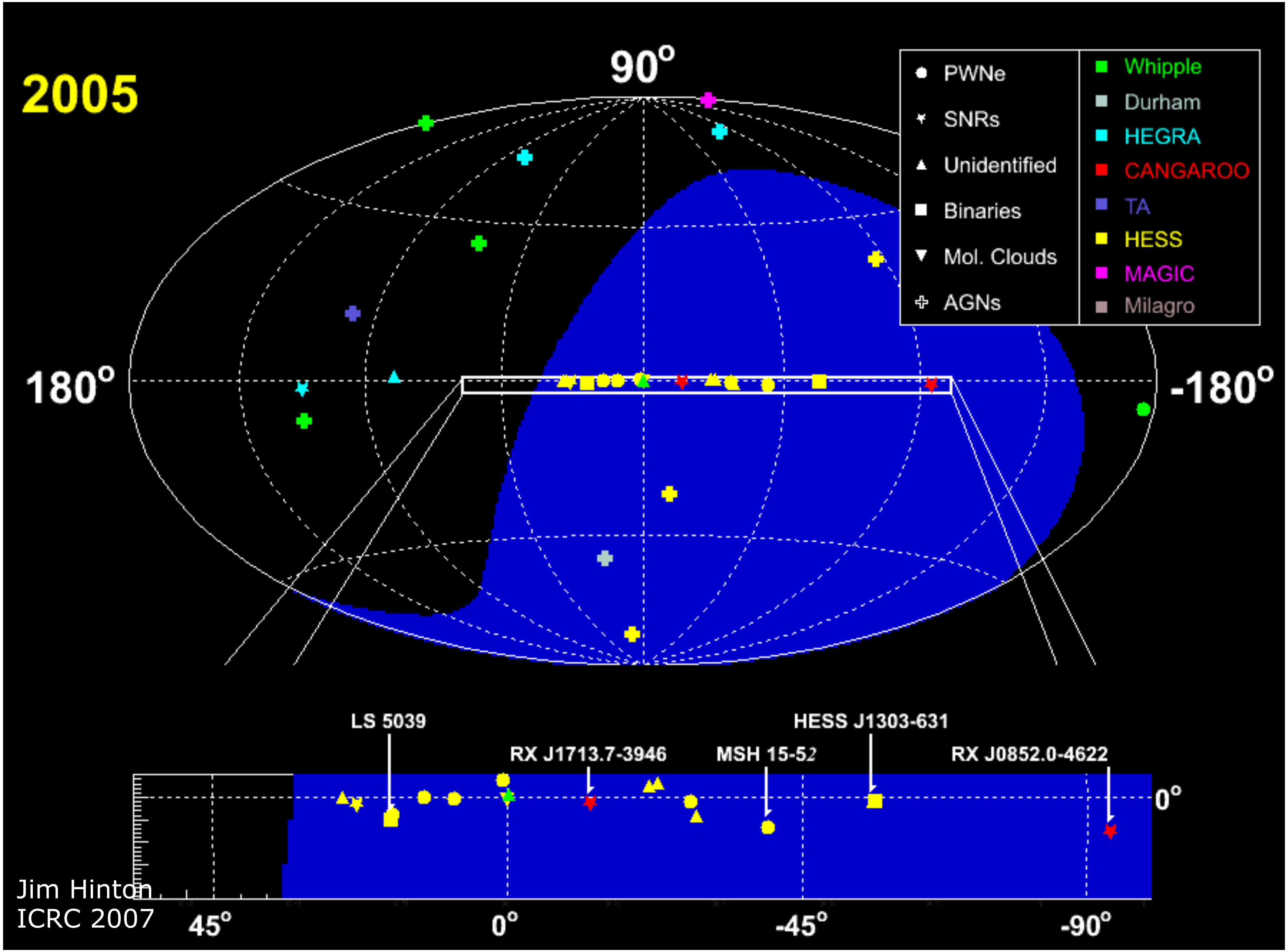
1995





Jim Hinton
ICRC 2007


2003
90°
180°
-180°
PWNe
Unidentified
SNRs
AGNs
Whipple
Durham
HEGRA
CANGAROO
TA
HESS
MAGIC
Milagro
RX J1713.7-3946
0°
45°
0°
-45°
-90°
Jim Hinton
ICRC 2007



2005
90°
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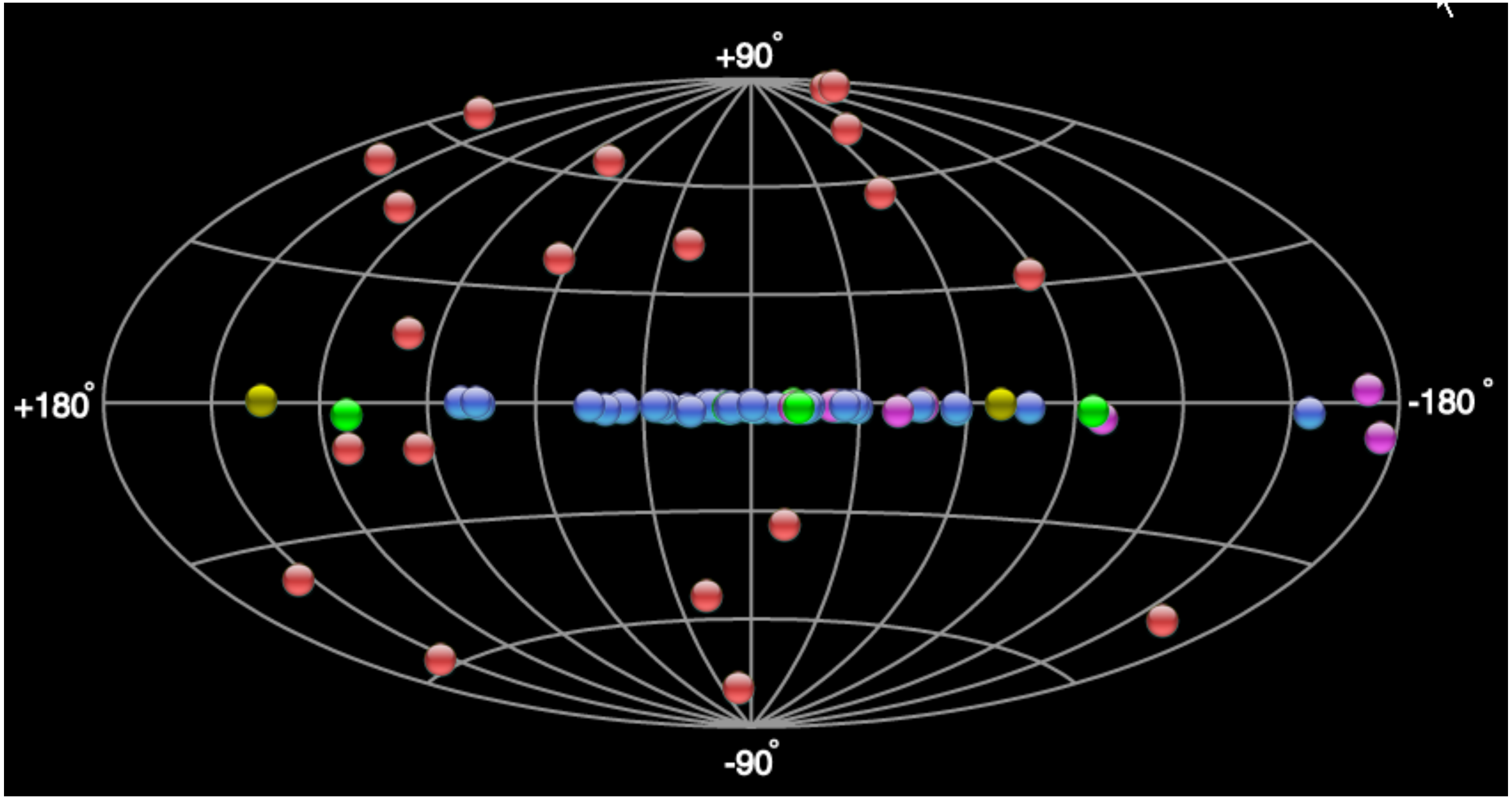
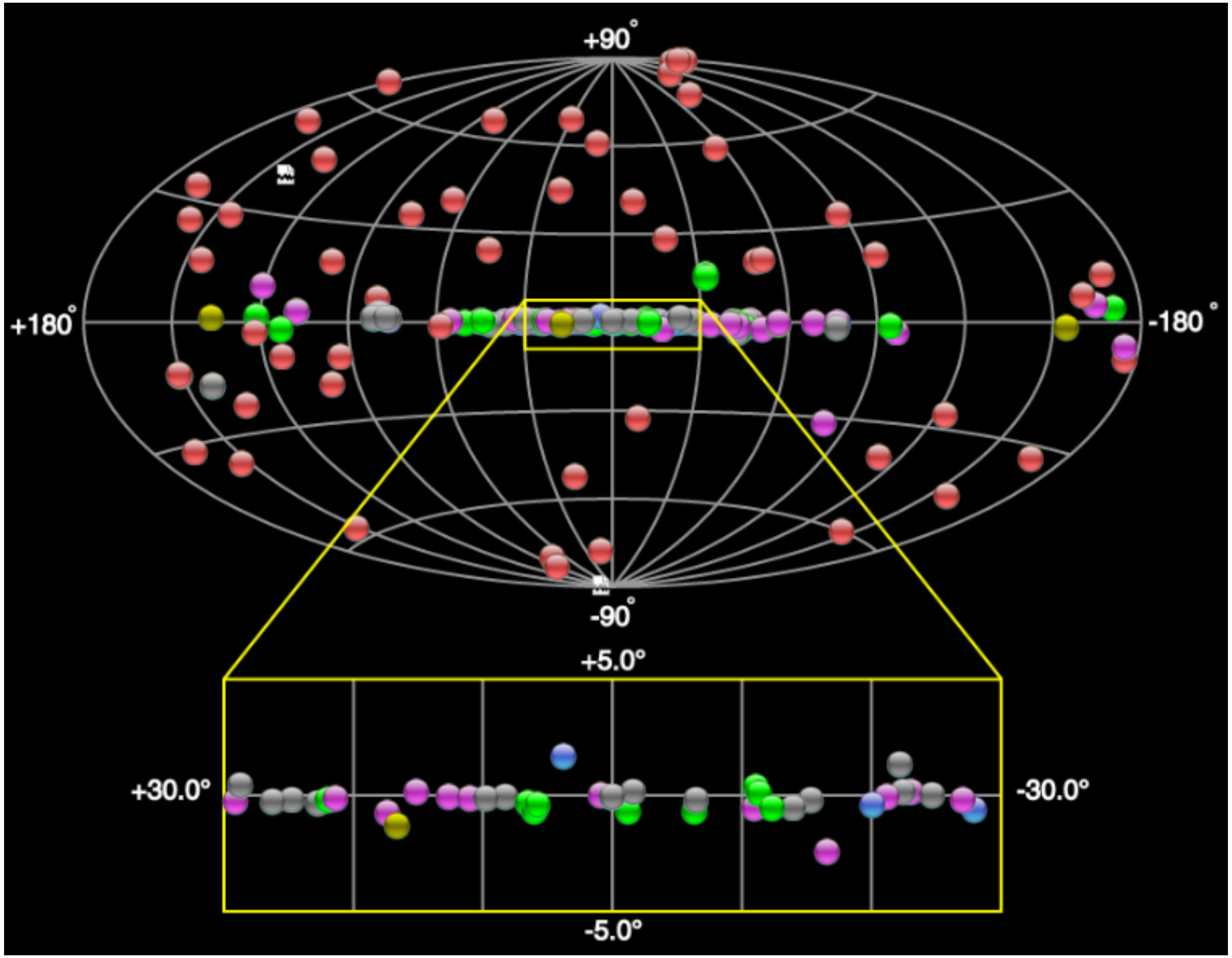
CANGAROO
TA
HESS
MAGIC
Milagro
LS 5039
RX J1713.7-3946
MSH 15-52
HESS J1303-631
RX J0852.0-4622
0°
45°
0°
-45°
-90°
Jim Hinton
ICRC 2007

TeV Source Catalog

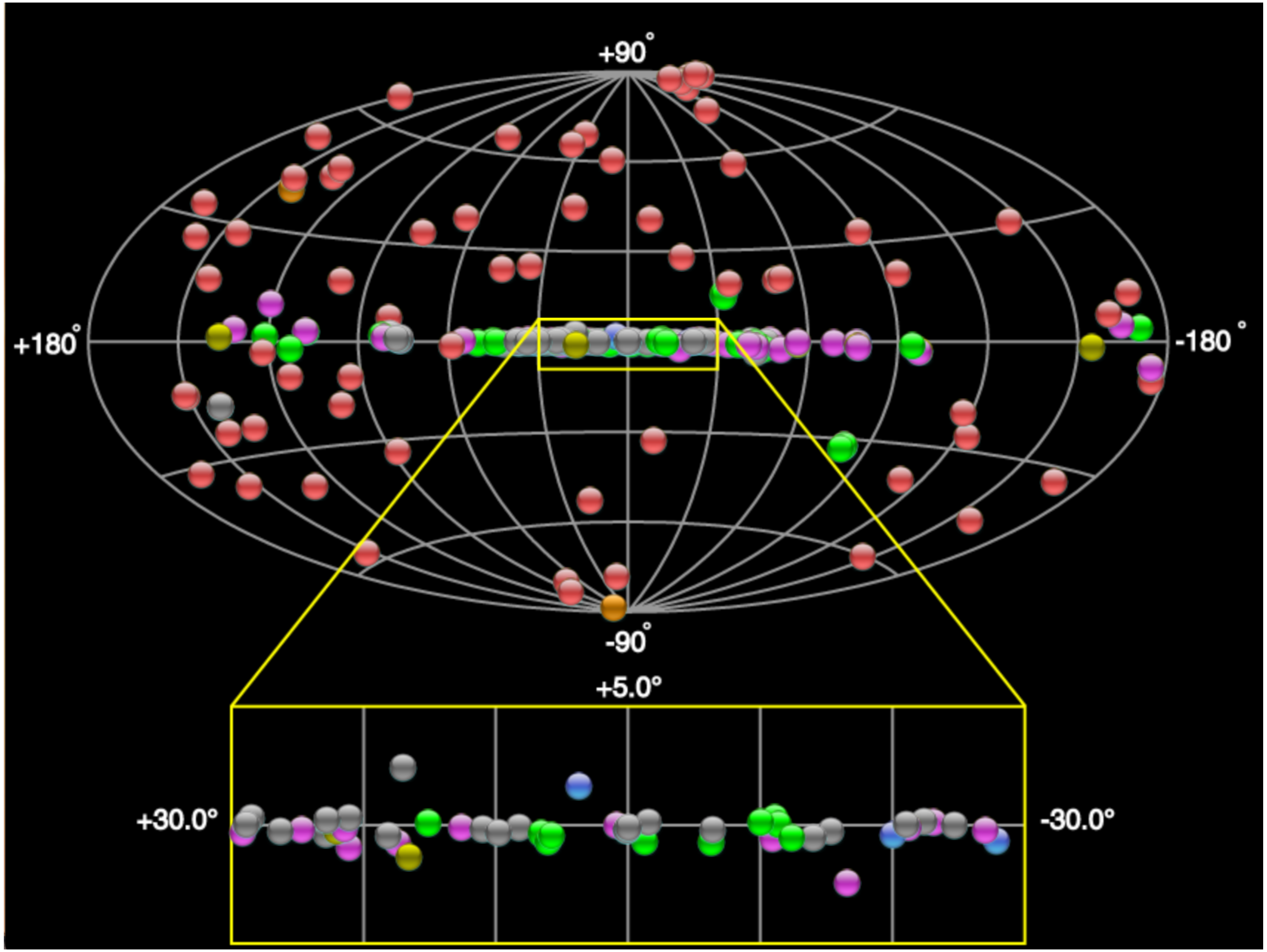


http://tevcat.uchicago.edu/

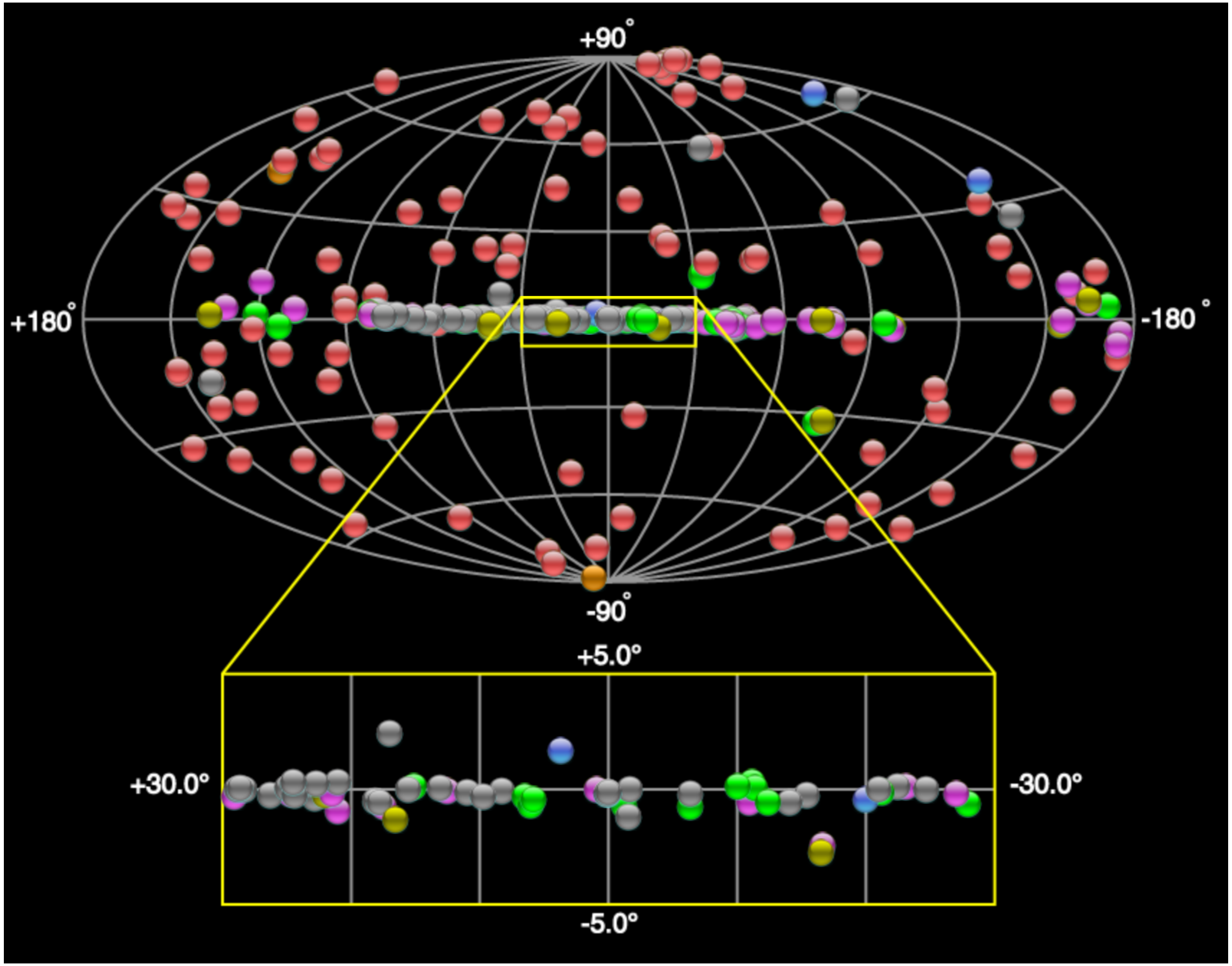
The TeV Catalog 2012



The TeV Catalog 2016

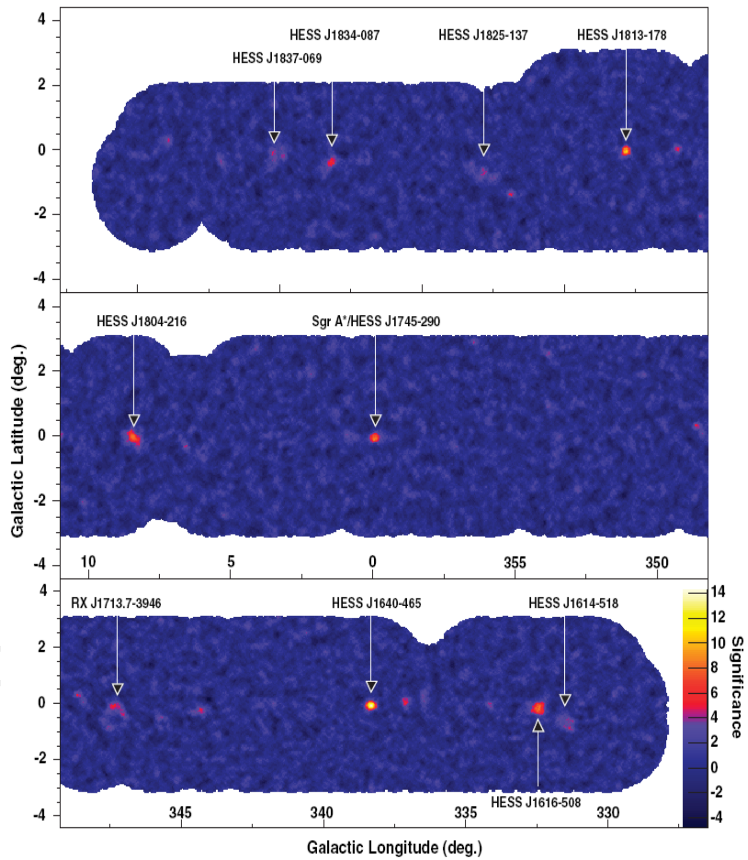


The TeV Catalog 2021

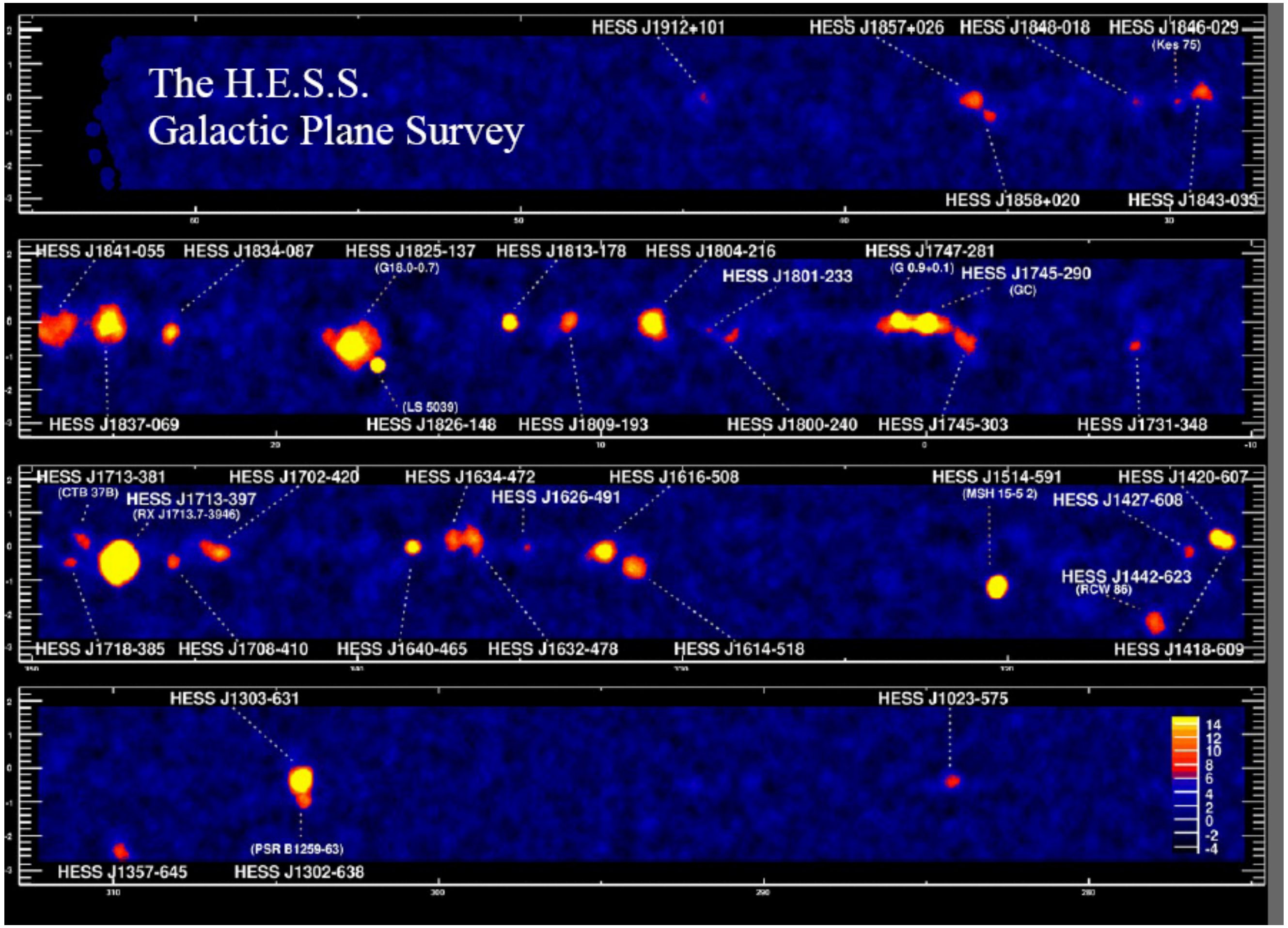


TeV Sky Survey

- HESS Galactic plane survey sees many new TeV sources (Aharonian et al. 2005)
  - This might possibly inform a detailed model of the distribution of CR sources, although the distribution is so confined to the plane that the sources (probably plerions and SNR) are at least several kpc distant

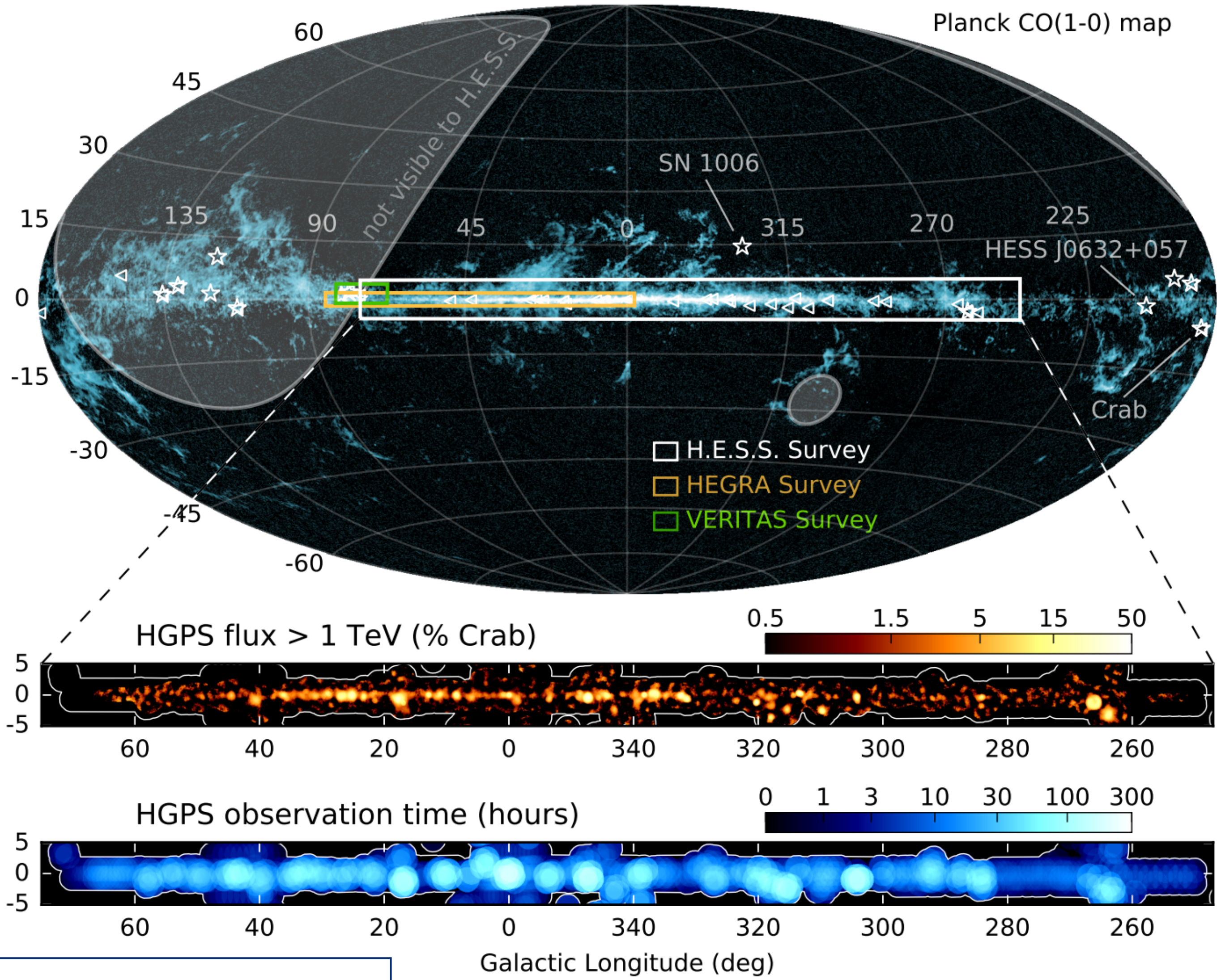


The Galactic Plane survey



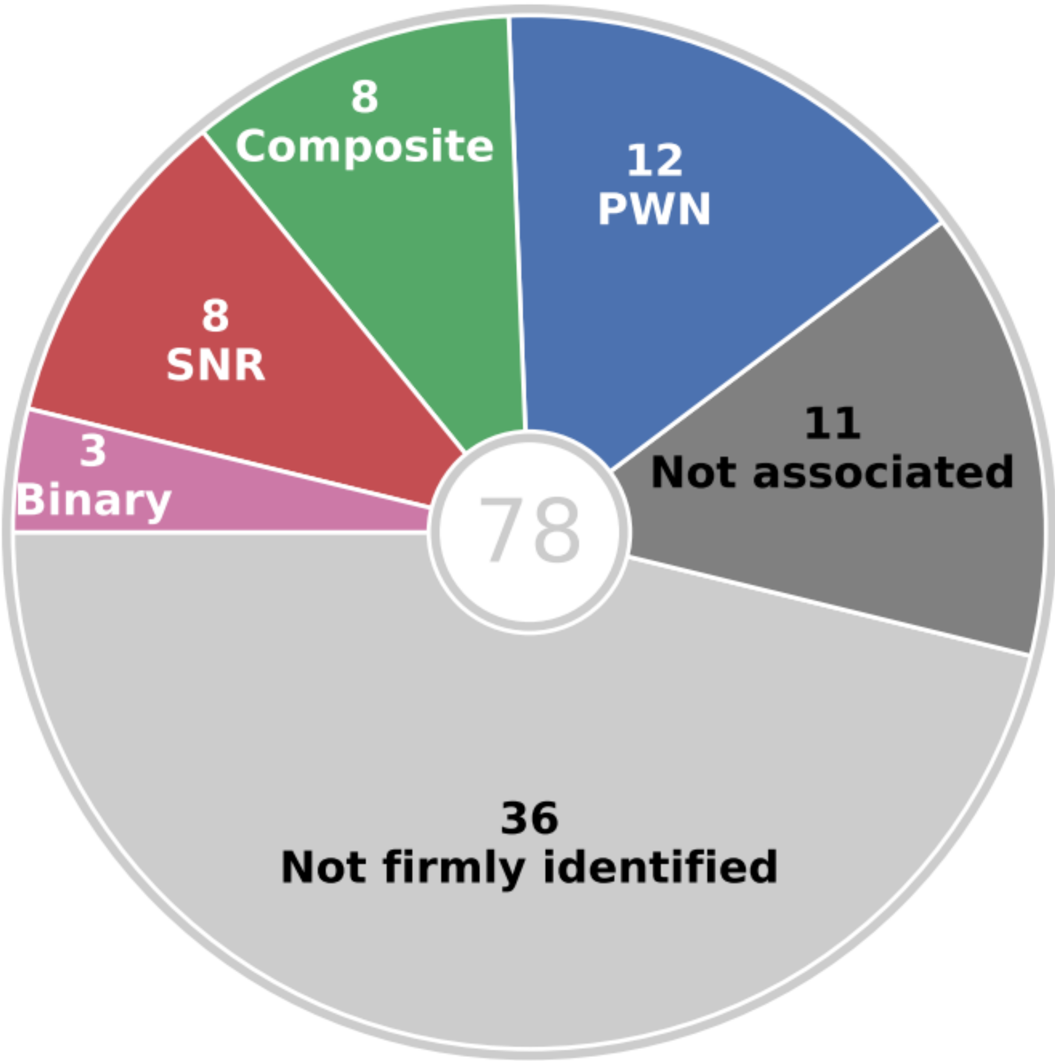
Aharonian et al. 2006

The Galactic Plane survey



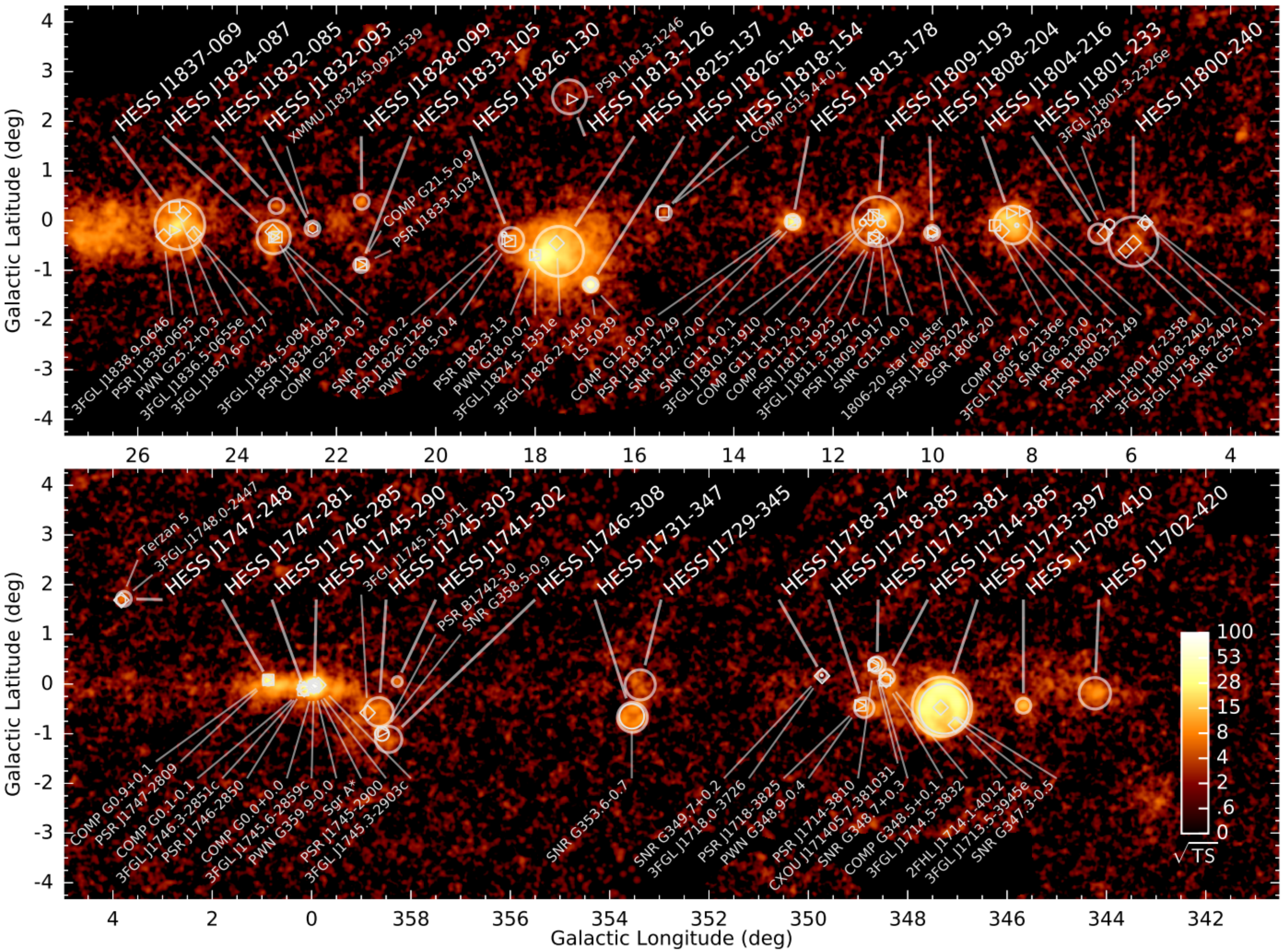
Aharonian et al. 2018

The Galactic Plane survey



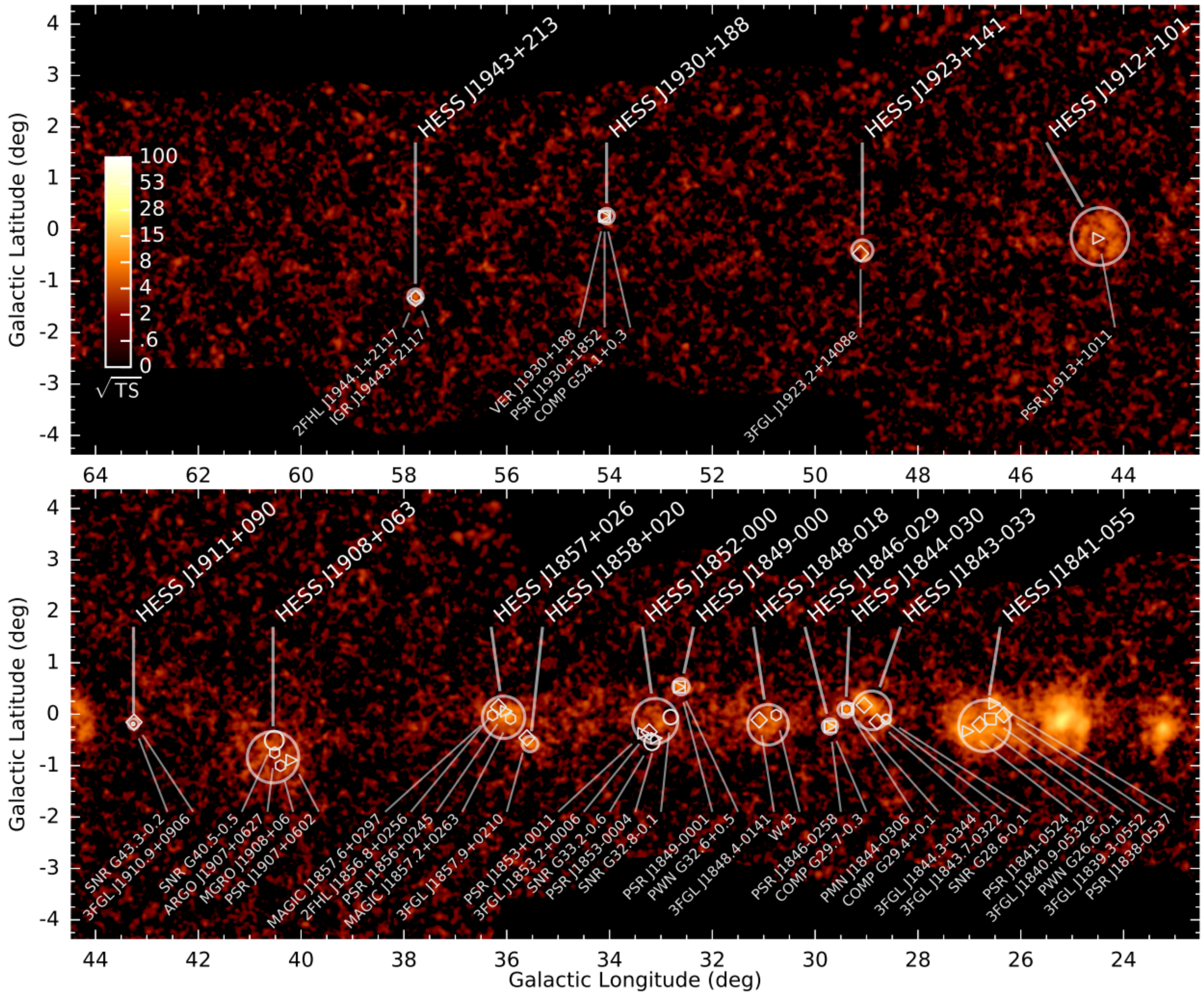
Aharonian et al. 2018

The Galactic Plane survey



Aharonian et al. 2018

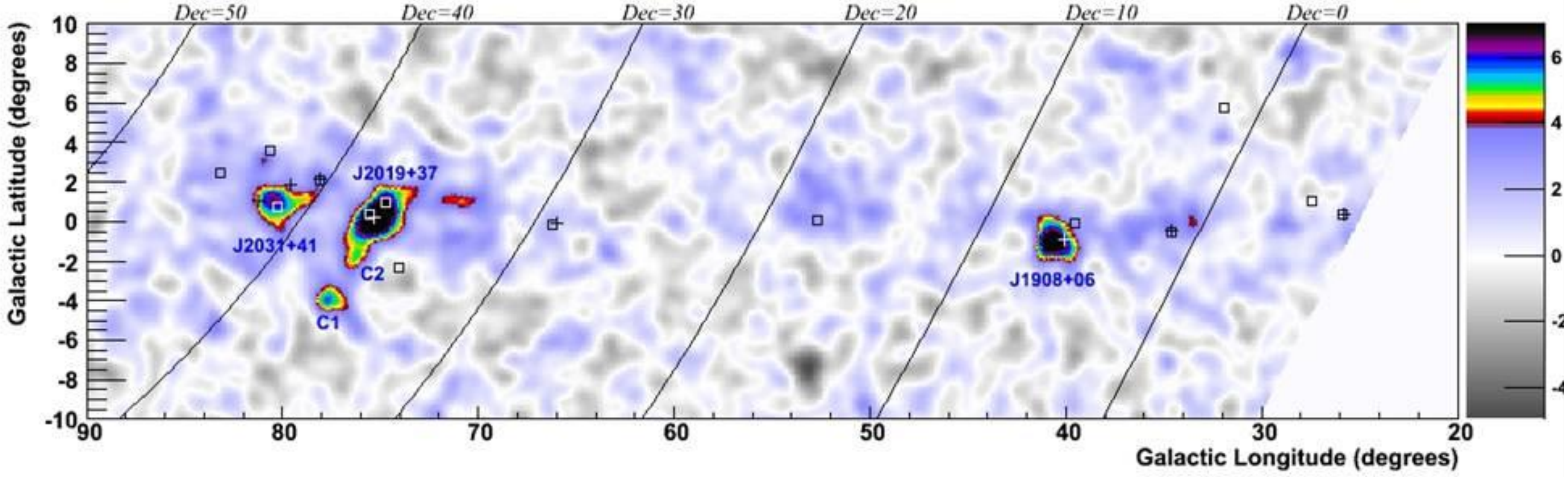
The Galactic Plane survey



Aharonian et al. 2018

MILAGRO Sky Survey

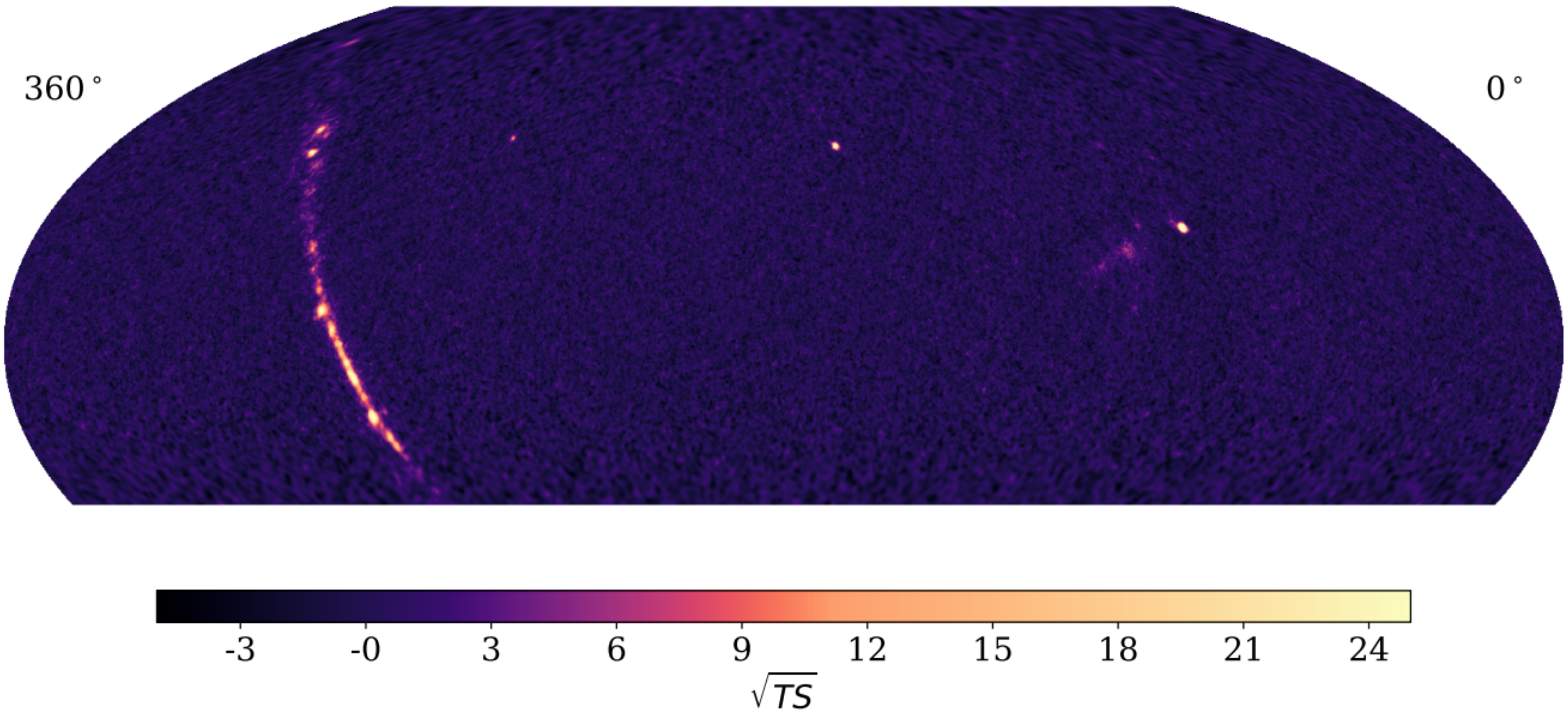
- Milagro reports detecting the diffuse emission of the Milky Way at >1 TeV energies (Abdo et al 2008)



Abdo et al. 2008

HAWC Sky Survey

- HAWC 3rd catalog of Gamma Ray sources



Albert et al. 2021

HAWC Sky Survey

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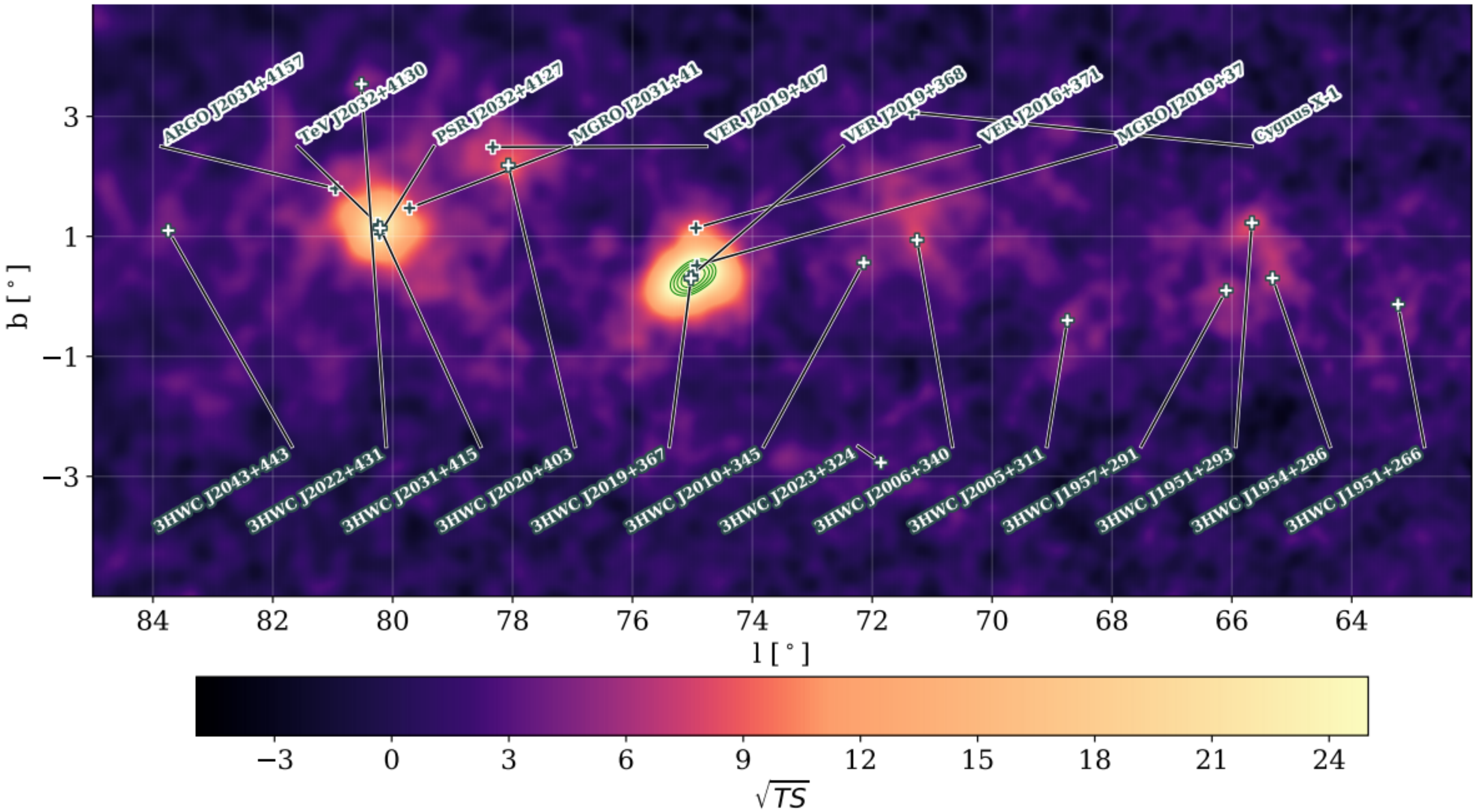
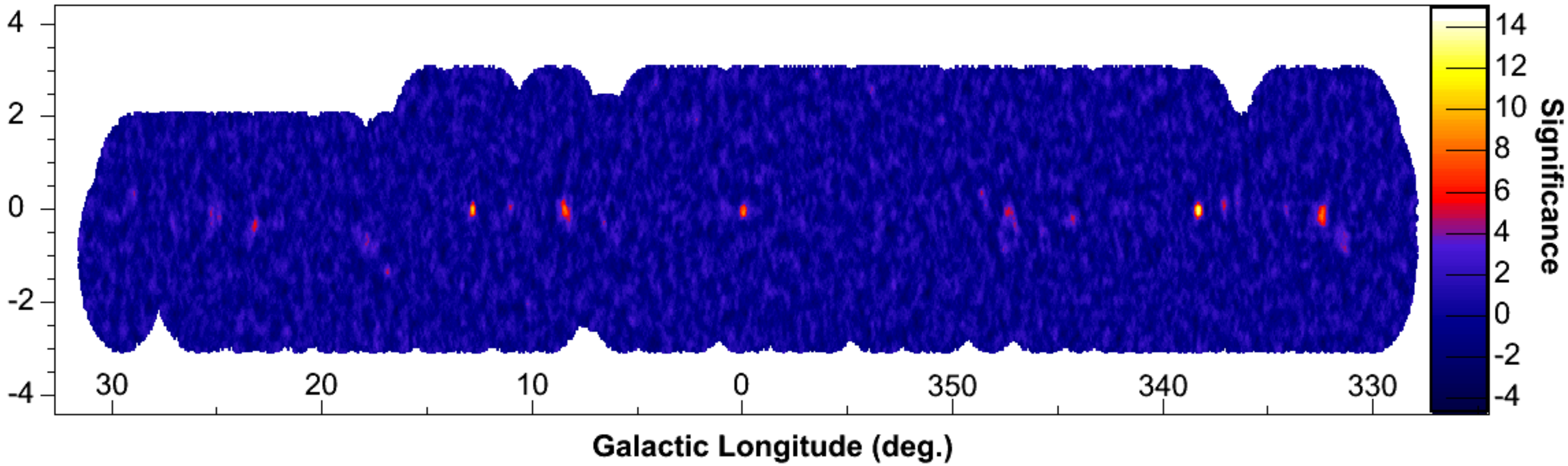
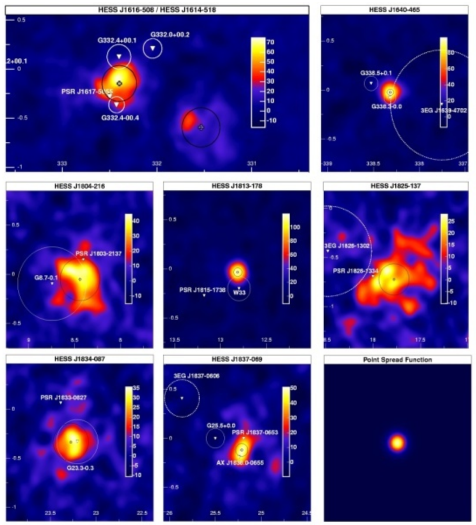


Albert et al. 2021

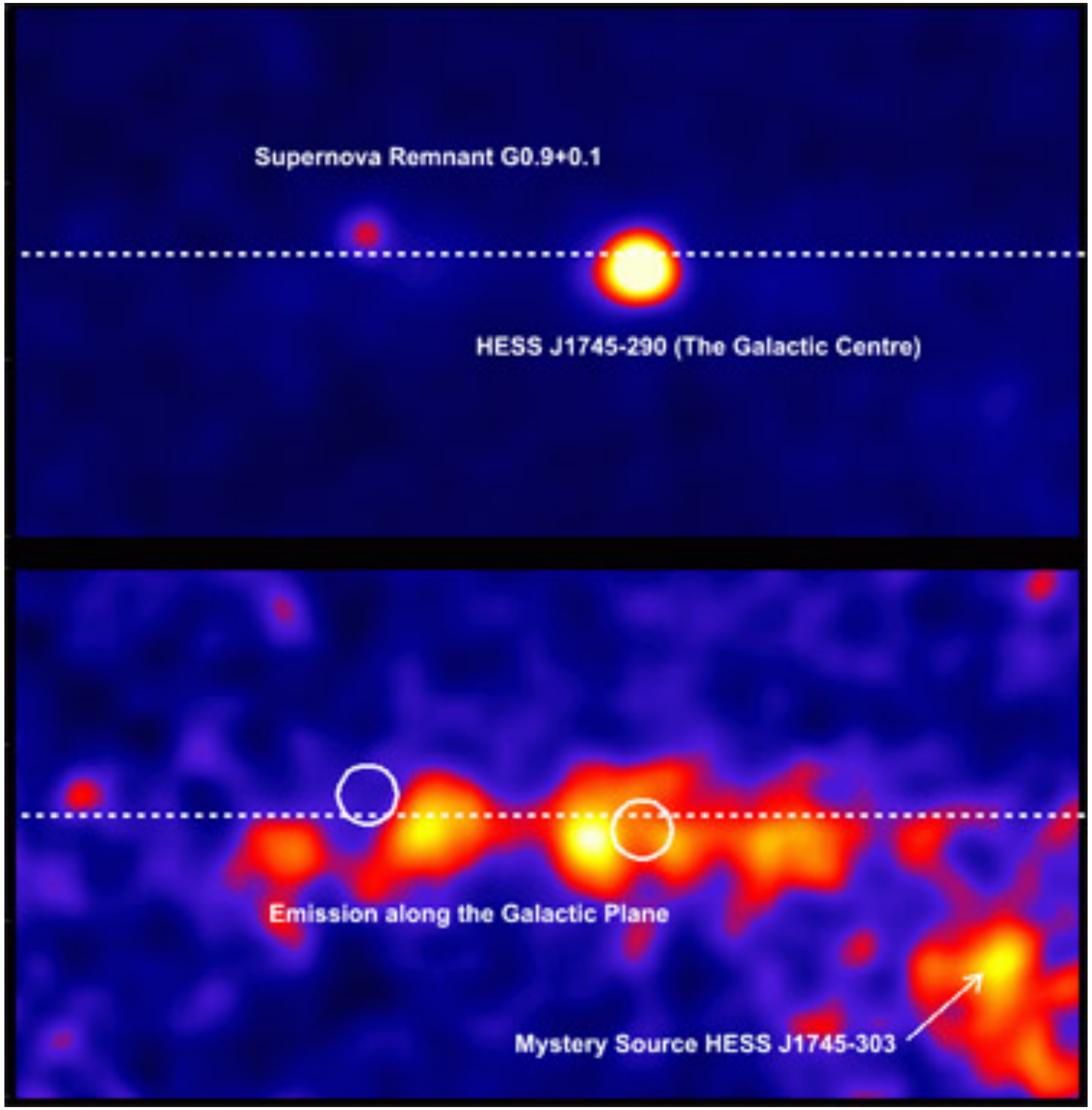
HESS “new” sources



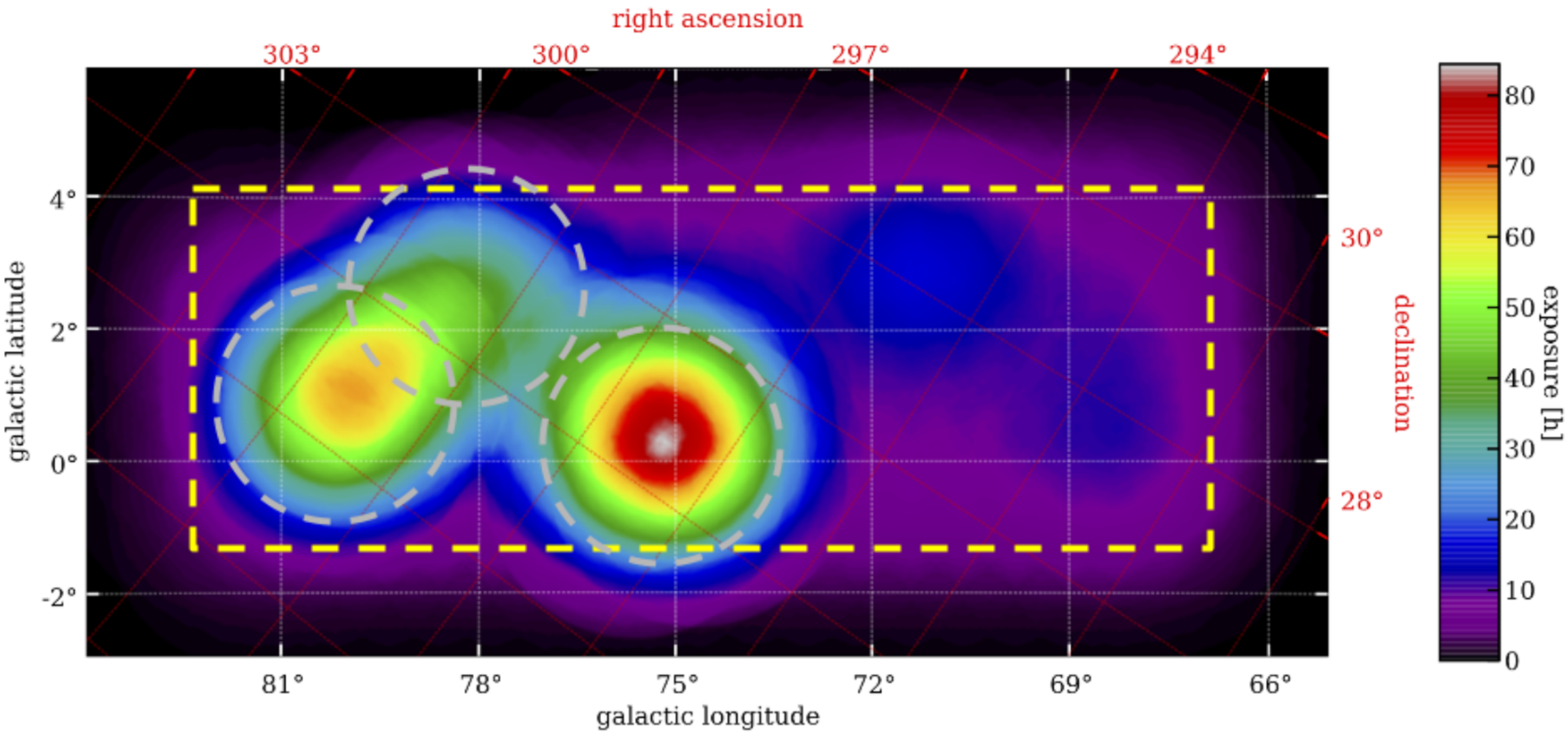


Close-up view of the new sources, discovered in the Galactic plane scan. Shown as white circles are close-by supernova remnants , that are known to be sources of very high energy gamma-rays (with the radius of the circle representing the size of the supernova remnant). Also shown in white are close-by pulsars, another class of sources of very high energy gamma-rays.

HESS Diffuse Gamma-Ray

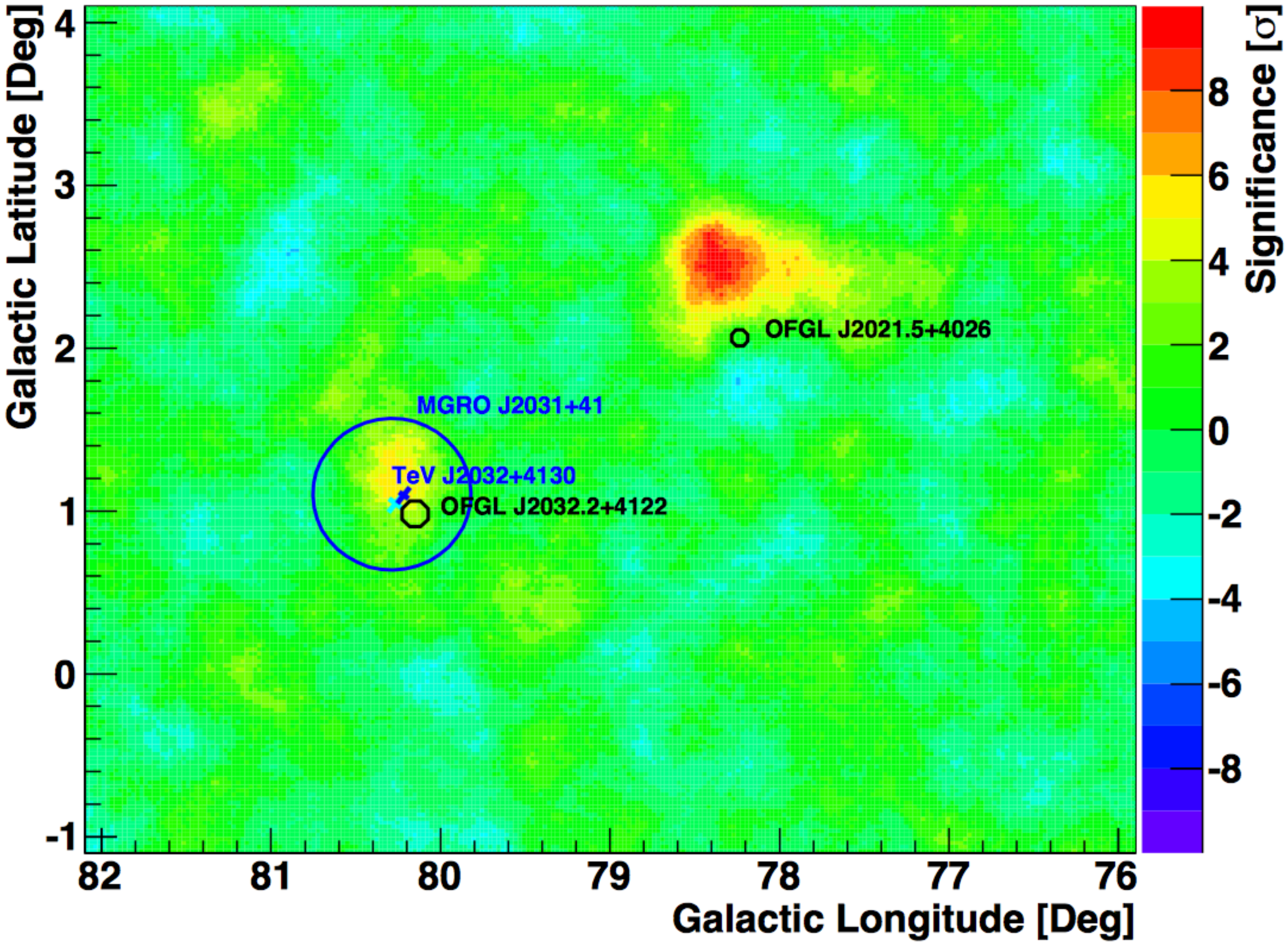


VERITAS Cygnus Survey



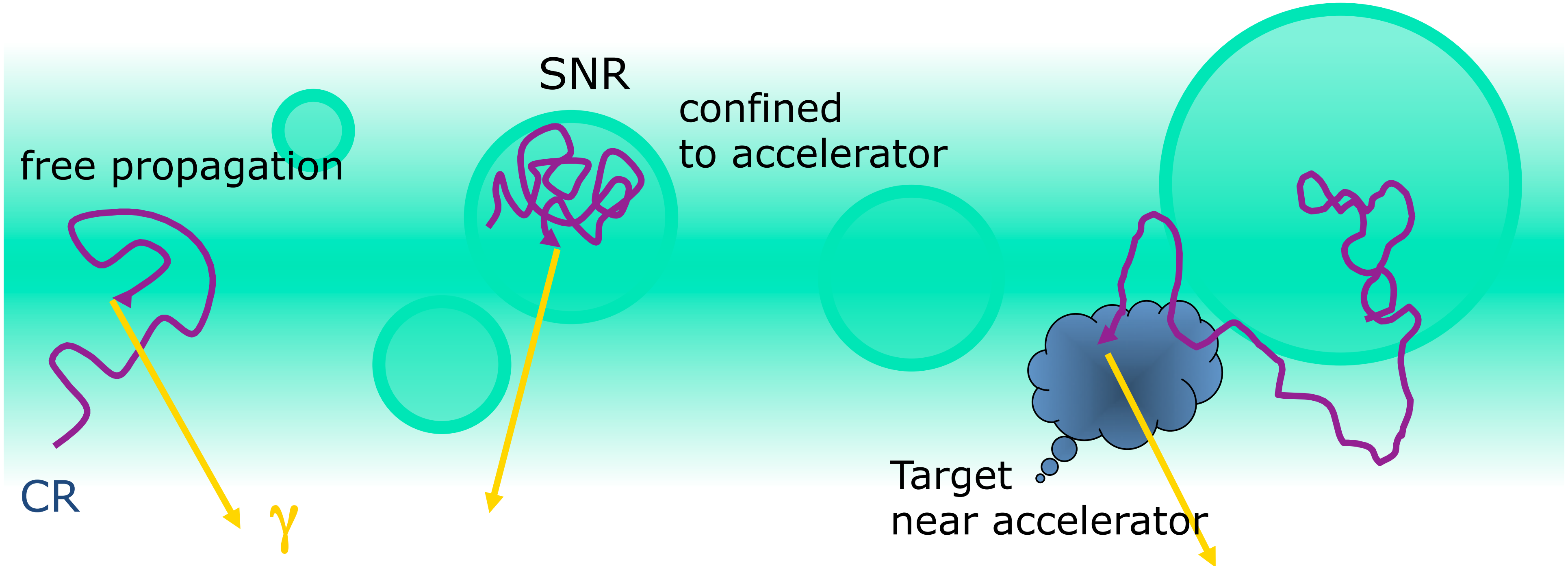
http://arxiv.org/abs/1508.06684

VERITAS Cygnus Survey



http://arxiv.org/abs/0912.4492

CR origin and propagation



VHE gamma rays from secondary interactions:

p: π^o production and decay

e: Inverse Compton scattering and Bremsstrahlung

Trace beam density x target density