Yesterday: QCD

local version QCD

local version QCD

Photons in Astroparticle Physics

Photon 2011, Spa, Belgium

High-Energy Photons from the Cosmos: Experimental Aspects

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Astroparticles: particles from astrophysical sources

... The highest energy particles in the universe !!!!!

Energies kev ... Mev ... Gev ... Tev ... Pev ... Eev ... Zev

10^3 ... 10^6 ... 10^9 ... 10^{12} ... 10^{15} ... 10^{18} ... 10^{21} eV

Cosmic Rays: p, He, ... Fe, ... fully ionised nuclei, $>10^{20}$eV

electrons ~10^{15}eV

Photons: classical astronomy + high-energy gamma rays ~10^{13}eV

Neutrinos: astrophysical ν (solar, SN, AGN, ...) ~10^{7}eV

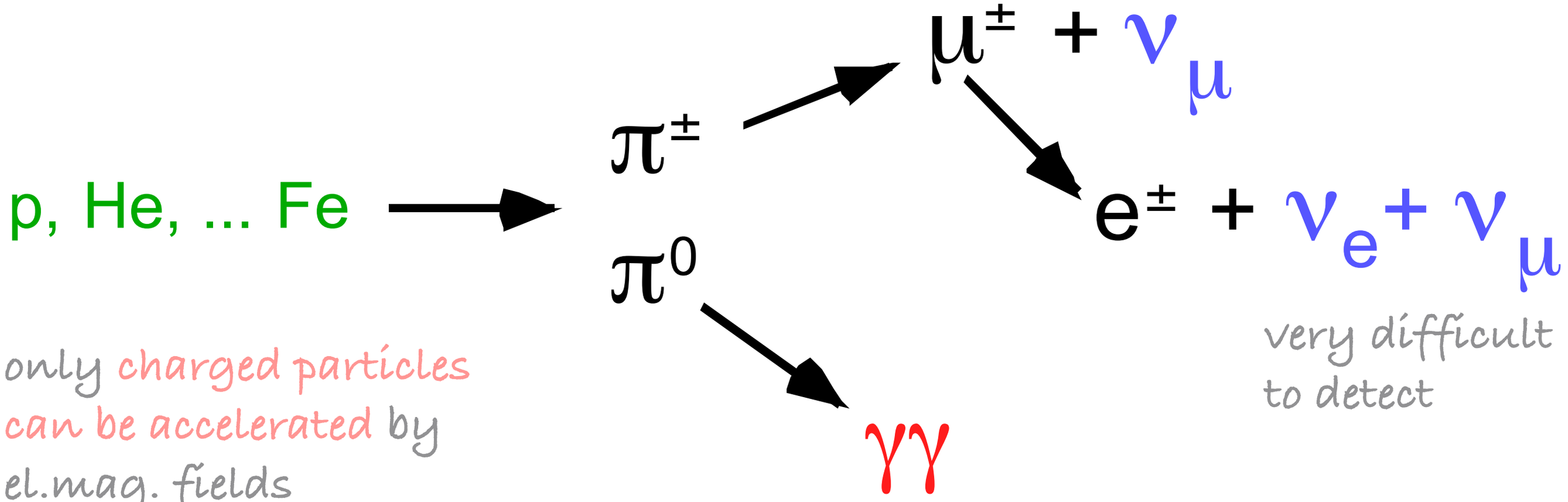
highest energies particles -

acceleration in most extreme environments

If Cosmic Rays exist,

then also γ and ν must exist at similar energies.

Cosmic Rays, Gamma Rays and Neutrinos are linked



only charged particles can be accelerated by el.mag. fields

very difficult to detect

can't travel far at high energies

γ and ν travel in straight lines, i.e. point back at source.
CRs are deflected in gal. and intergal. magnetic fields.

But:

Can γ and ν be detected above backgrounds ???

γ : 10^3-10^4 x more charged cosmic rays

ν : low interaction cross section
atmospheric neutrinos from atmosphere

Fermi

≈ 1 m^2 2.5 sr

30 MeV - 300 GeV

Fermi - LAT

pair-conversion telescope with:

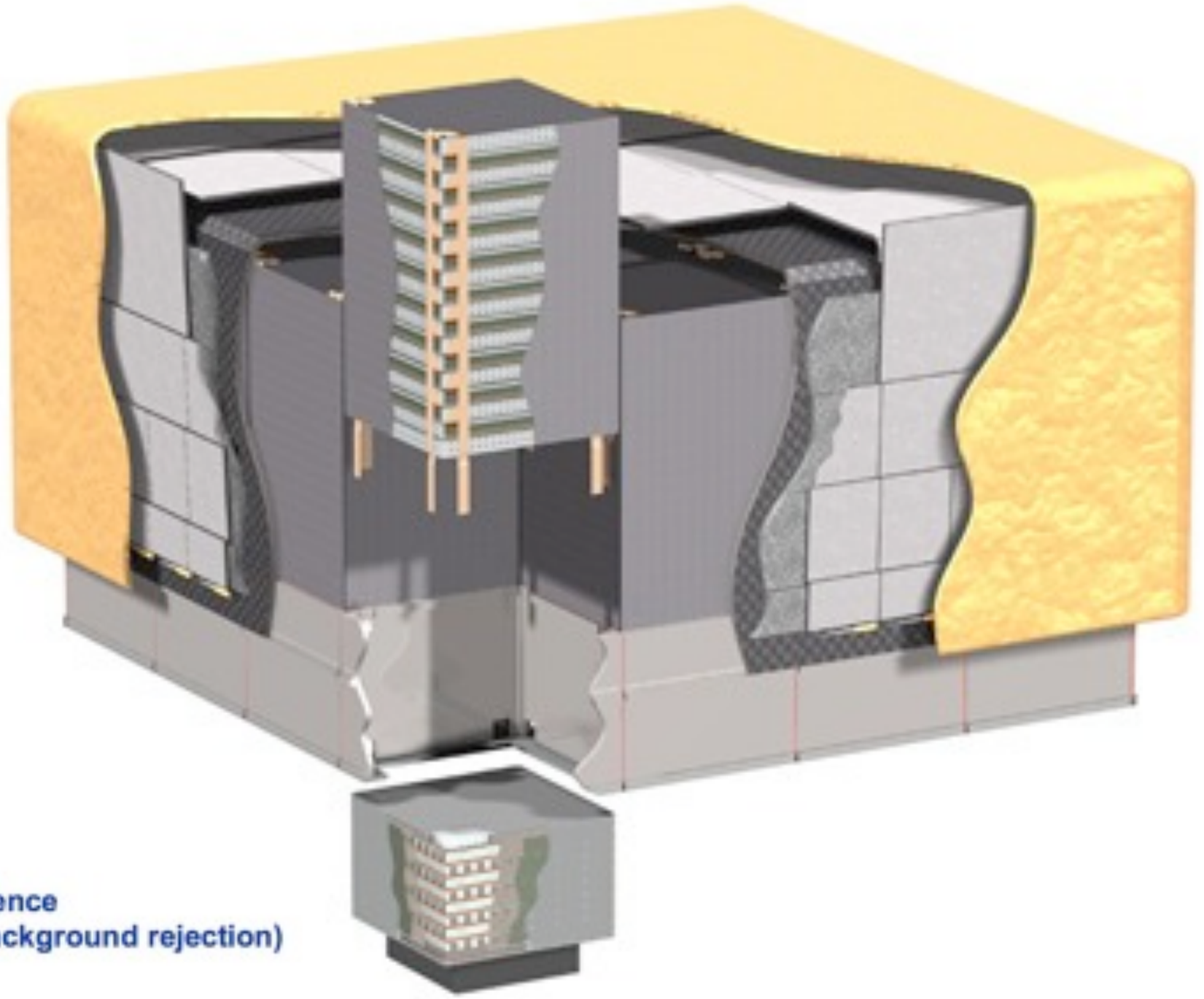
precision trackers

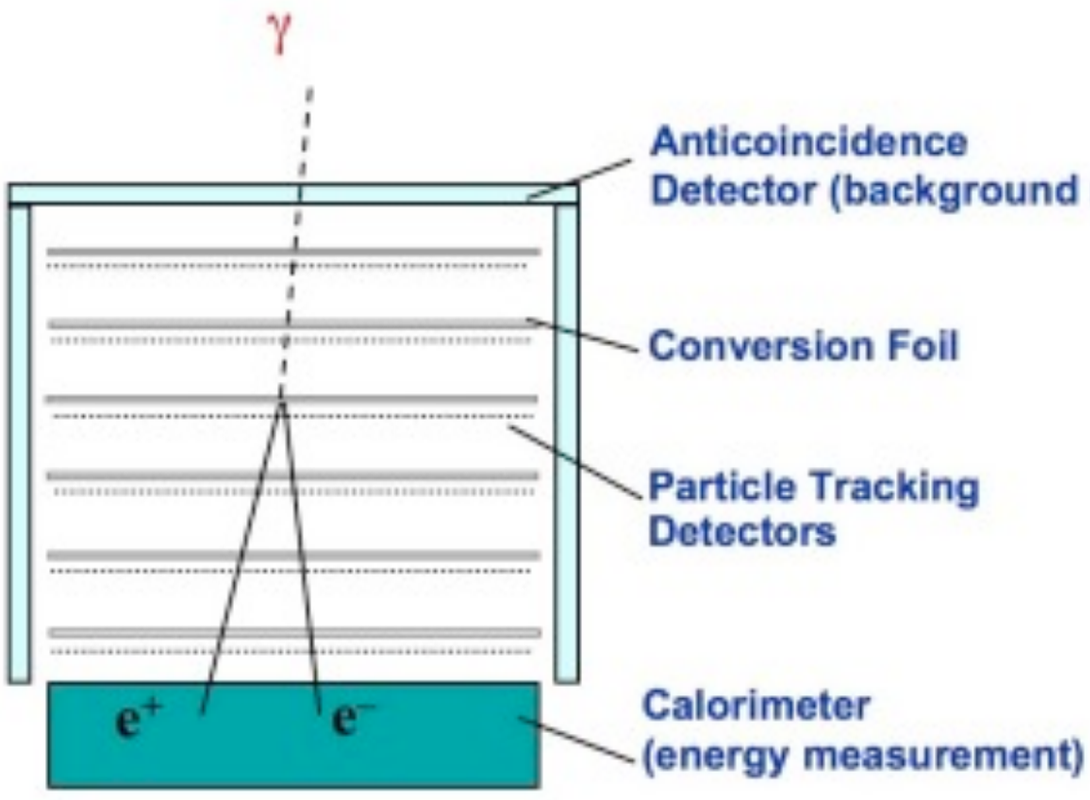
18 layers tungsten converters and x, y silicon strip detectors.

calorimeter

96 CsI(Tl) crystals in an 8 layer hodoscope (depth: 8.6 X_0)

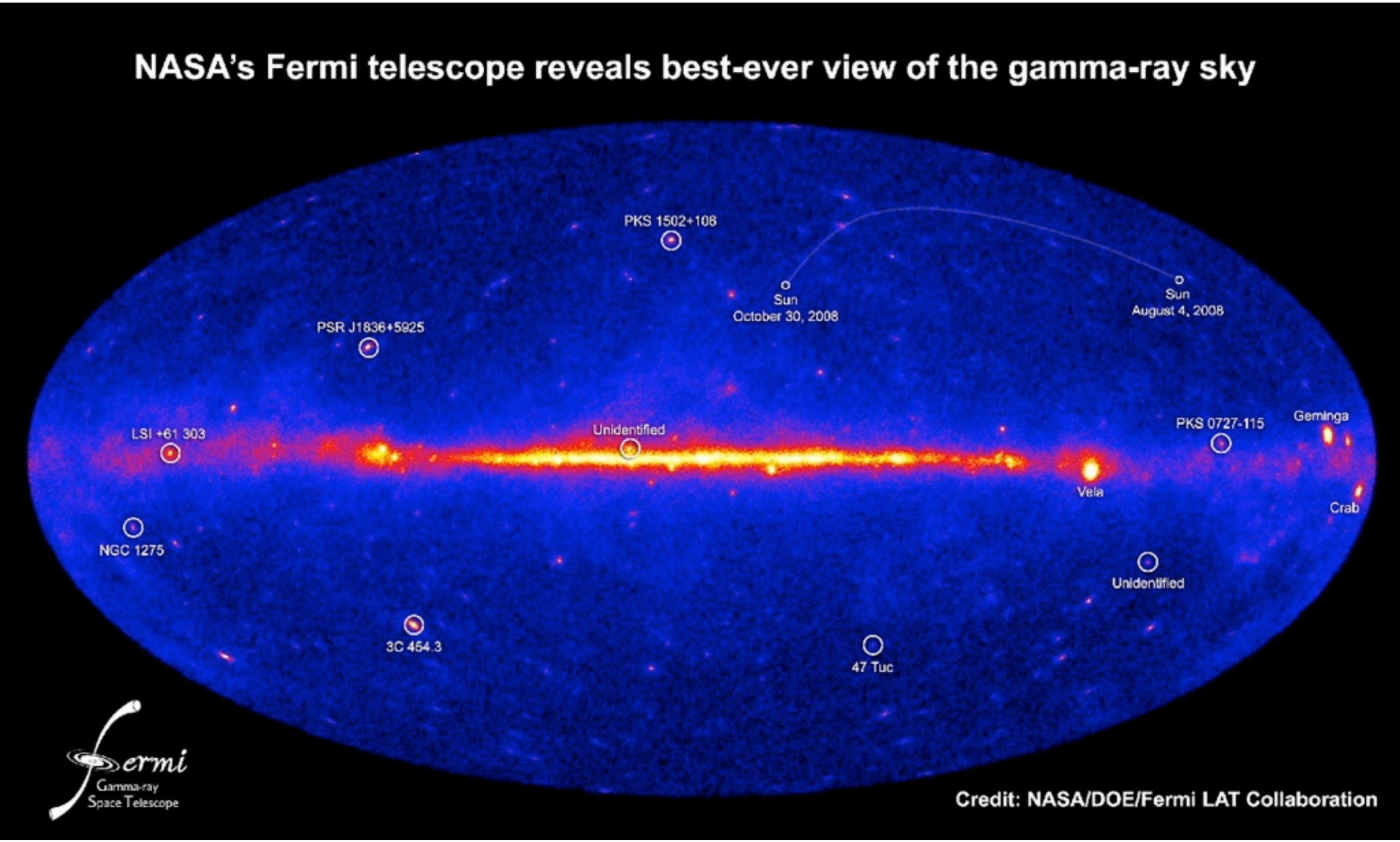
4x4 modules covered by anti-coincidence shield





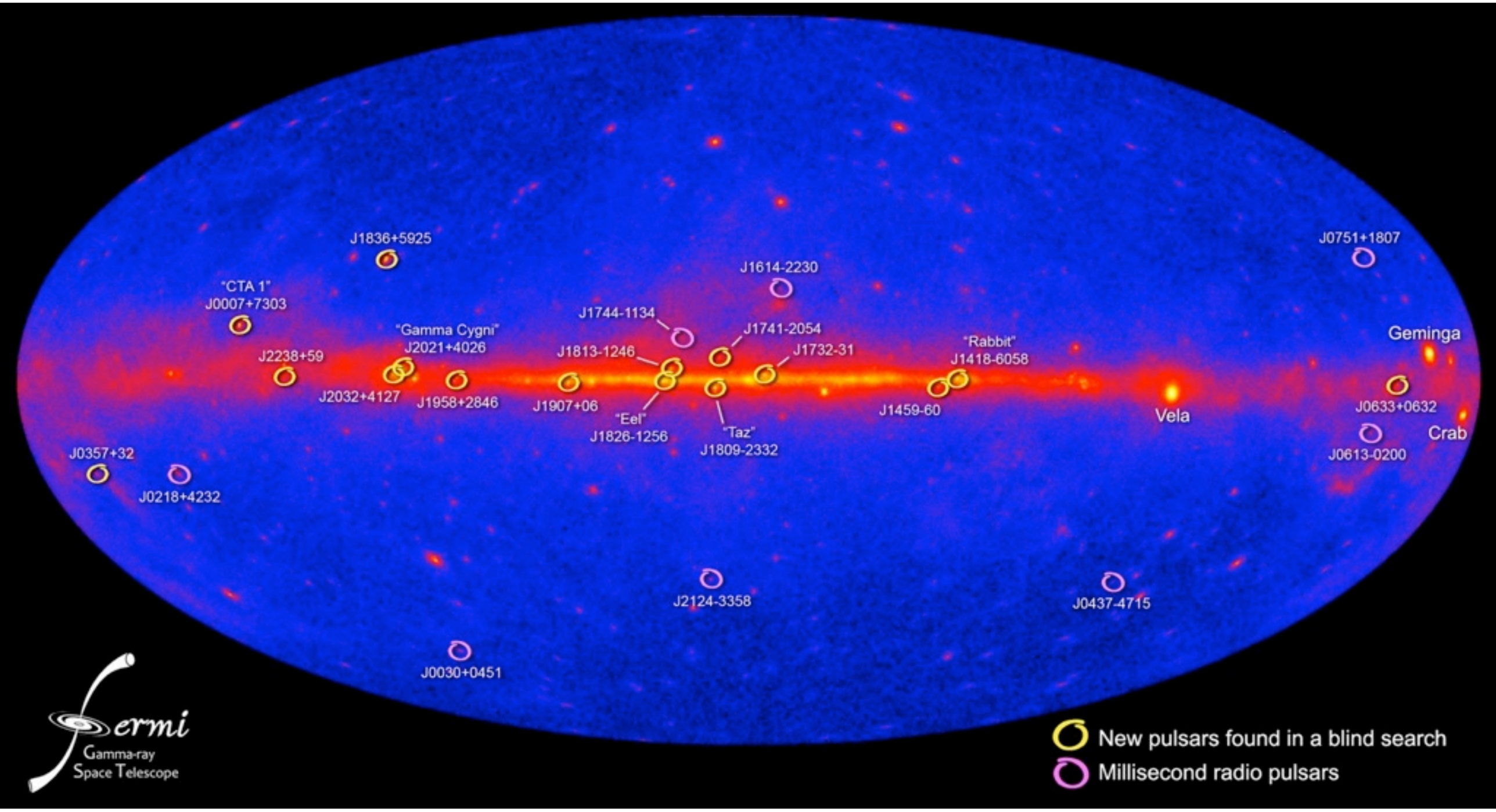
≈ 1 m^2 2.5 sr

near perfect rejection of charged primaries

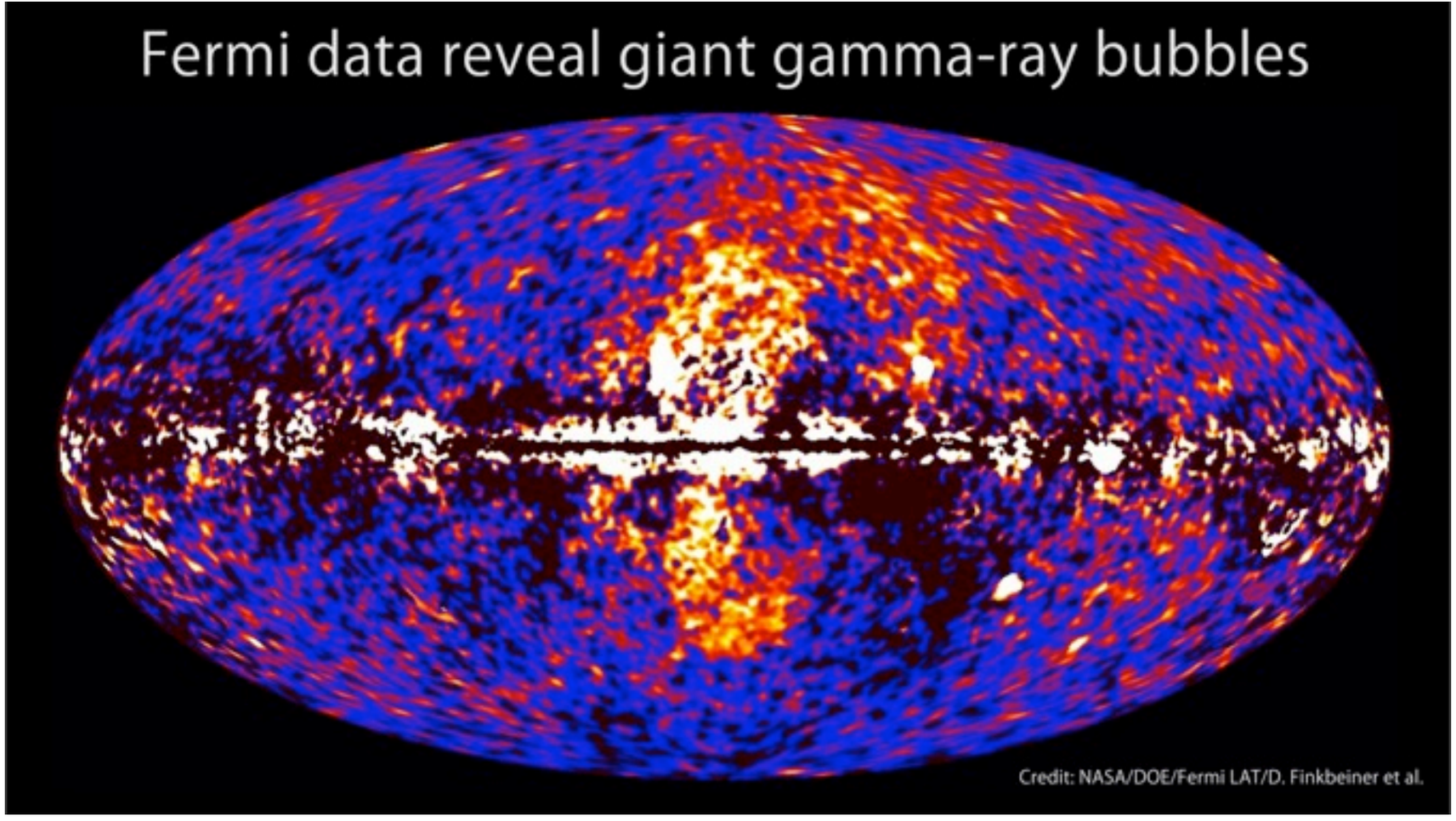


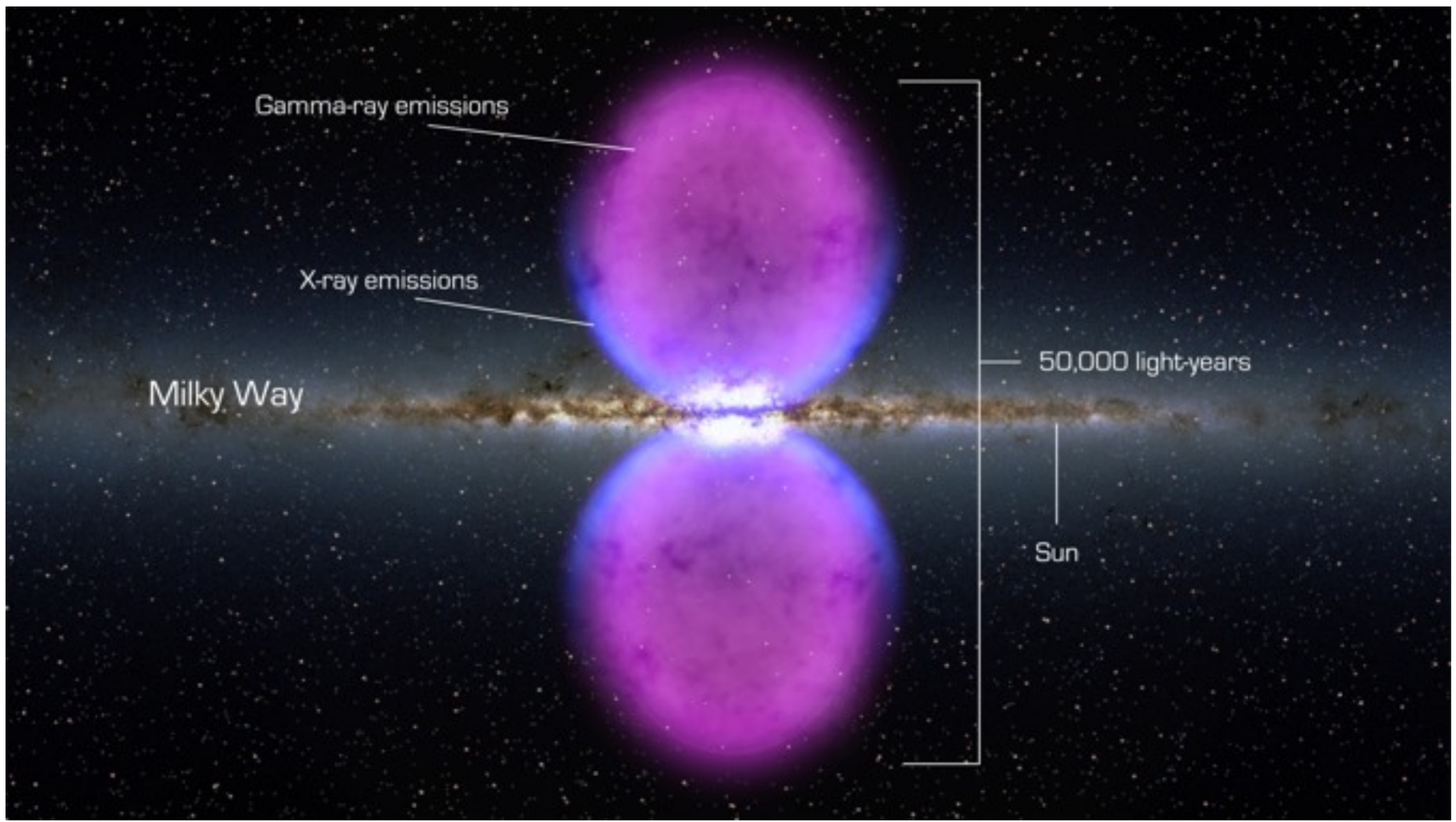
point sources, extended sources and diffuse emission

… many old and new gamma ray pulsars



The Fermi bubble

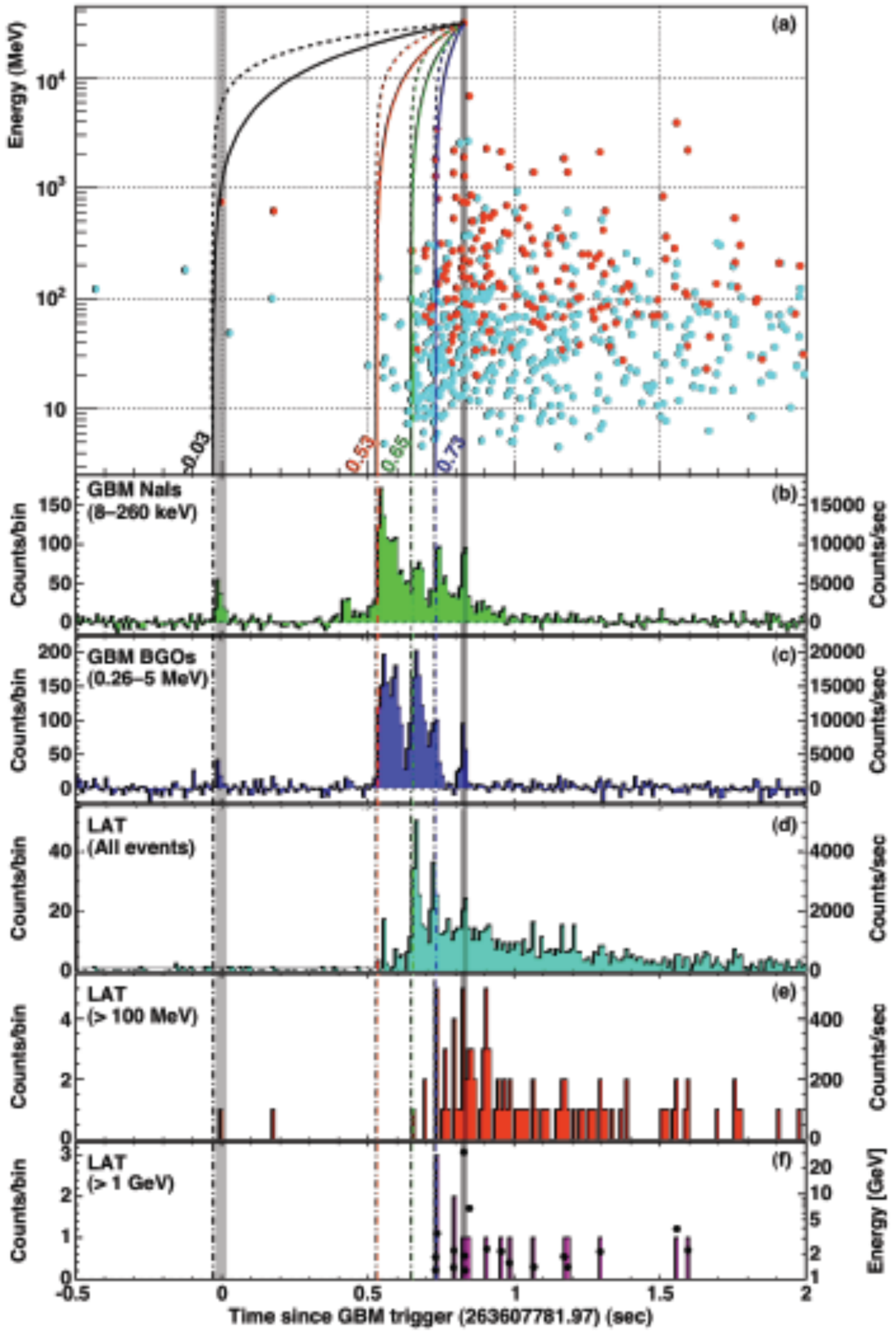




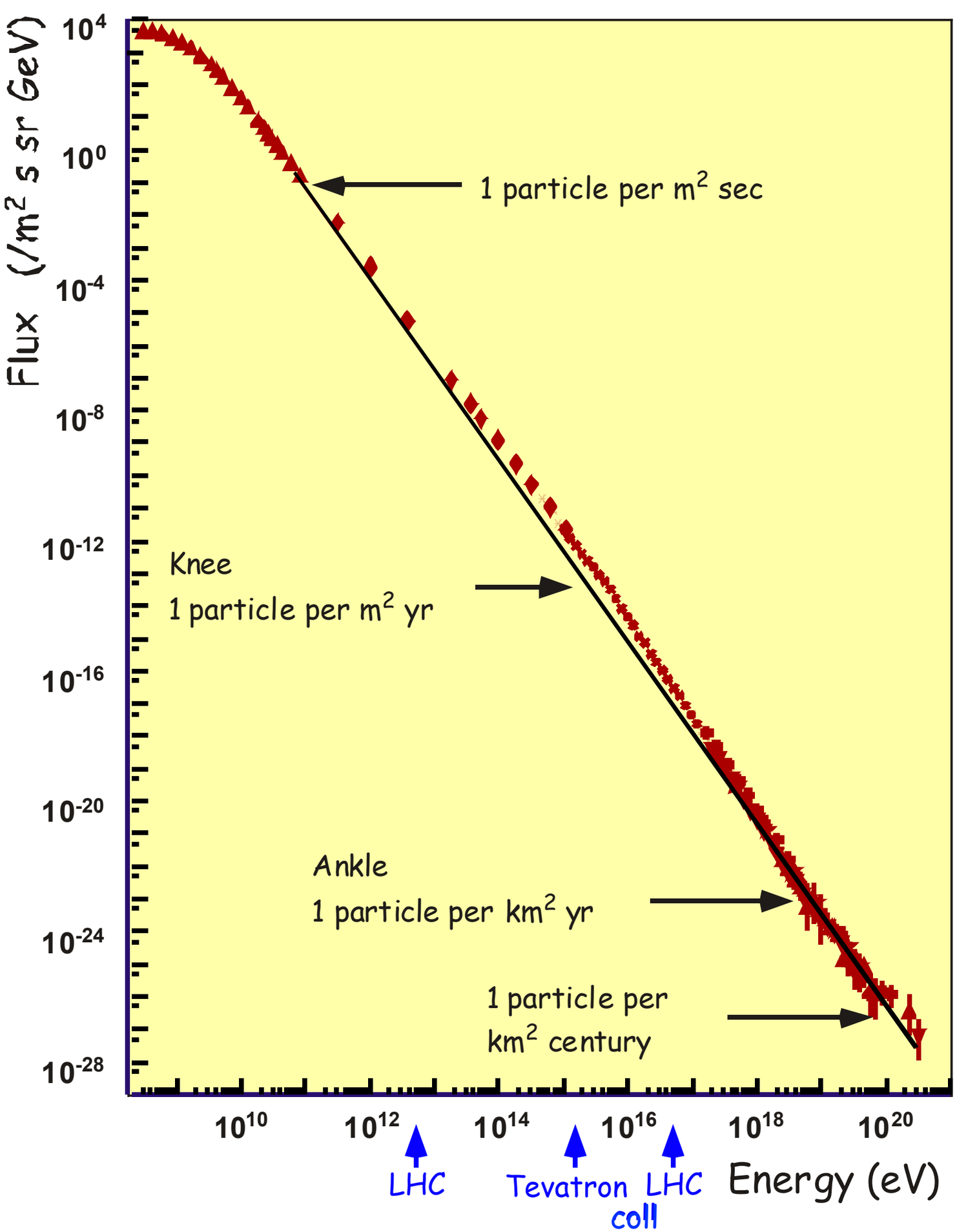
Fermi:

LIV test: GRB

... plus many more exciting results.
100s of papers...



Flux of Cosmic Rays



11 orders of magnitude in energy,
32 in flux !!!!

CR are detected up to
highest energies:

AGASA ~3 x 10^{20} eV

Fly's Eye ~3 x 10^{20} eV

Power law with not much structure.
(makes it difficult to interpret)

$$N_{evts} = flux \times area \times time$$

N_{evts}	flux	area	time
> 100	low, given by nature	$\approx 1\ m^2$	≈ 3 yrs
for <10% stat. error		for space exp.	for a PhD

Size of detector limits the fluxes that can be observed

High-energy astro particles are very rare:

Therefore, HUGE detection volumes (i.e. target materials) need to be instrumented

Natural detector: the atmosphere is first target for particles from space

Beyond 100 GeV...

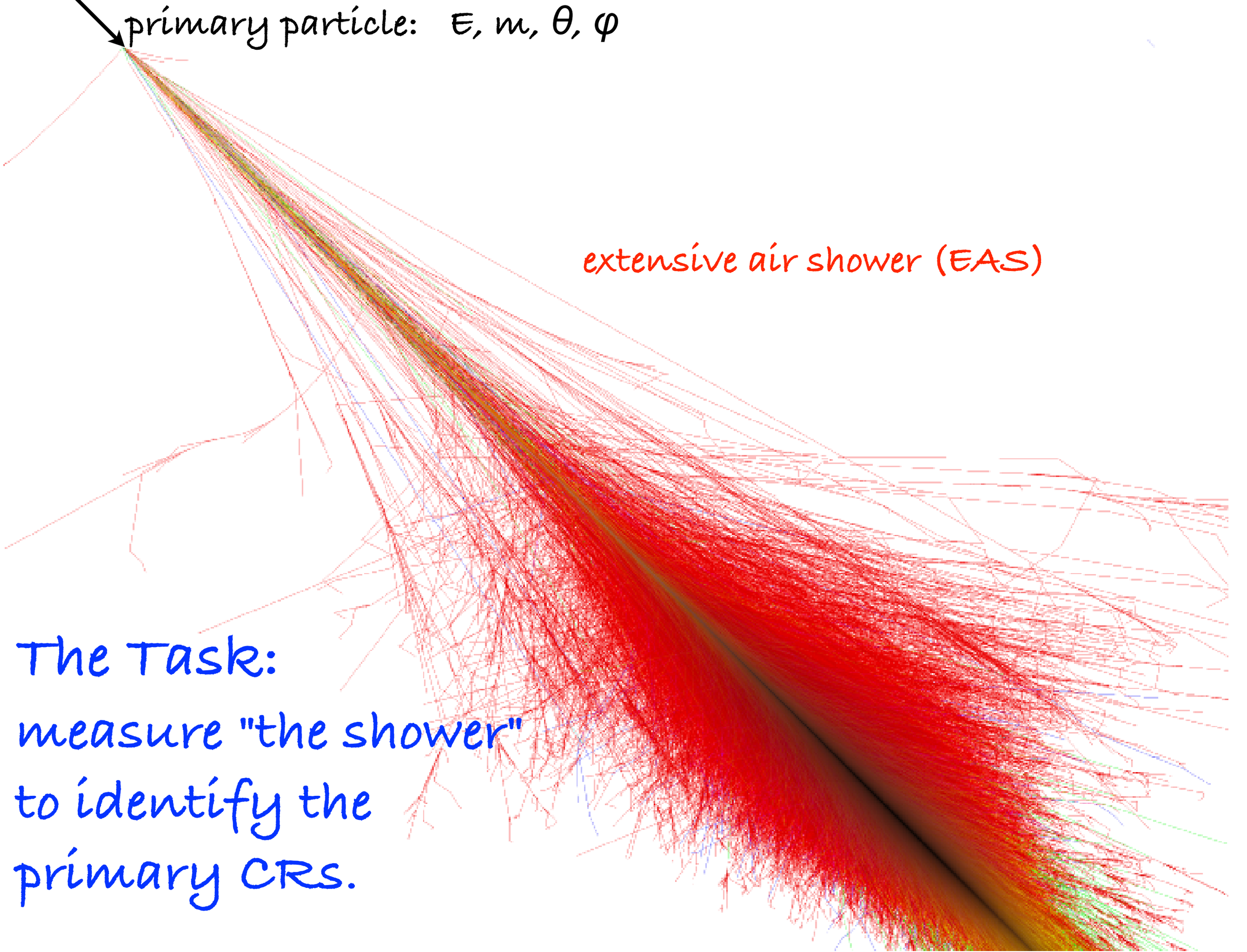
Steeply falling spectrum: 10x in energy /500 in flux !

Higher energy astro particles require very large detectors:

- need to instrument large "natural" absorbers
  (e.g. the atmosphere, lakes, sea water, antarctic ice shield, ...)
- detect reaction products of primary CR

Indirect Measurements: Extensive Air Showers (EAS)

primary particle: E, m, θ, φ



extensive air shower (EAS)

The Task:
measure "the shower"
to identify the
primary CRs.

+ Particle Multiplication:

Instead of 1 particle (the primary) one has to detect
a shower with many particles scattered over a wide area.
much easier to detect !

- Indirect Measurements:

Deduce properties of primary particles from
the shape and particle content of the shower of secondaries.

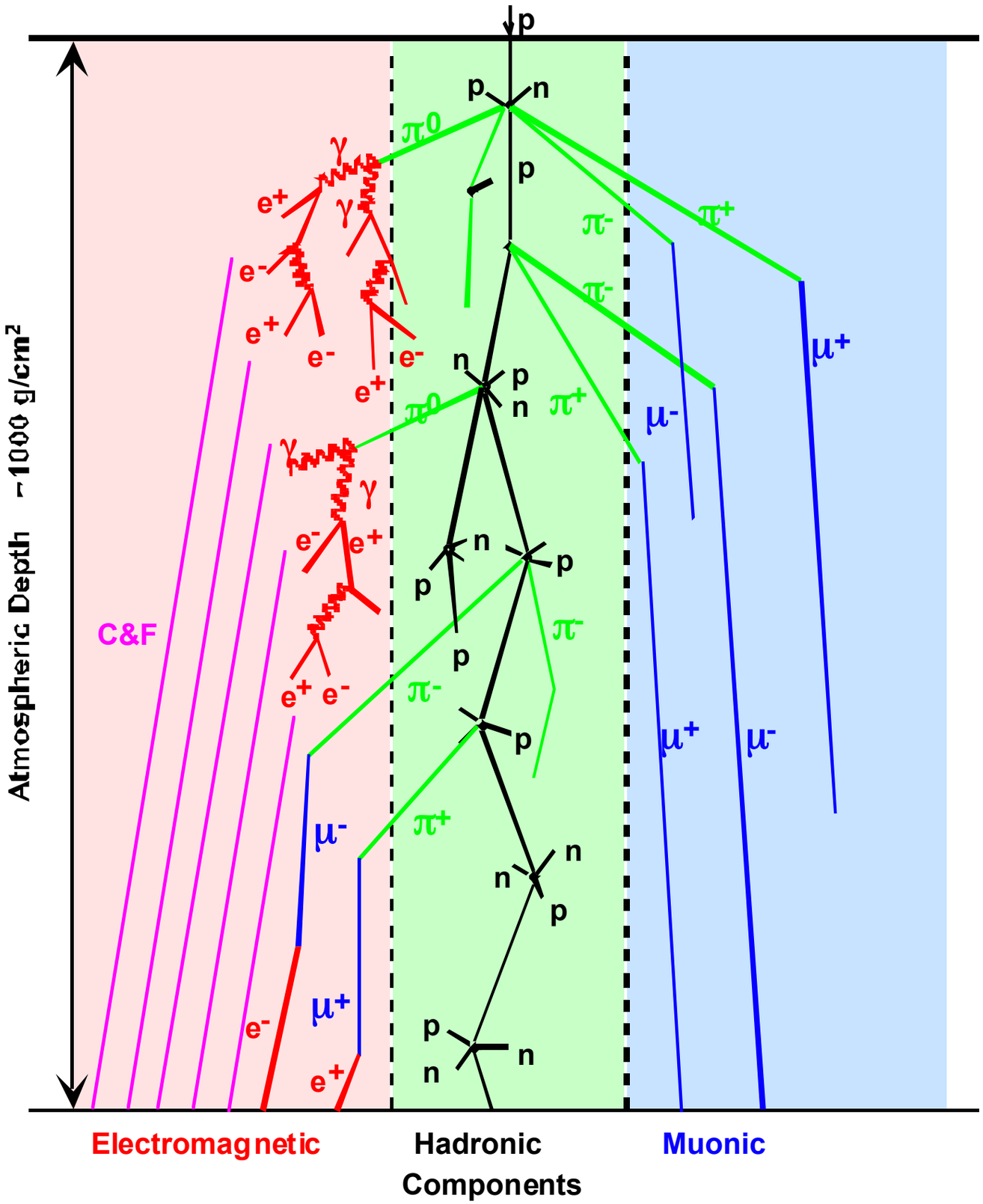
- particles (e, γ , μ , ...) at ground level
- Cherenkov light from charged secondaries (forward)
- Fluorescence light from ionised air (isotropic)
- Radio emission from charges in Earth magnetic field (forward)

for all: density, lateral-, energy-, time distributions

This is tricky:
it requires knowledge on how a shower develops
depending on its primary, energy, angle,
el.mag. / hadronic interactions, ...

MC sims!

Hadronic Air Shower (schematic)



p, n, π : near shower axis

μ, e, γ : widely spread

e, γ : from π^0, μ decays ~ 10 MeV

μ : from $\pi^{\pm}$, K, ... decays ~ 1 GeV

$N_{e,\gamma} : N_{\mu}$ ~ 10 ... 100 varying with core distance, energy, mass, Θ, ...

Details depend on:
- interaction cross-sections,
- hadronic and el.mag. particle production,
- decays, transport, ...

at energies of MeV to 10^{20} eV
(well above man-made accelerators.)

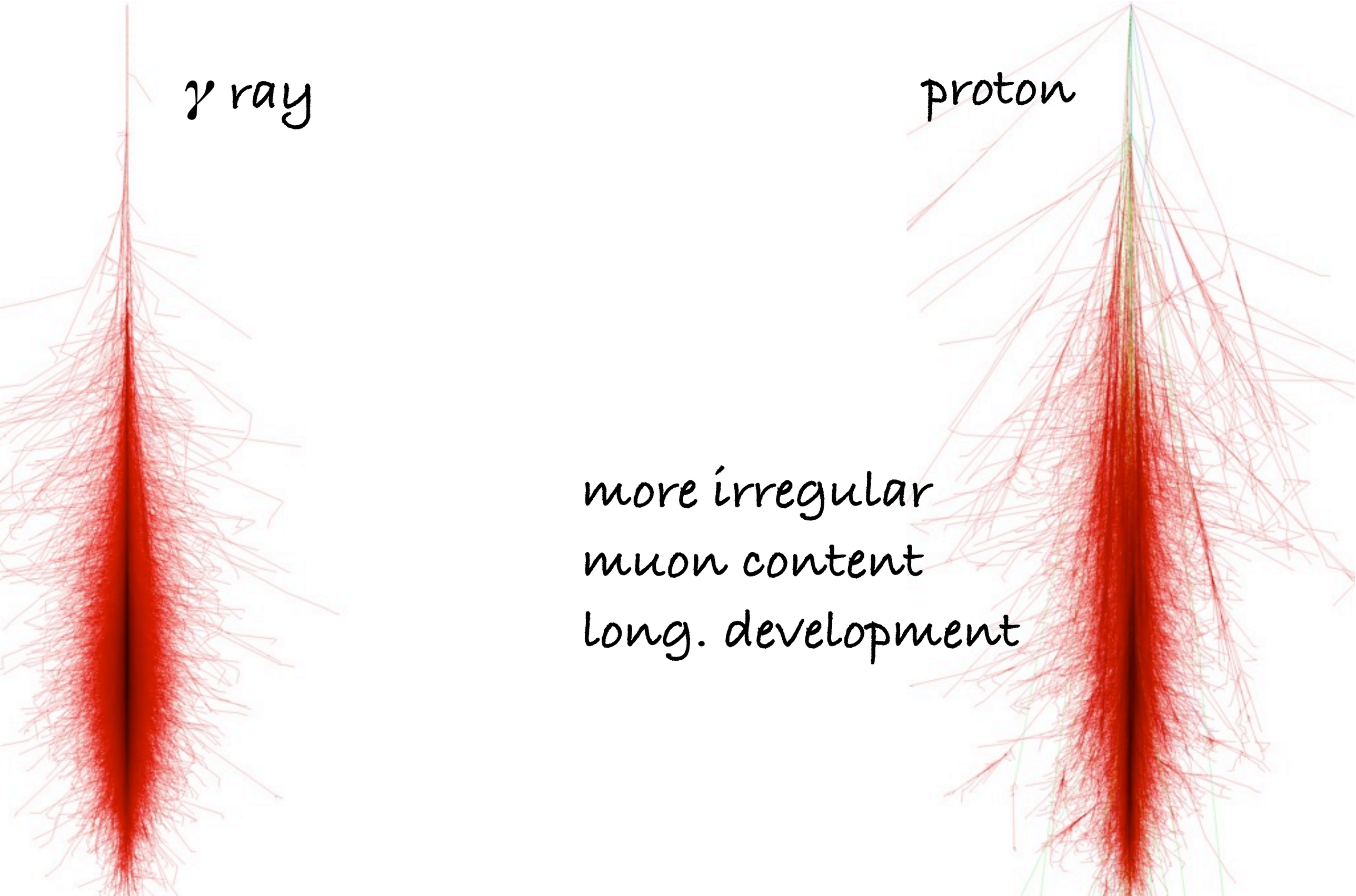
Complex interplay with many correlations
requires MC simulations

El.mag. Shower: QED

10^{12} eV γ ray vs hadronic showers

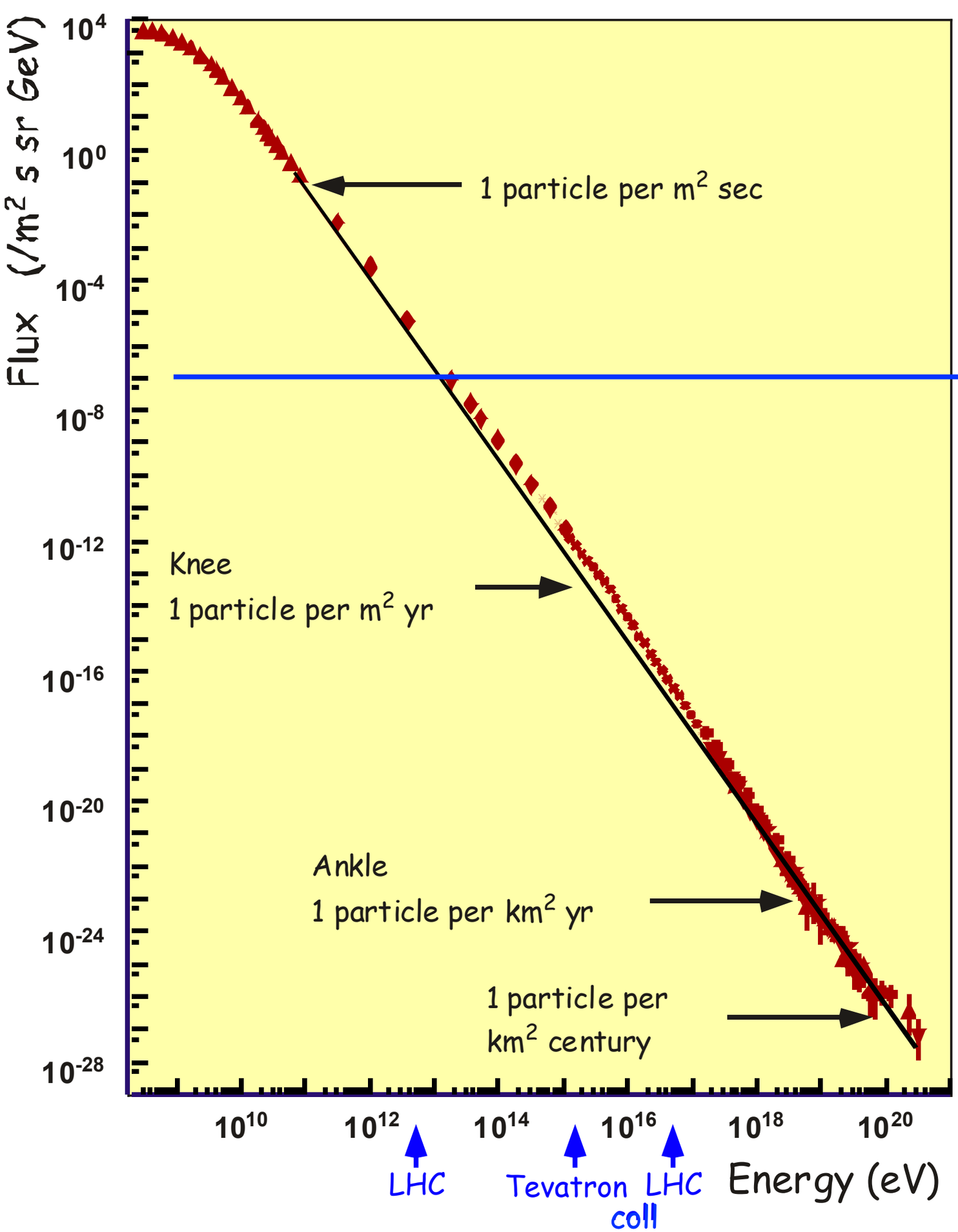
γ ray

proton



more irregular
muon content
long. development

Flux of Cosmic Rays



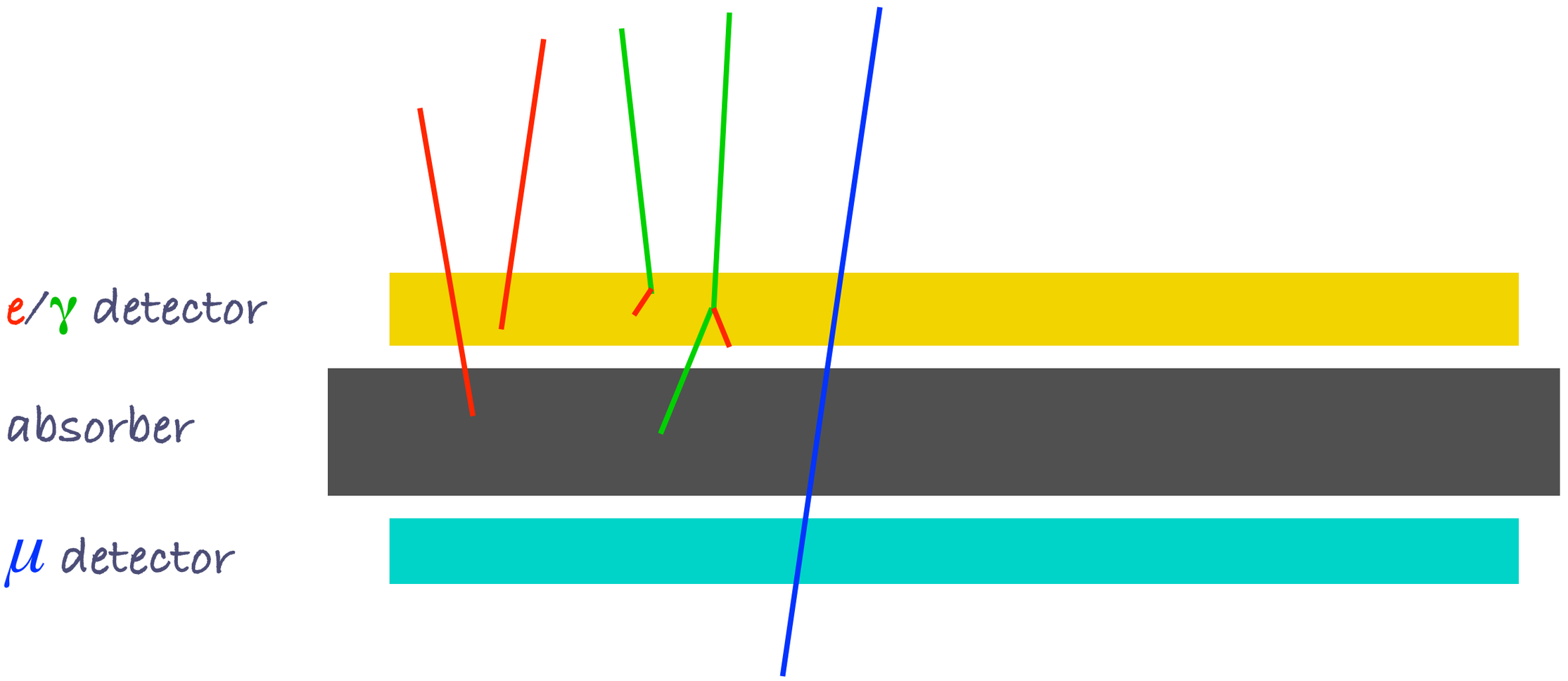
Steeply falling spectrum:
10 x in energy / 500 in flux

flux limit for ≈m² detectors

Different detectors for different purposes ...

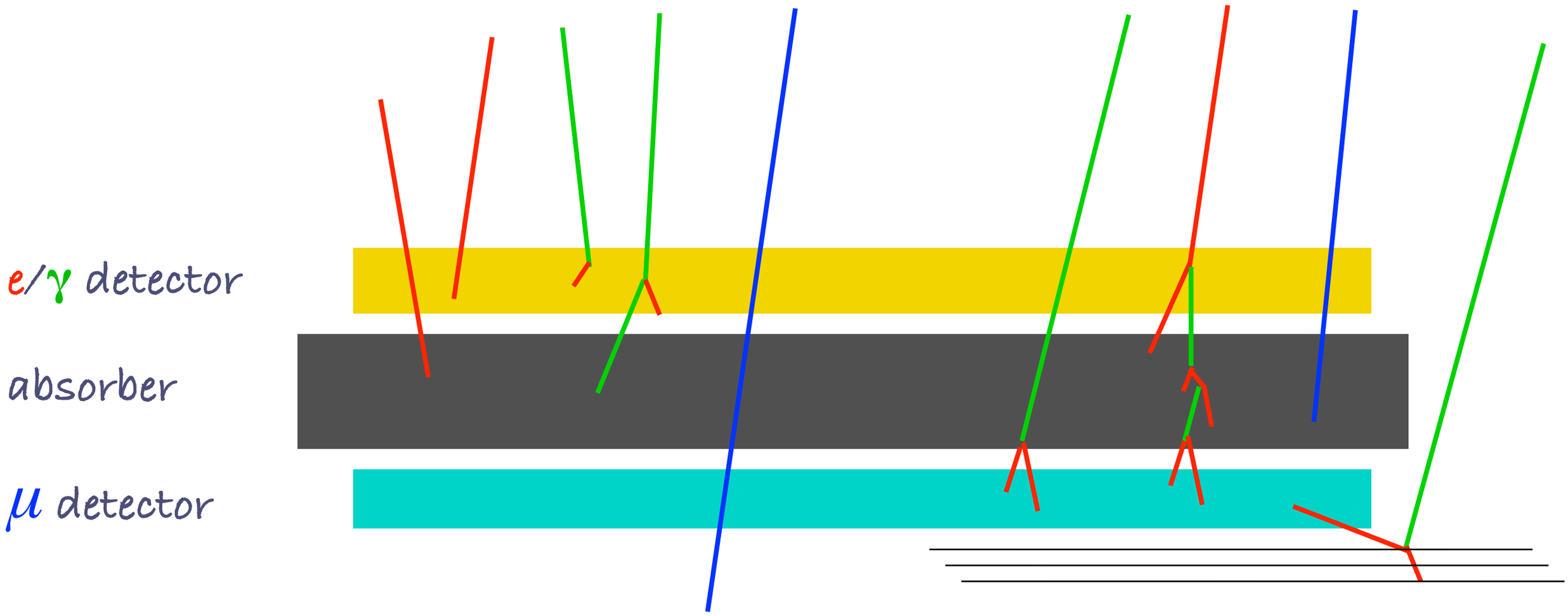
EAS Observables:		Suitable Detectors:
Number, distribution, fluctuation of electrons arrival times	.....	arrays of scintillators, water Cherenkov detectors or gas chambers
Number, distribution, angle, energy, fluctuation of μ	.....	buried detectors, tracking chambers
Number, distribution and energy of hadrons	.....	deep hadronic calorimeters
Number and distribution, angular distribution of Cherenkov photons	.....	wide angle and imaging Cherenkov detectors
angular distribution of fluorescence photons	.....	fluorescence telescopes
Depth of shower maximum	.....	Cherenkov or fluorescence detectors

Identifying secondaries is not so easy ....



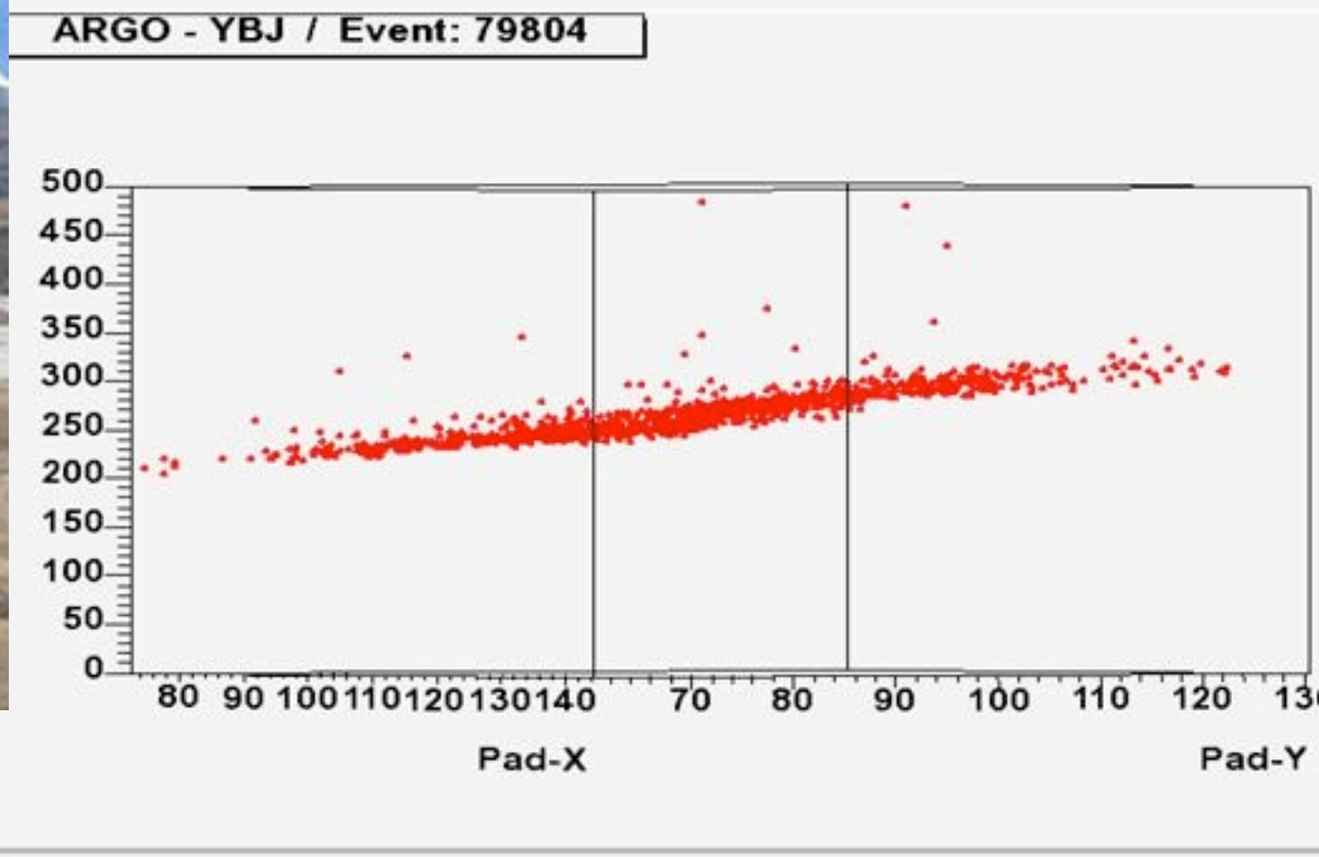
detector response is crucial

Identifying secondaries is not so easy ....



detector response is crucial

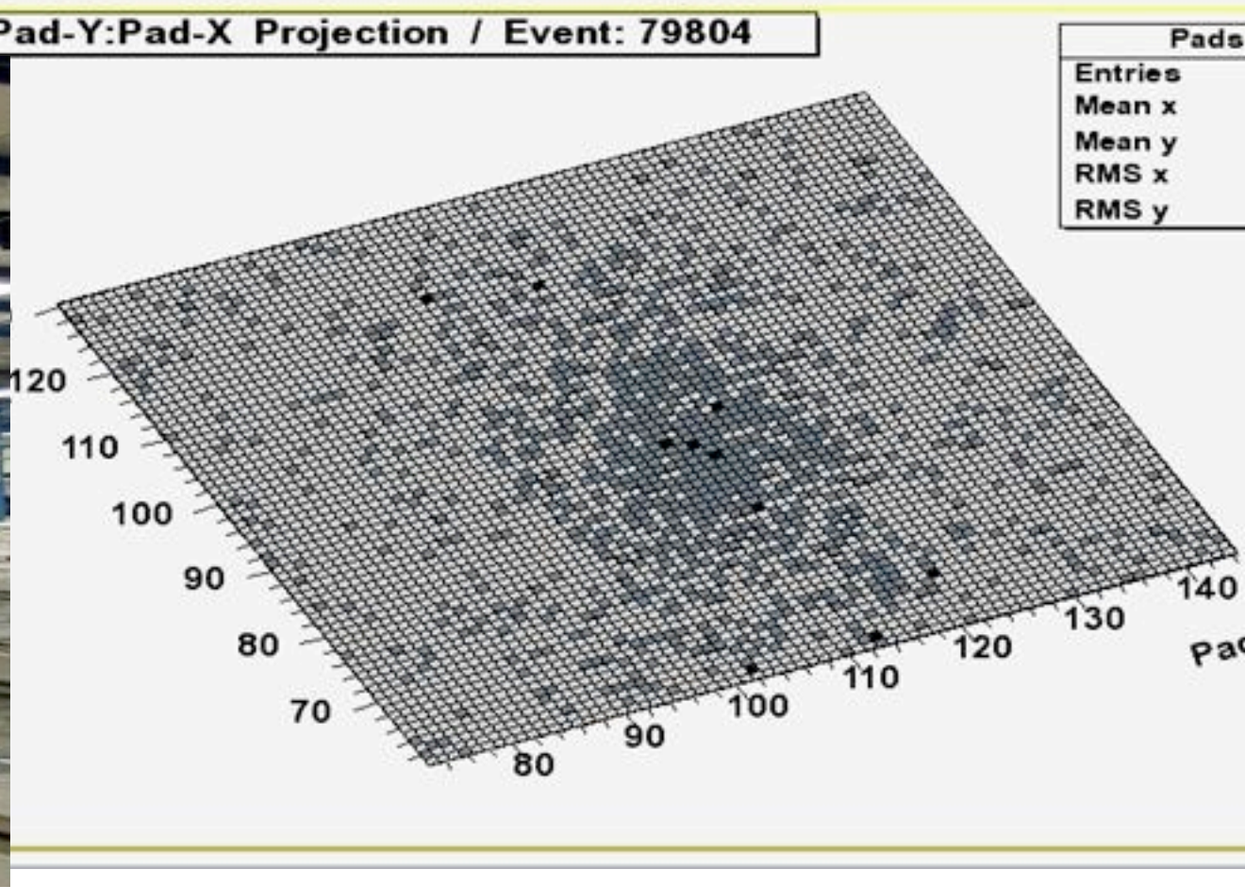
4200 m.a.s.l.



Argo

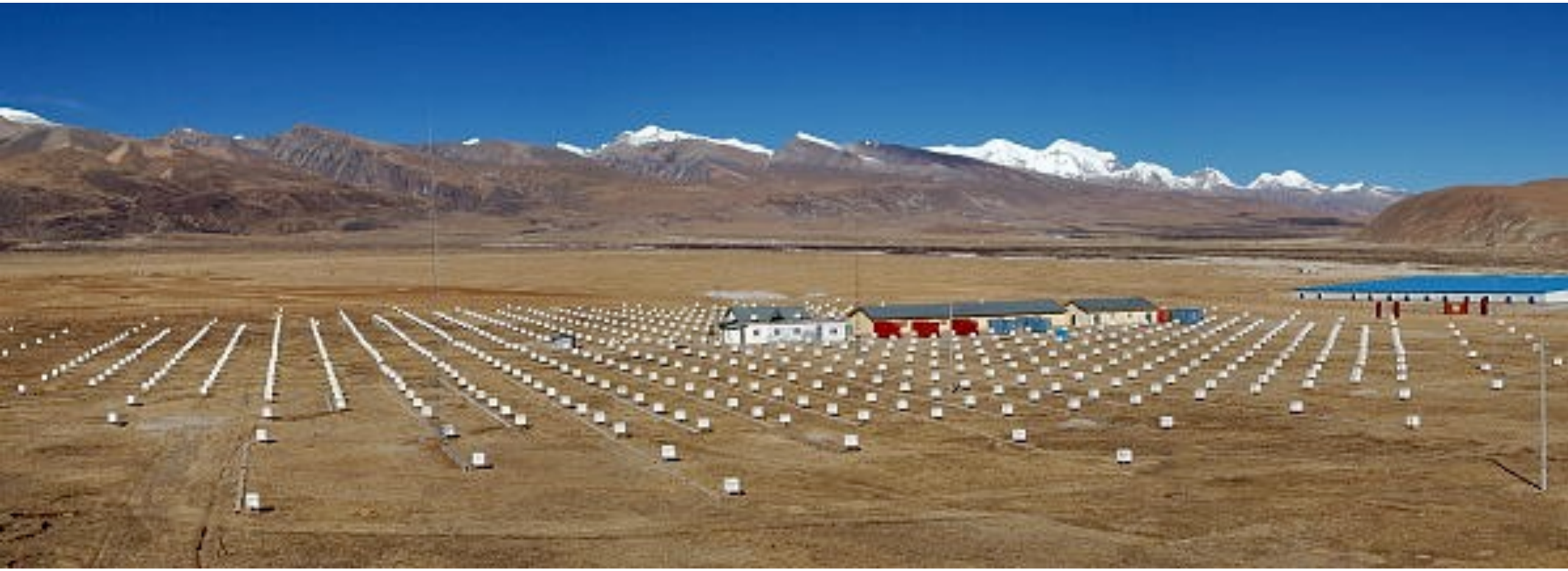
gamma sources

RPCs full coverage



Tibet AS Gamma

4200 m.a.s.l.



Milagro

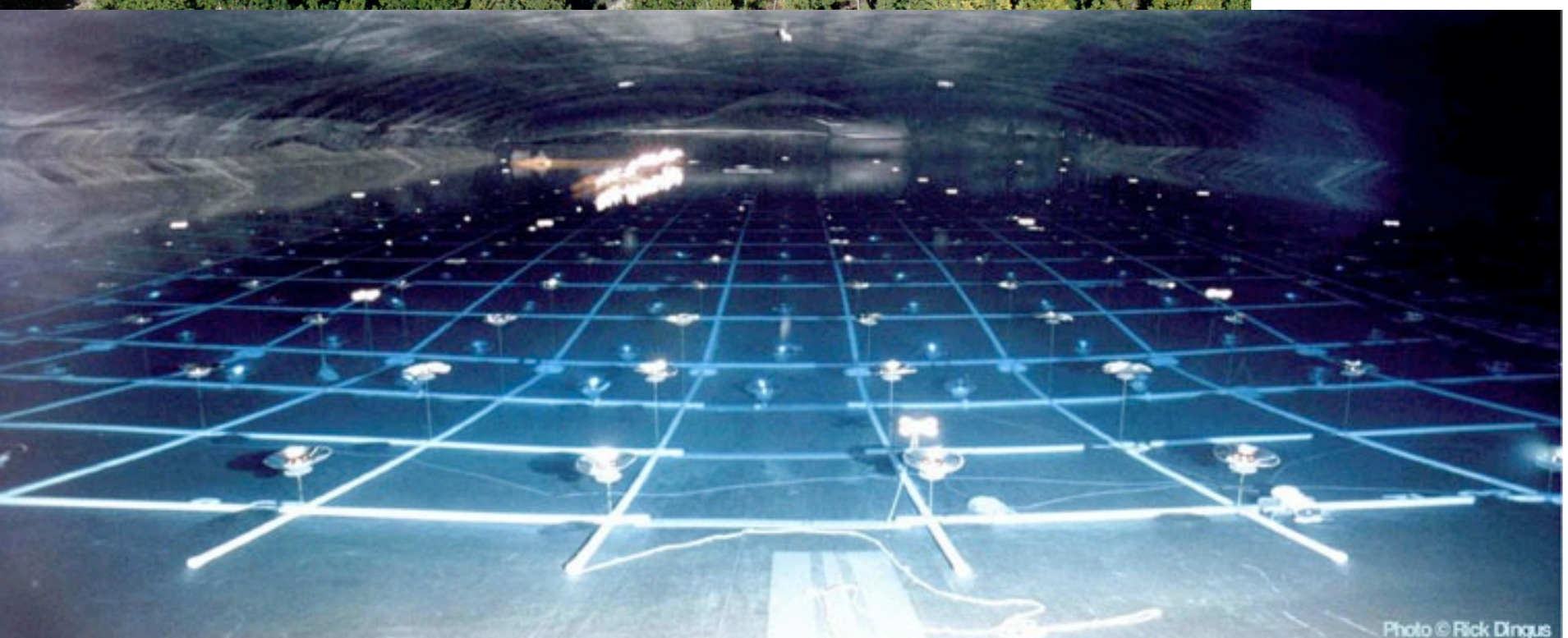
2650 m.a.s.l.

New Mexico

80 m x 60 m water pond
8 m deep.

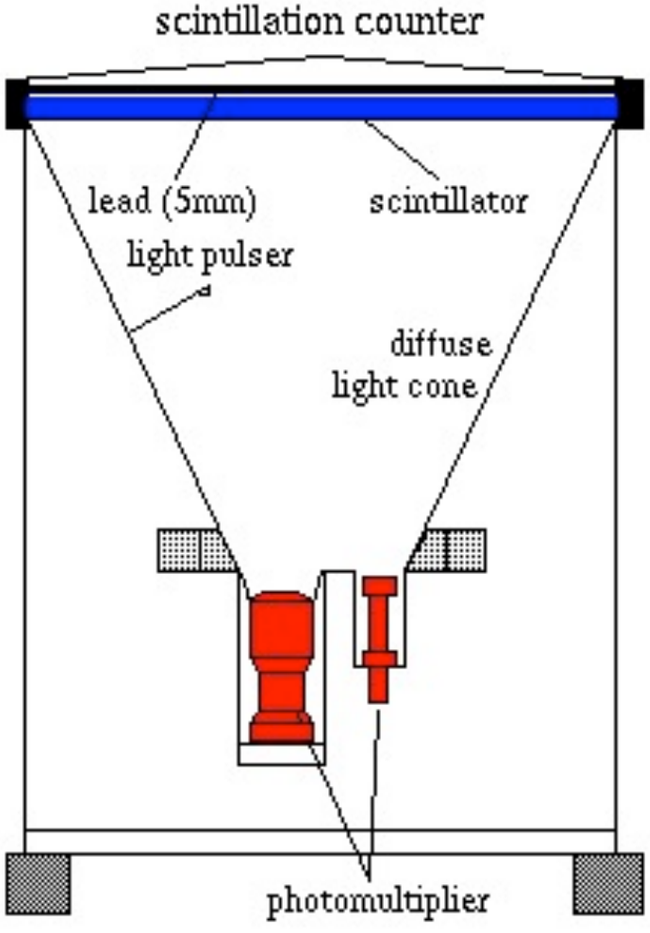
Detect shower particles via Cherenkov light in water

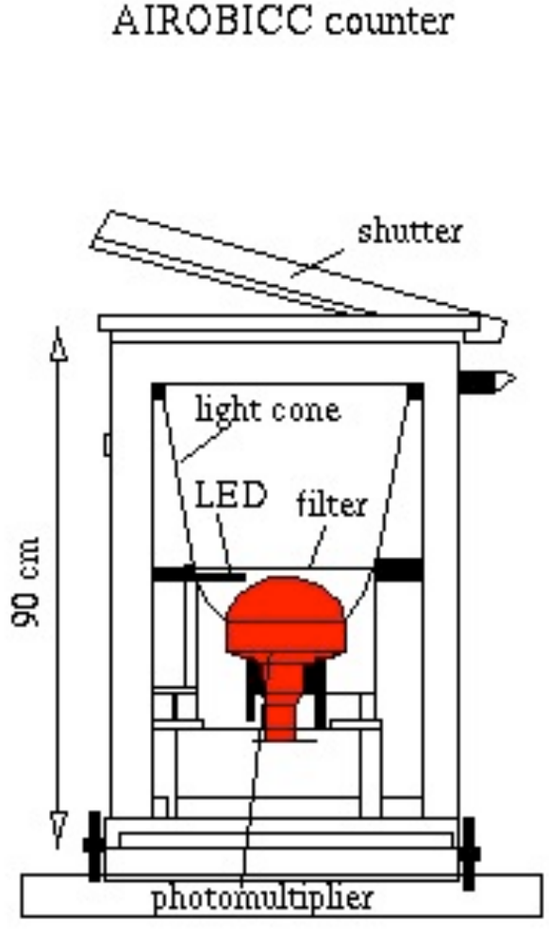
PMTs in 2 layers for el.mag. and muons.



look for excess: gamma sources

2π sky view





Hegra, Airobicc
La Palma

scintillator array

Muon detectors

Cherenkov counter

poor γ- hadron separation

via muon content or particle pattern at ground

γ sources detected by excess counts
from one direction

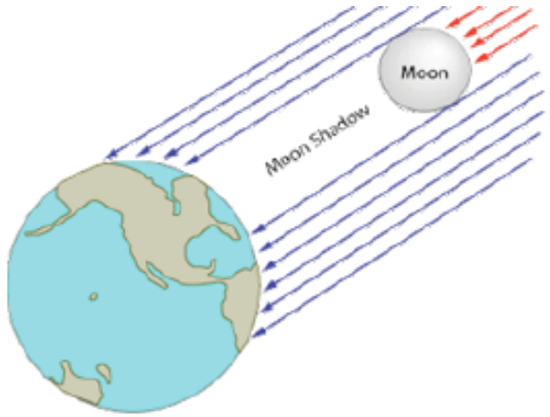
sources: Moon, Sun shadow

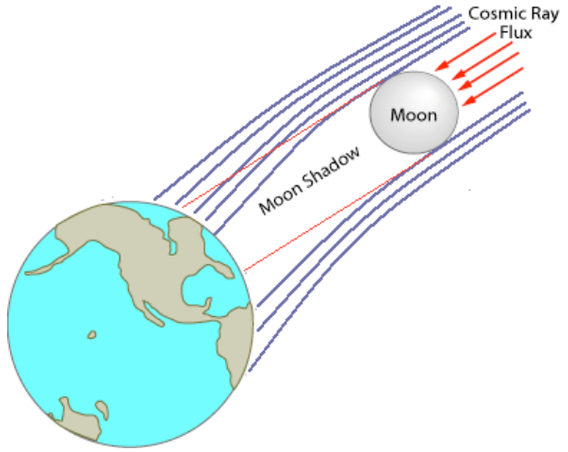
Crab nebula

few strong γ sources

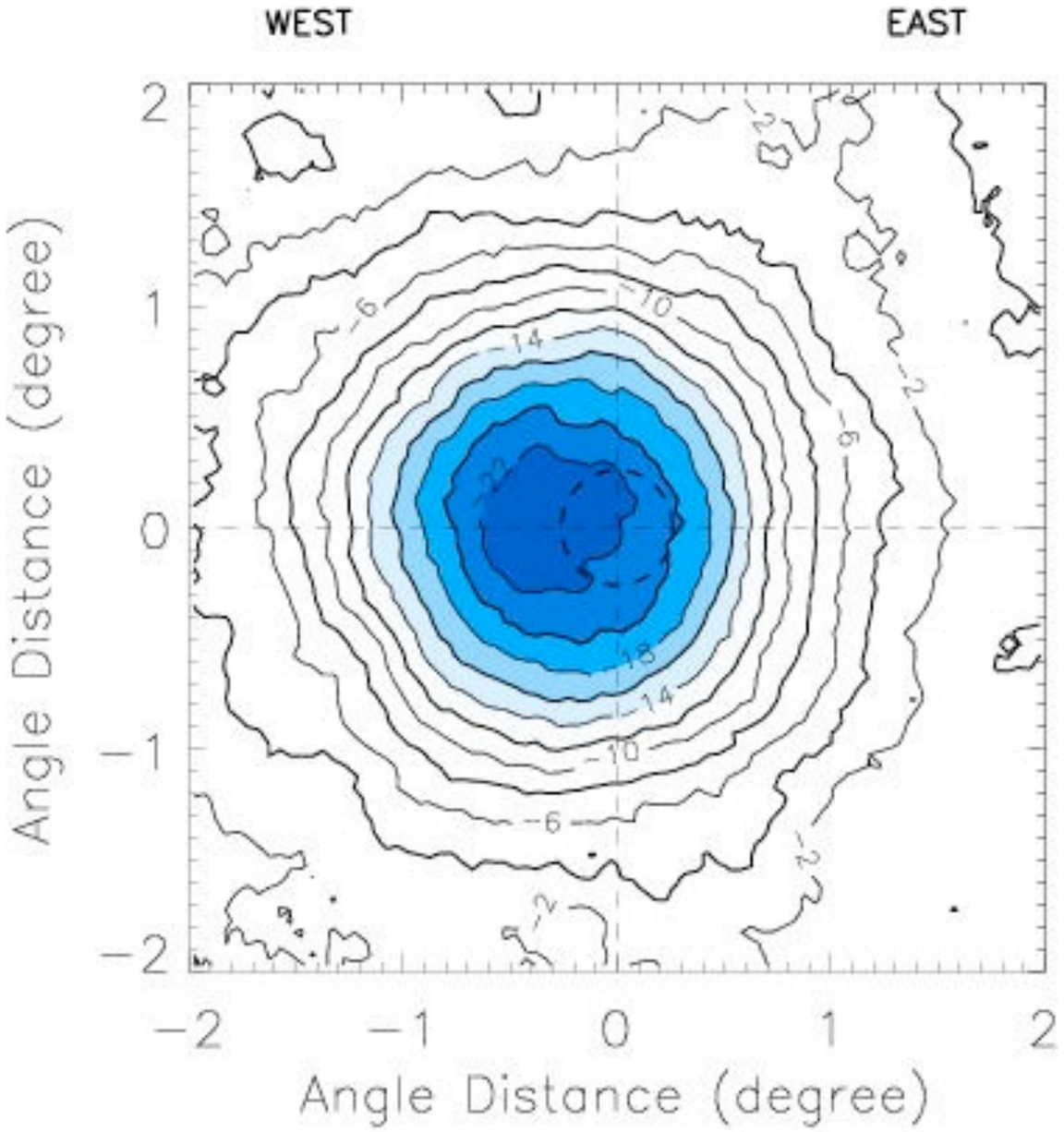
Moon Shadow ... calibration of direction reconstruction

$E \approx TeV$

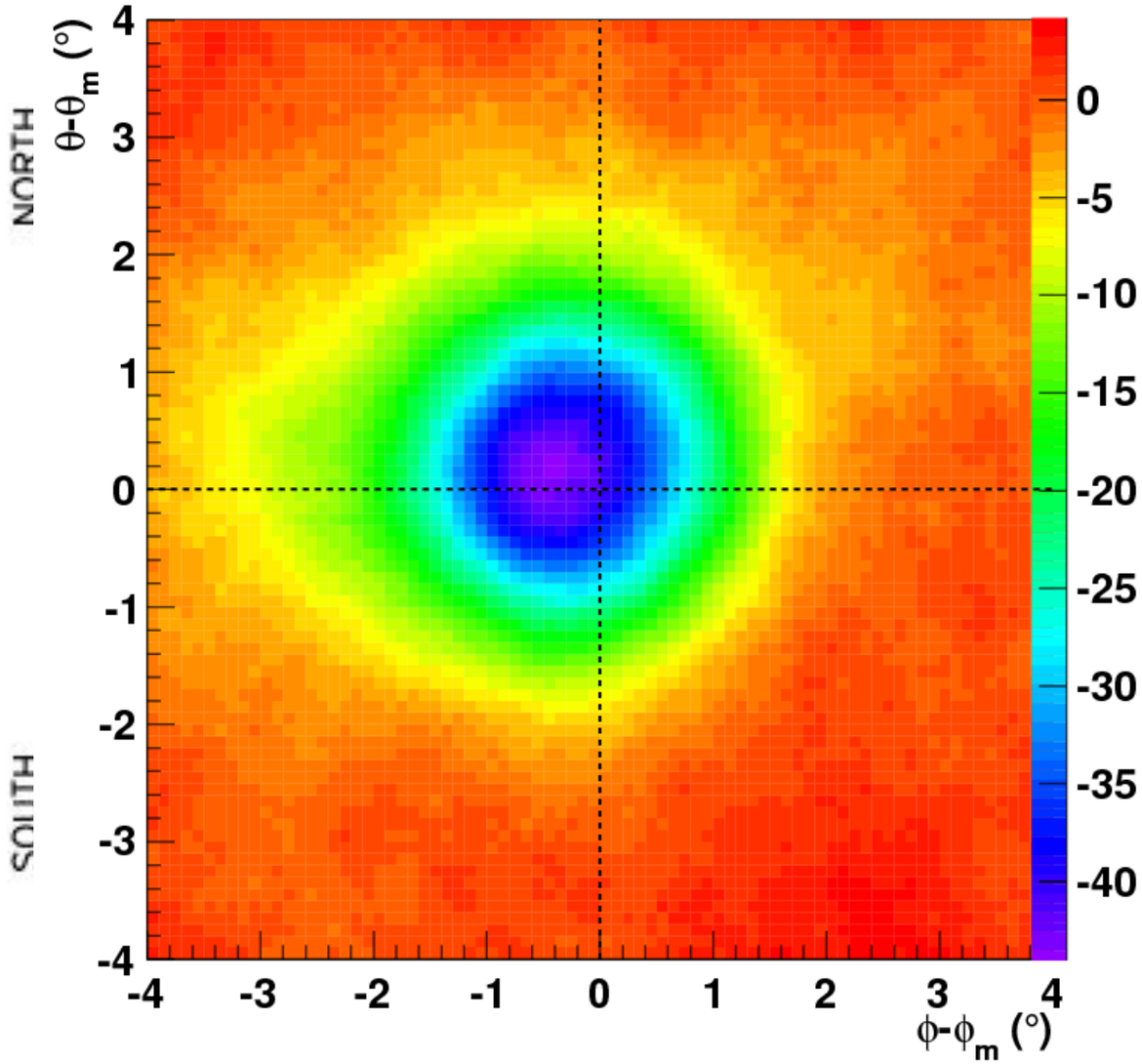




Tibet ASγ

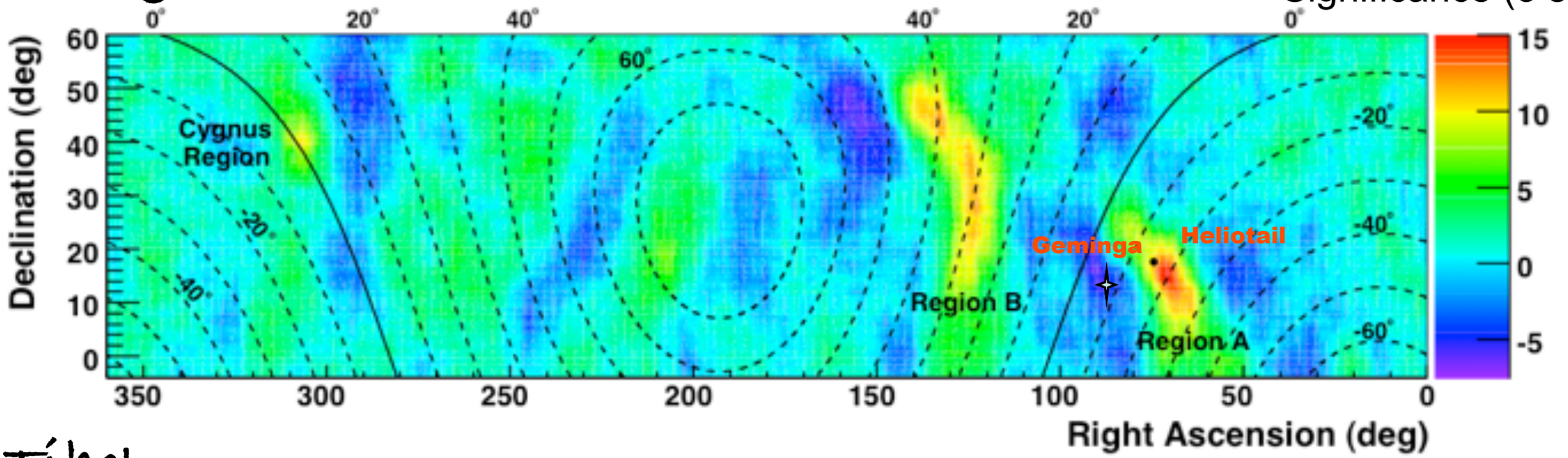


Argo

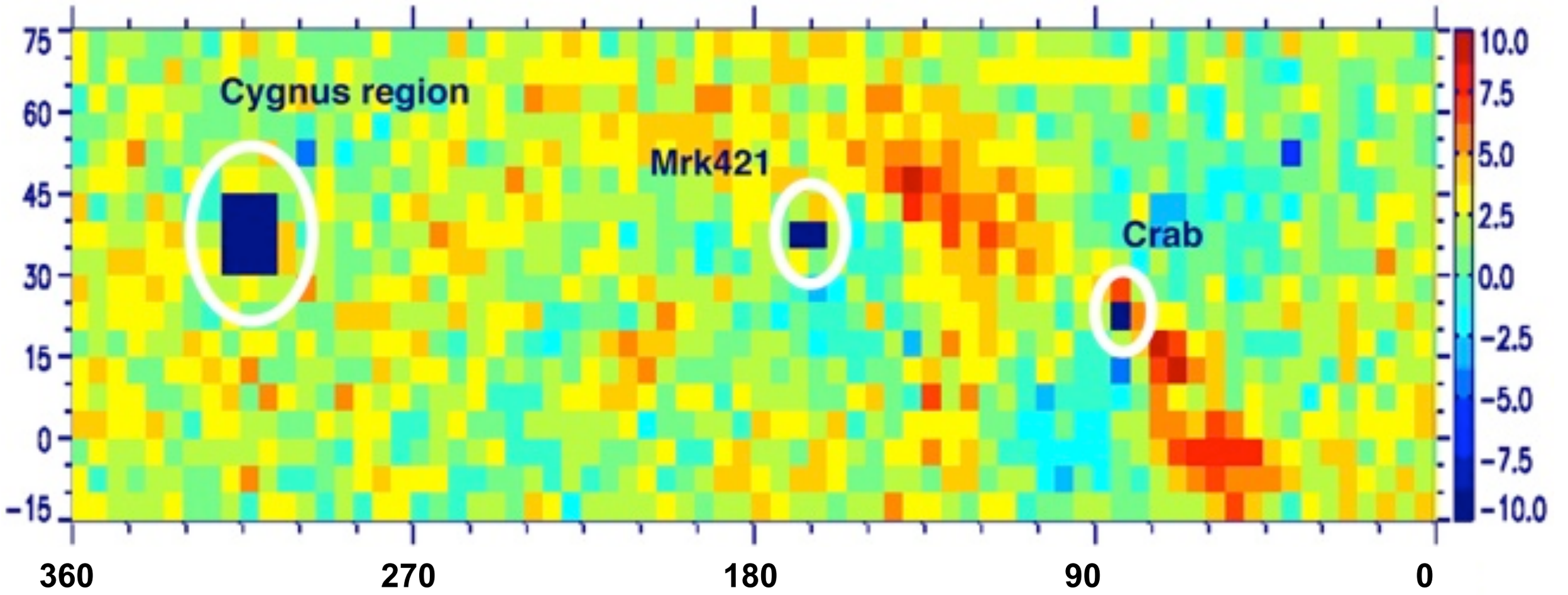


Milagro

15.0 σ and 12.7 σ fractional excess: ≈ 5×10^{-4}

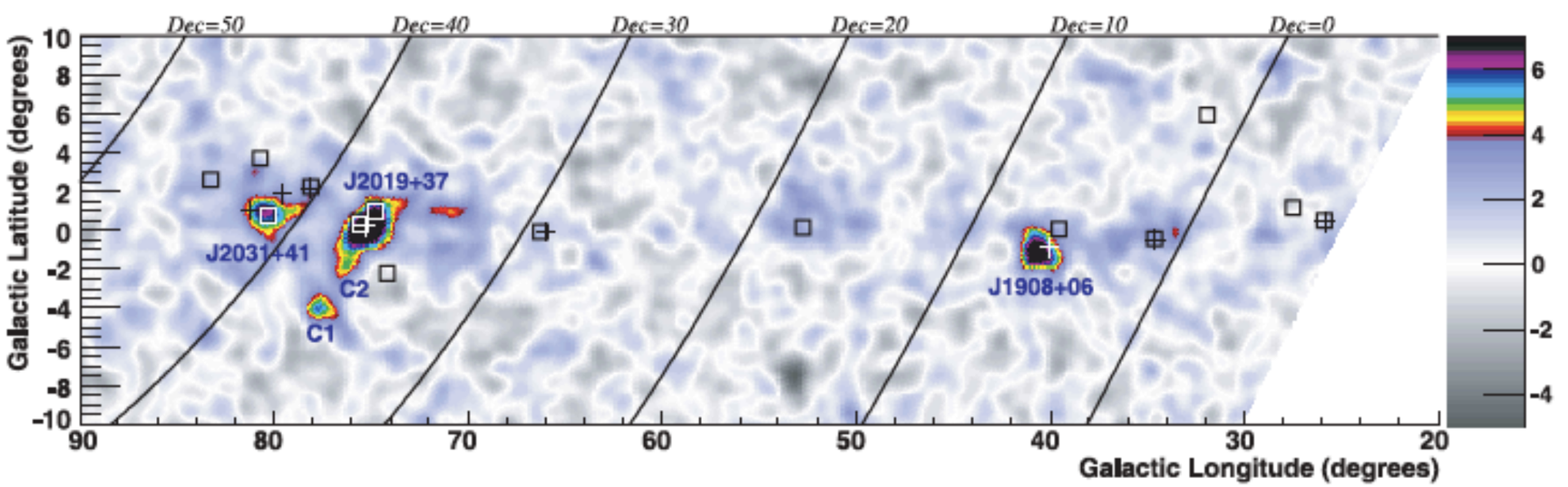


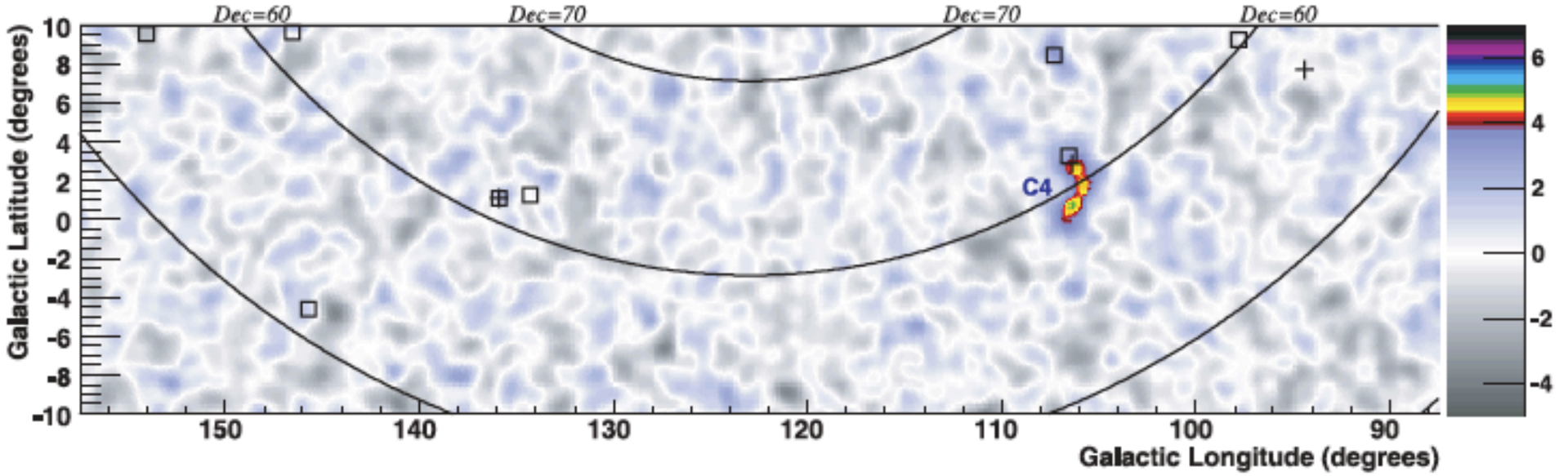
Tibet

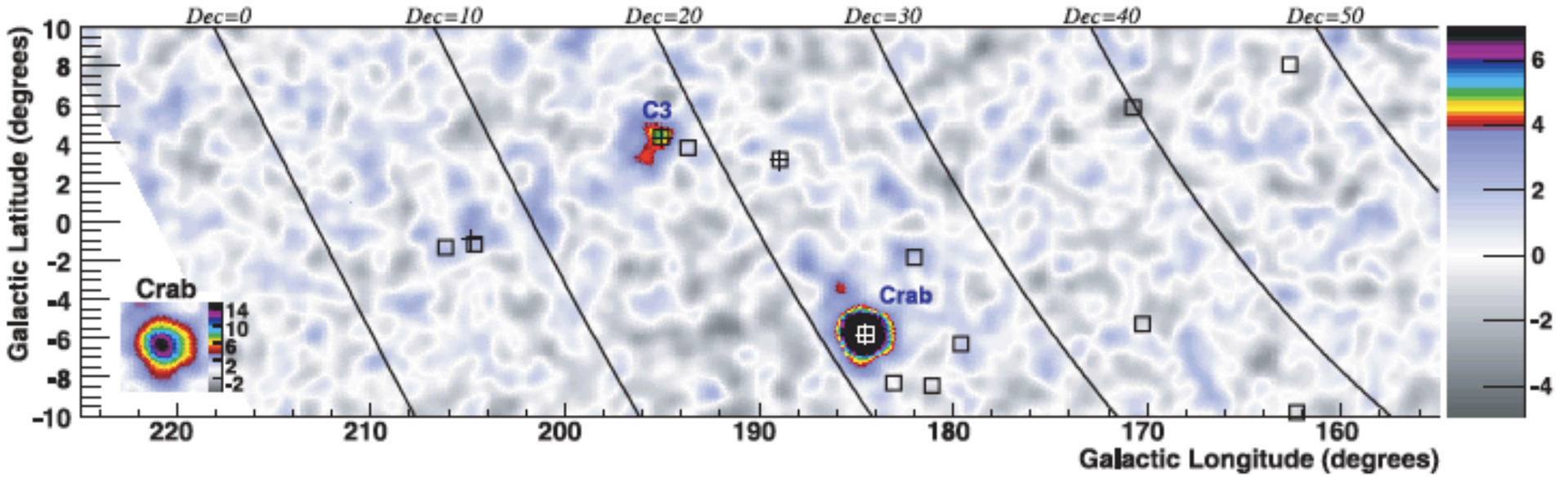


MILAGRO gal. plane

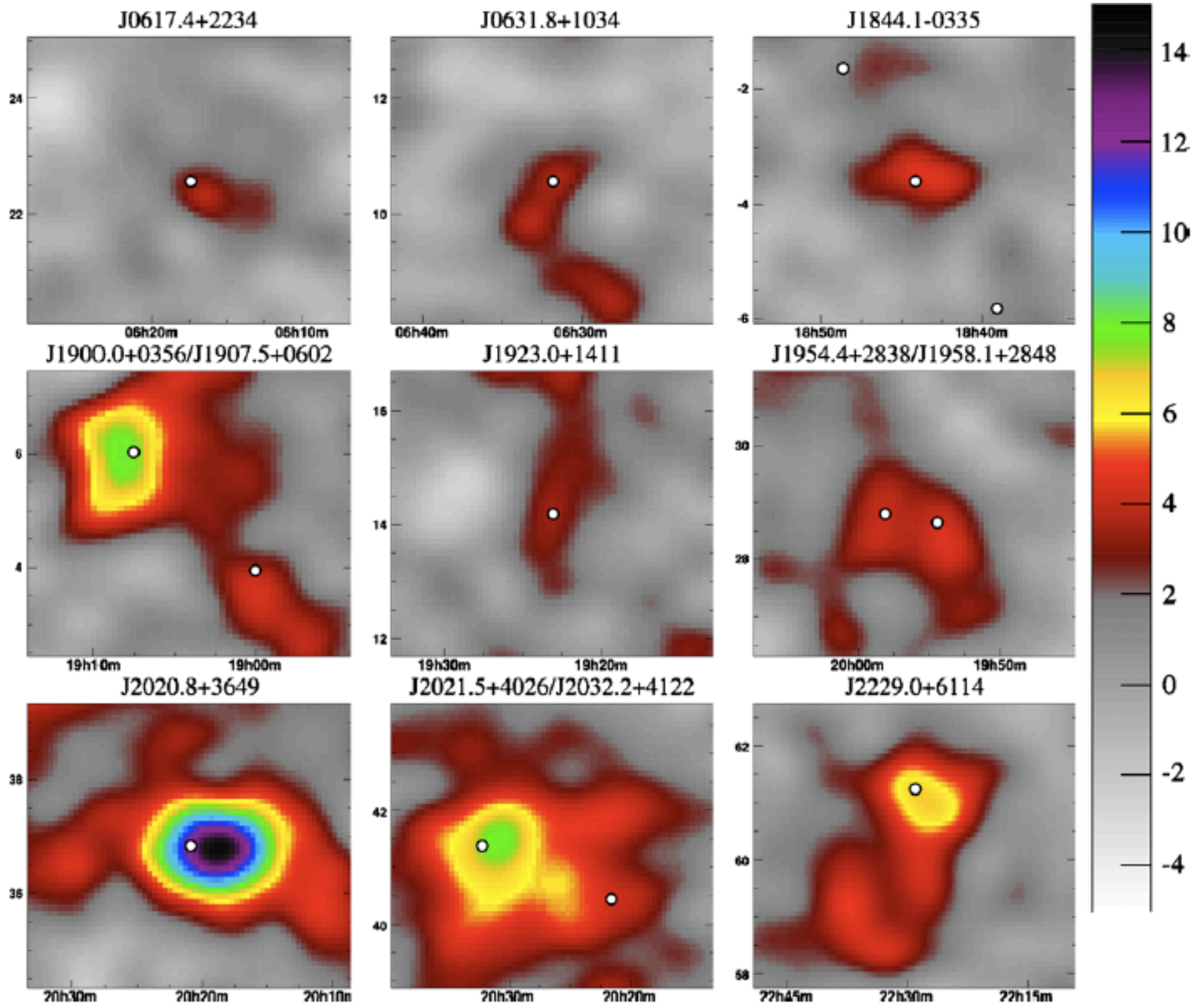
- EGRET sources







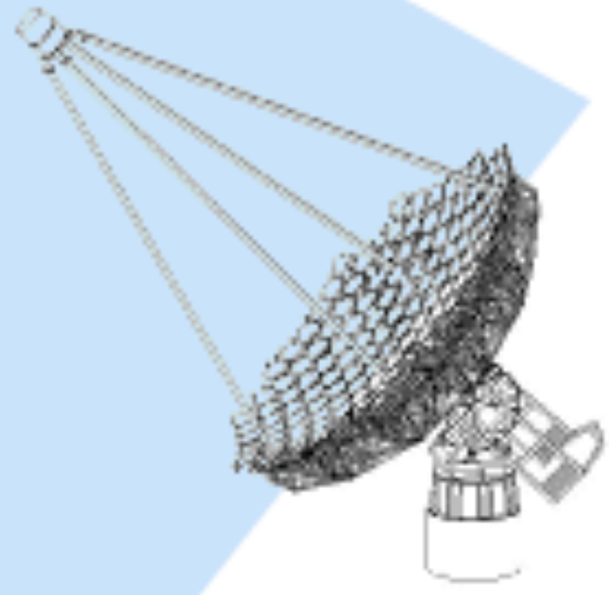
MILAGRO
Fermi srcs.



Cherenkov Telescopes

primary produces shower of secondaries
secondaries produce Cherenkov light

very forward emission, little absorption,
view all parts of shower
only in dark nights (10%)

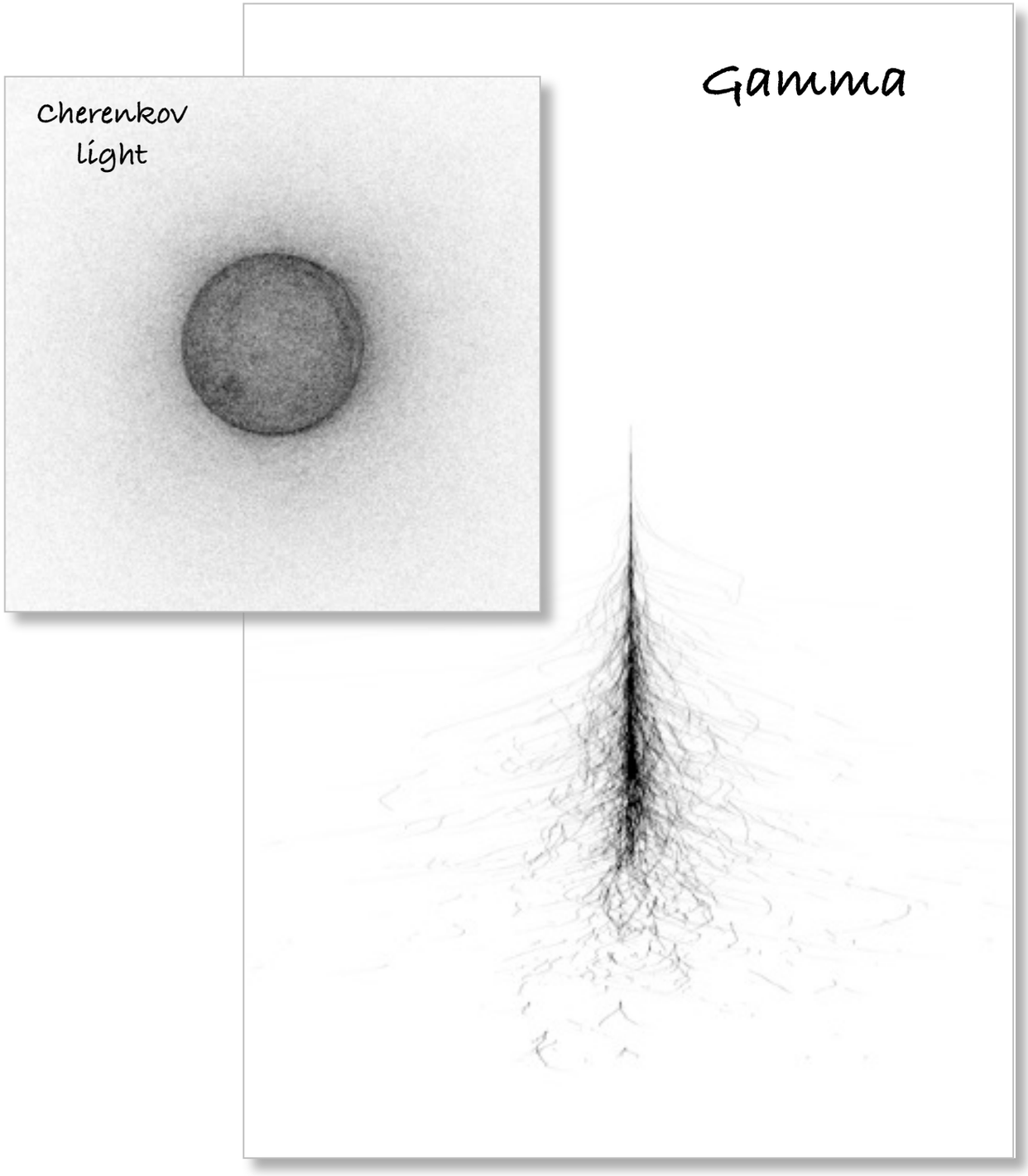


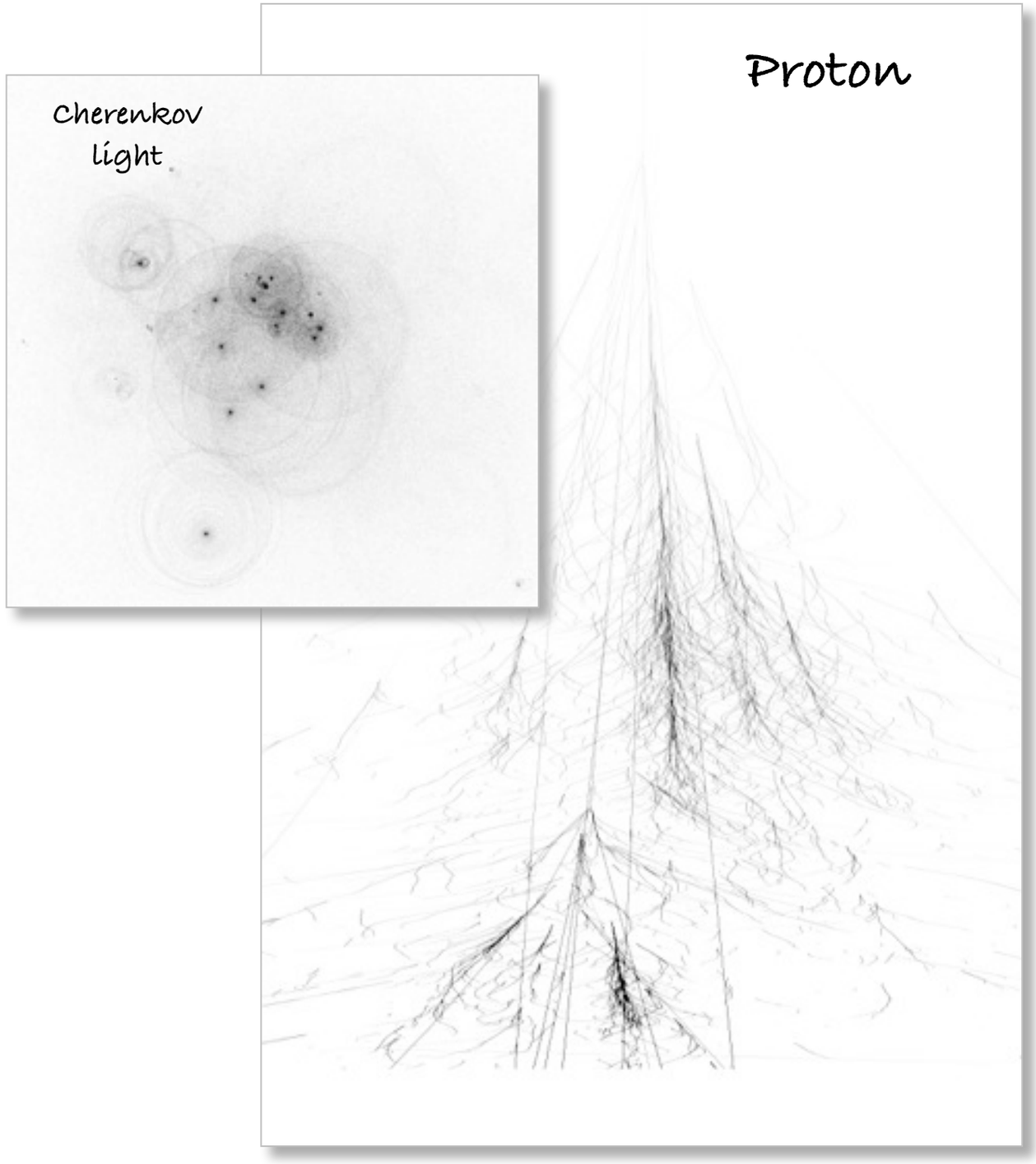
10 m Whipple Telescope

1989: Detection of the Crab Nebula

5σ signal in 50 h,
with 159 pixel camera
and
Hillas image analysis.

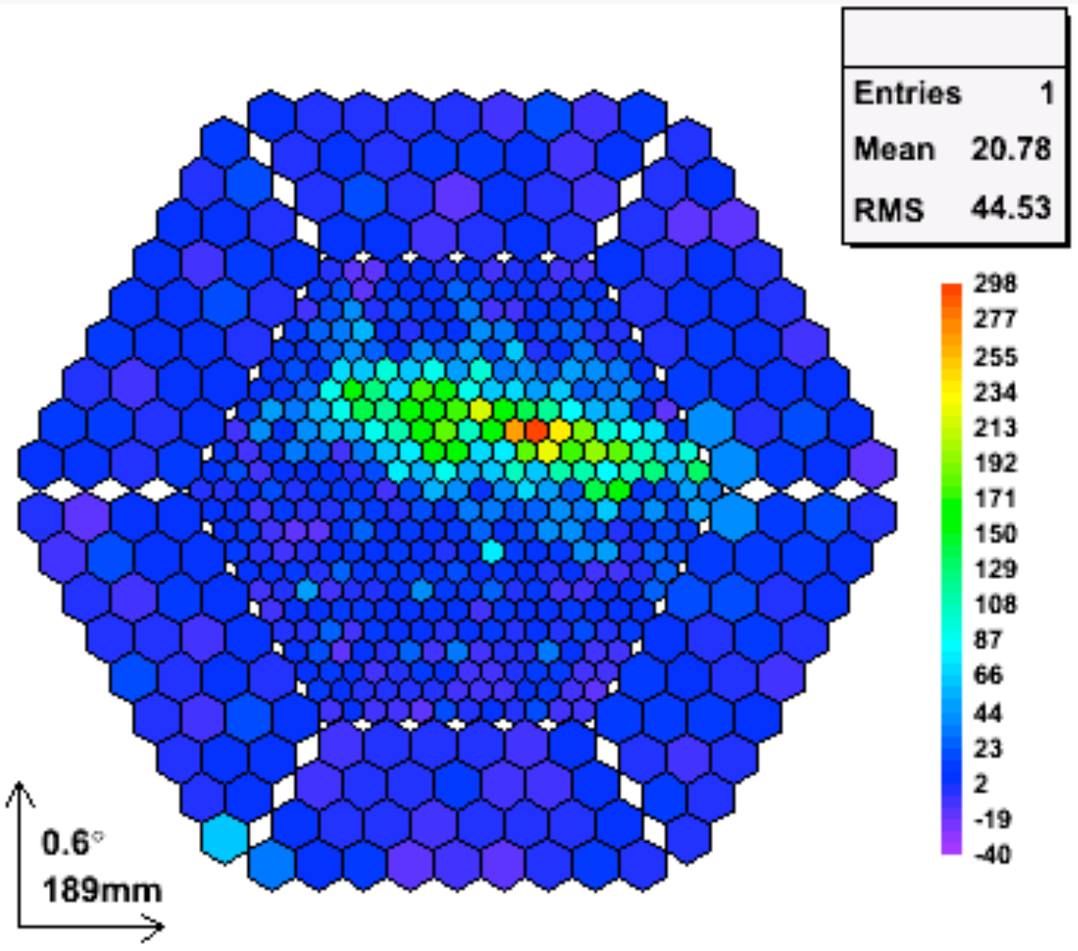
γ rays and Cosmic Ray background

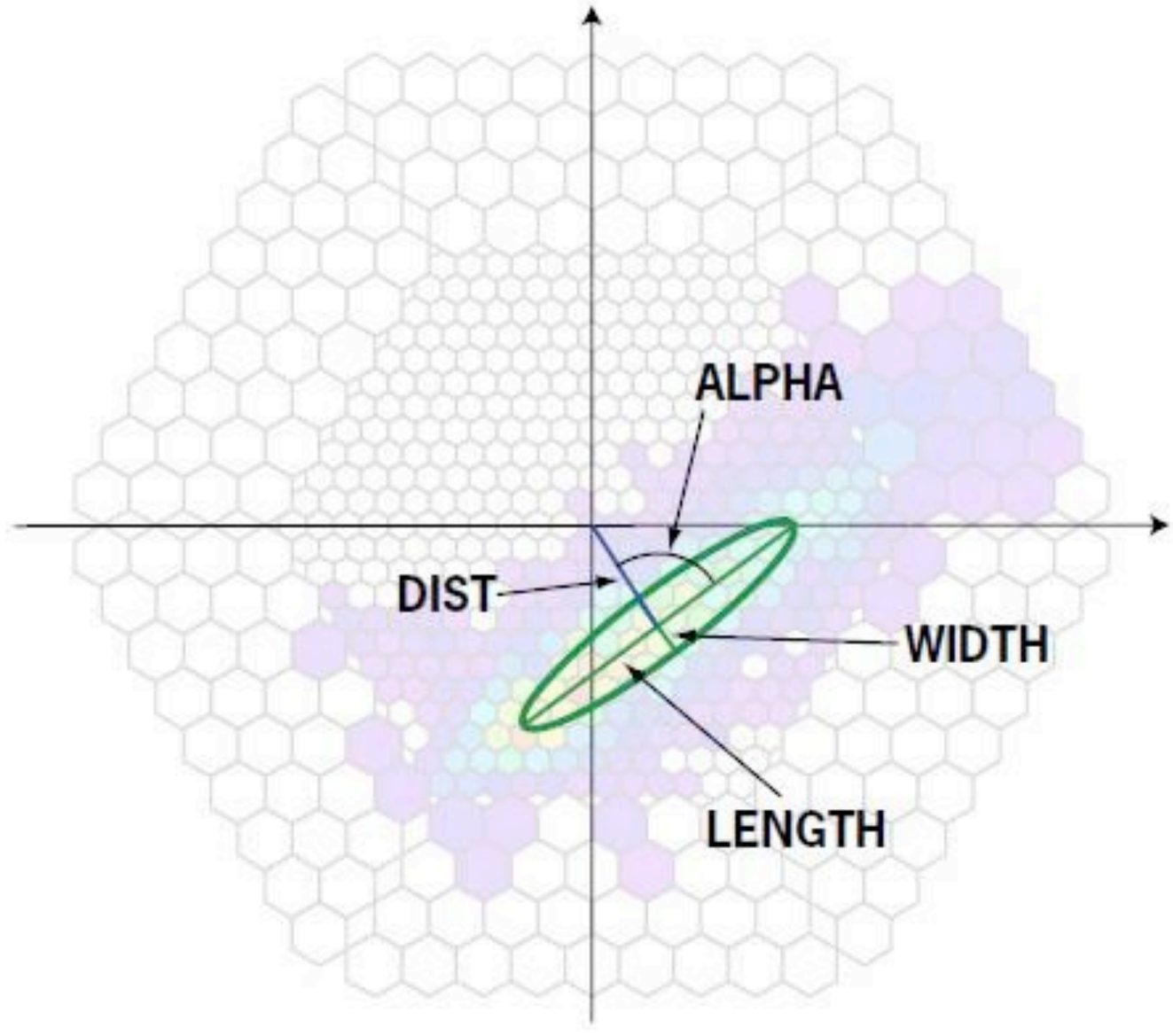




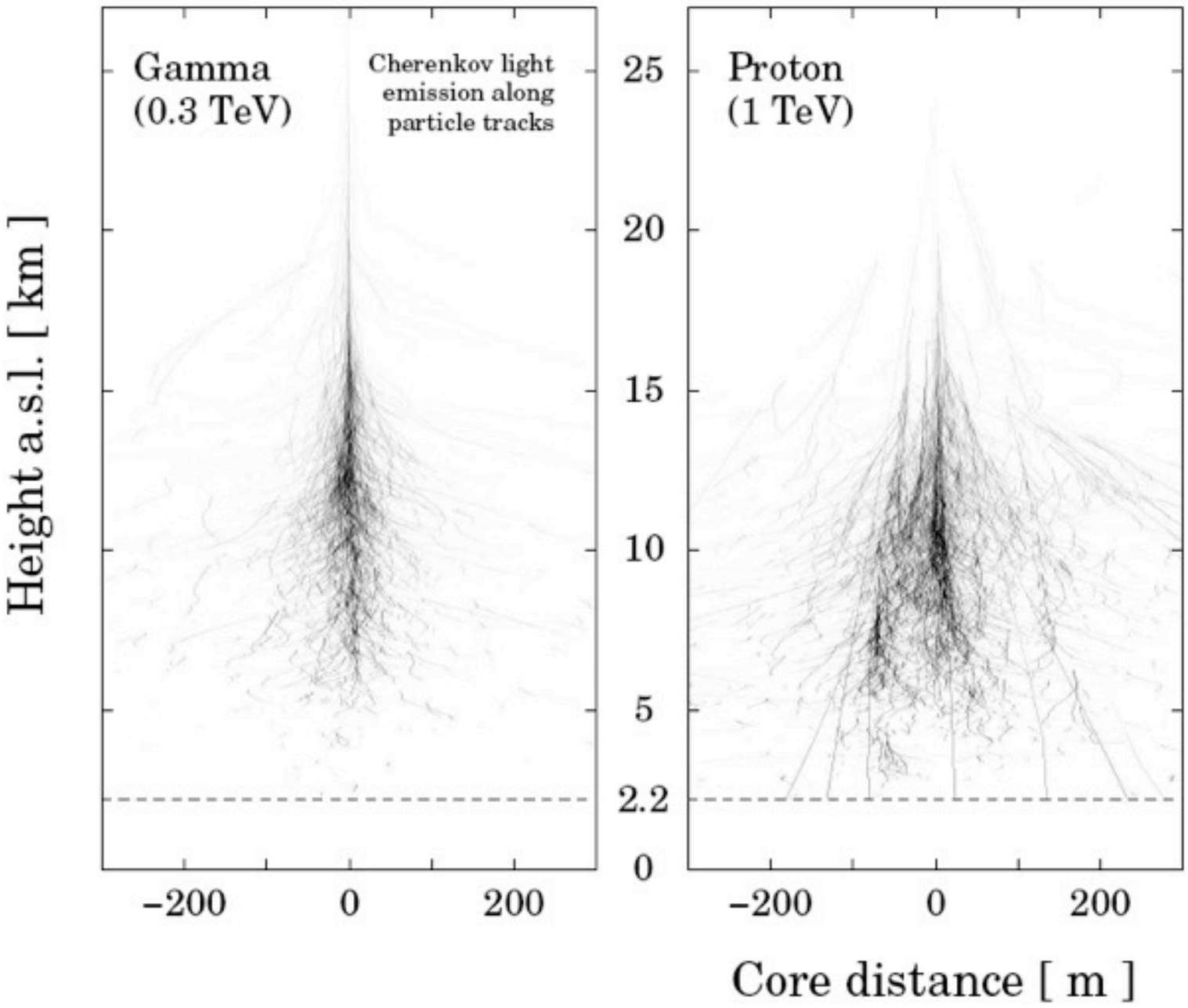
1 : $>10^4$

MAGIC Camera





Hillas image analysis



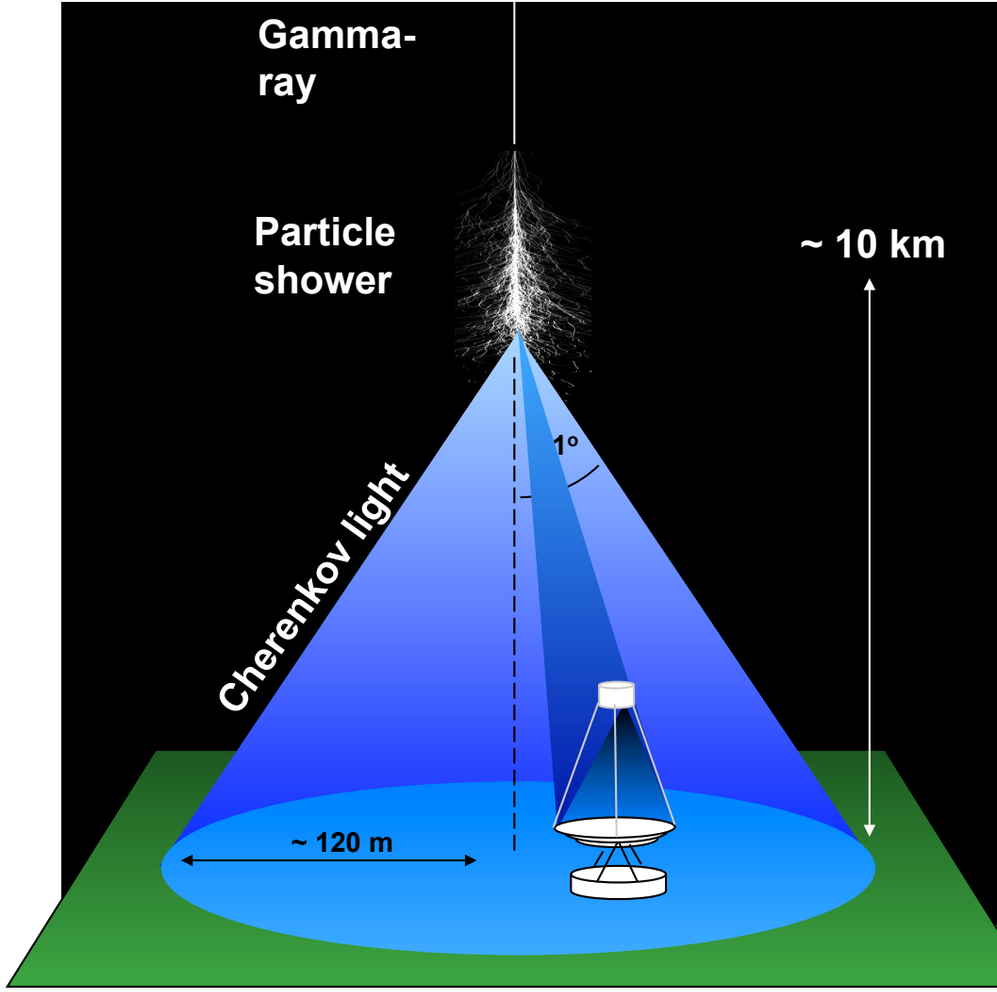


Image the shower,

distinguish protons and photons from the shape of their images.

.... very successful technique

also possible to identify e^- and Fe

Gamma-ray

Particle shower

Cherenkov light

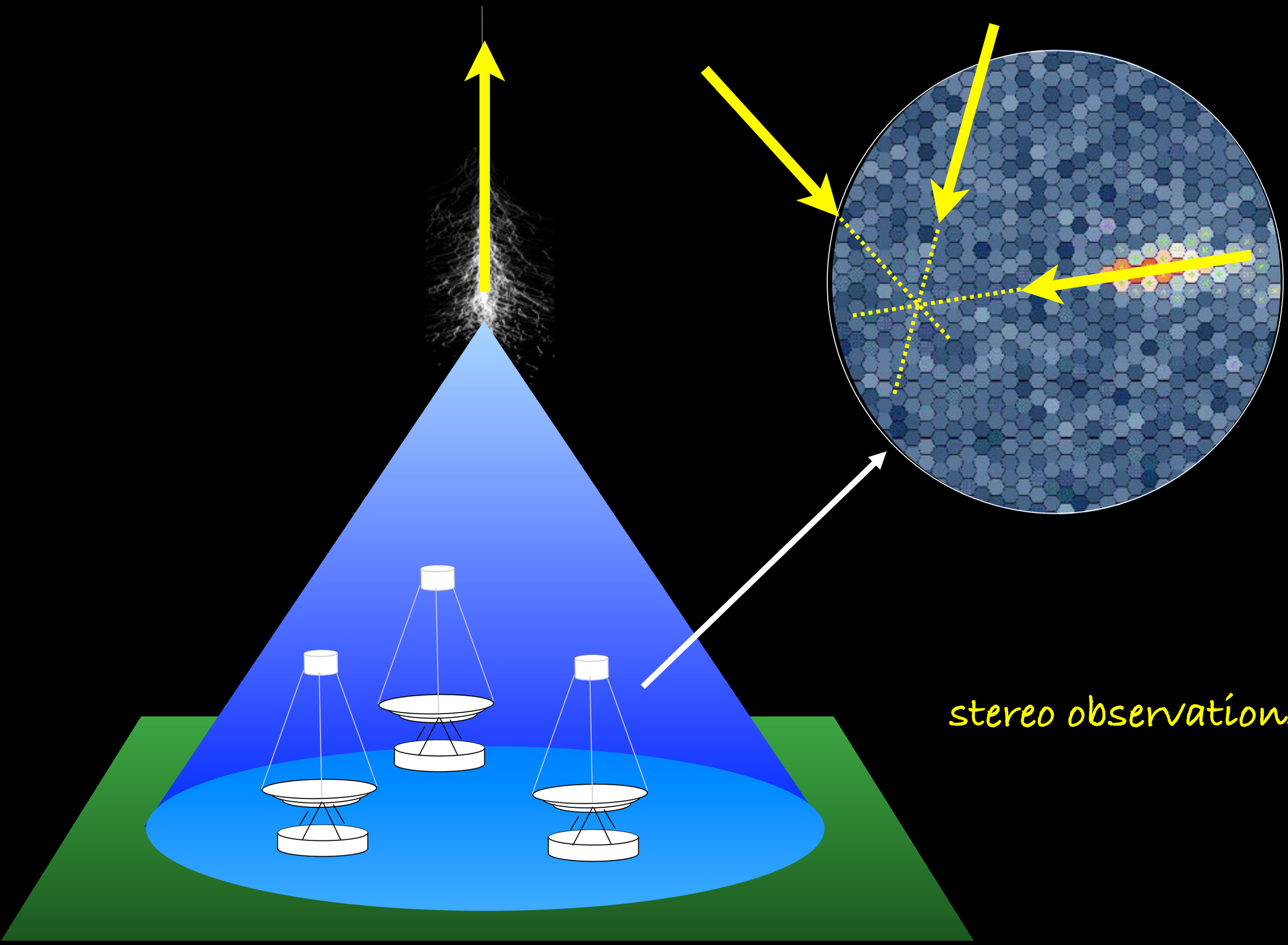
1°

~ 10 km

~ 120 m

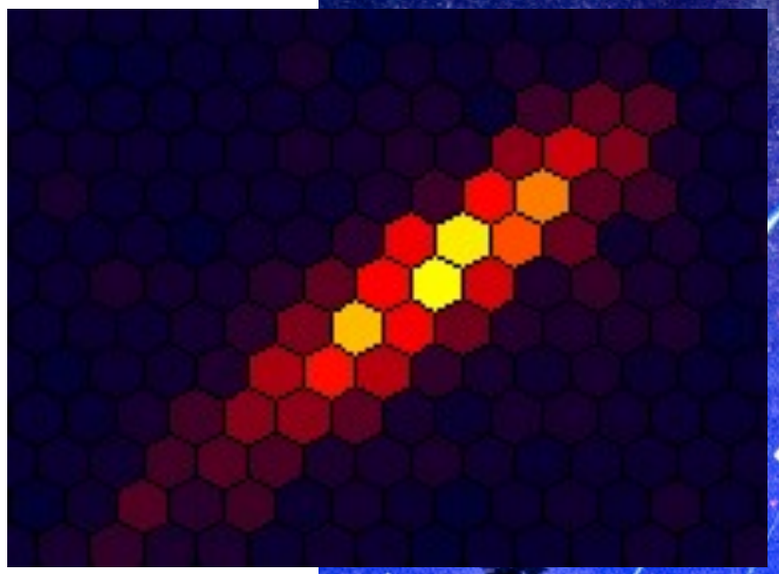
Detection of TeV γ rays with Cherenkov telescopes

huge detection area $\approx 10^5$ m^2



stereo observations

Air showers look like meteors

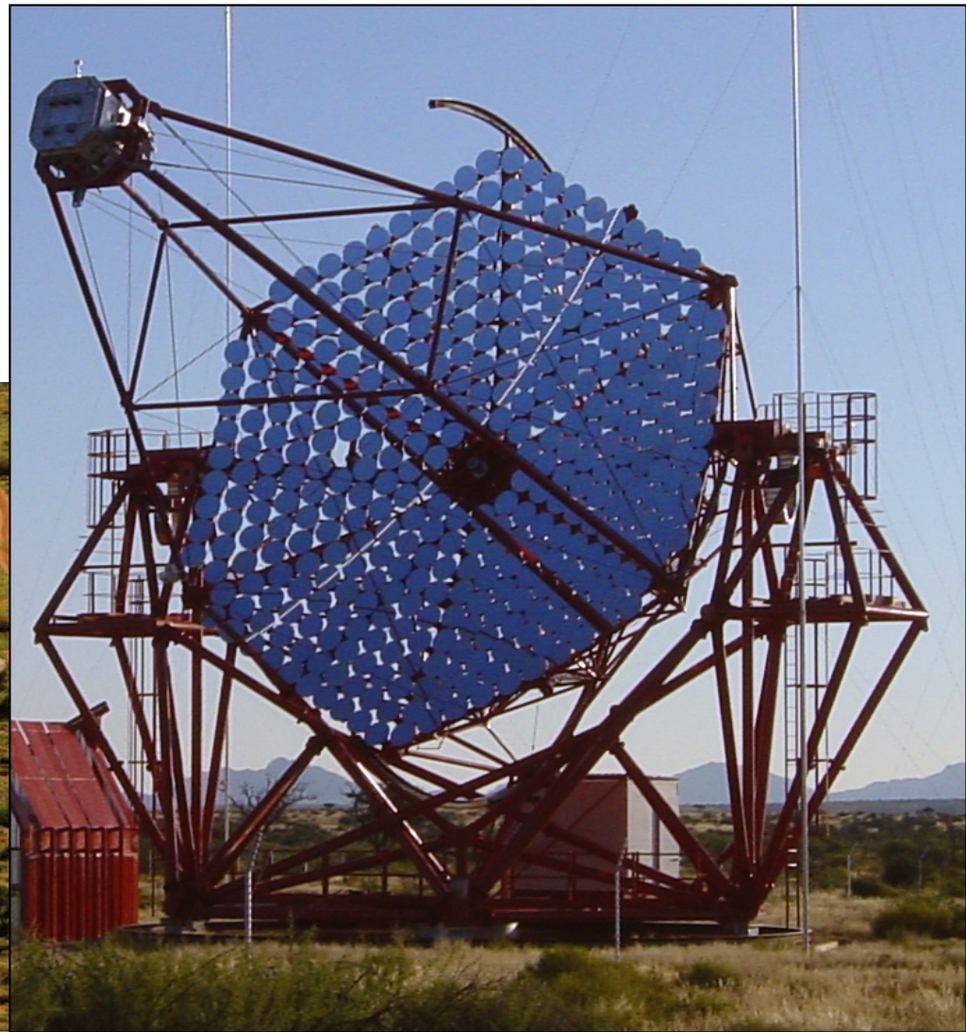


Imaging Cherenkov Telescopes

TeV gamma ray astronomy (100 GeV - 50 TeV)
requires good knowledge of atmospheric conditions

Imaging Atmospheric Cherenkov Telescopes:

e.g. HESS, MAGIC, VERITAS,



HESS, Namibia
detects Crab
in 30 seconds
1% Crab in 25 h
4 x 12m telescopes
5° FOV, 0.16°
960 pixels

Current IACTs

VERITAS

Whipple

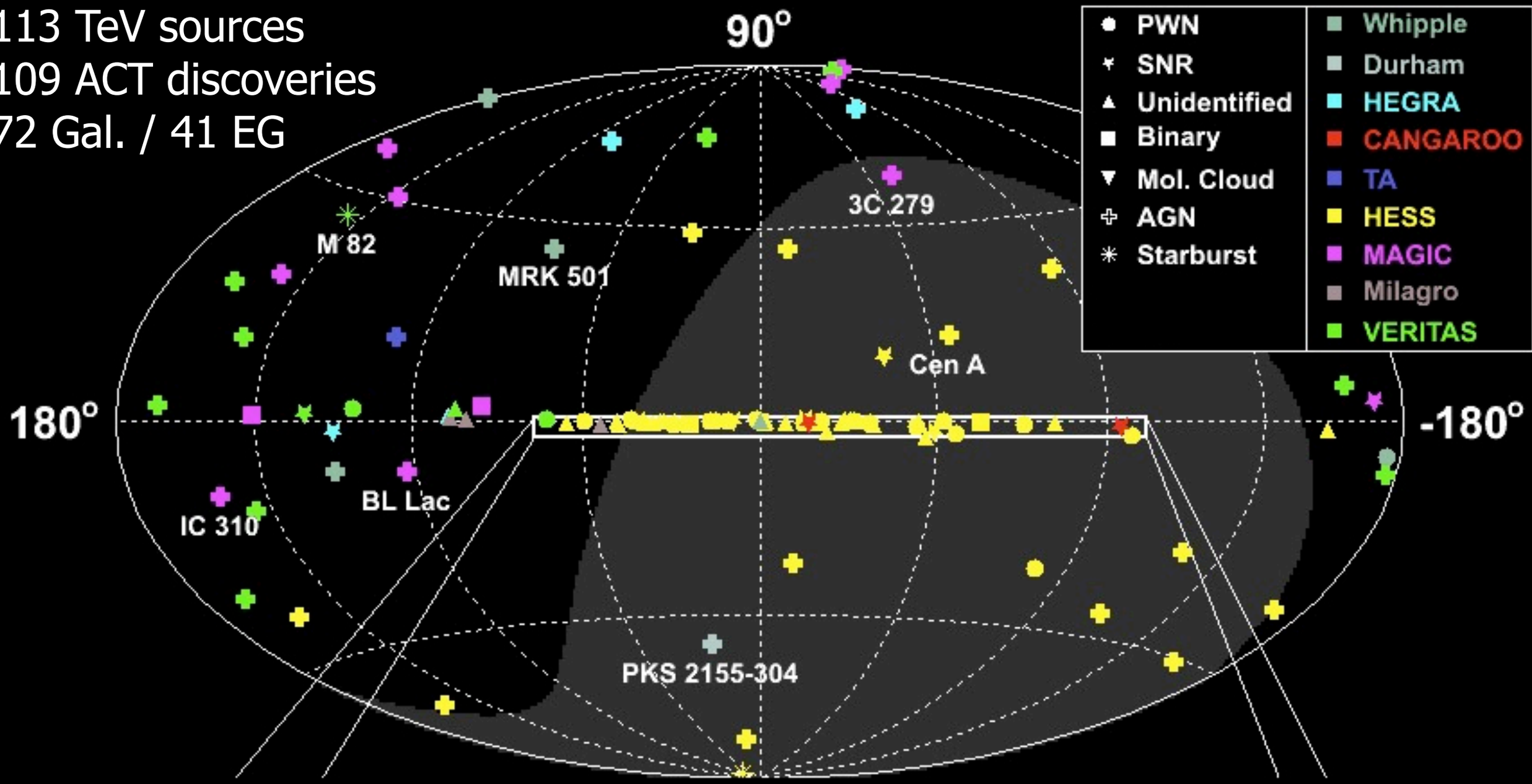
MAGIC

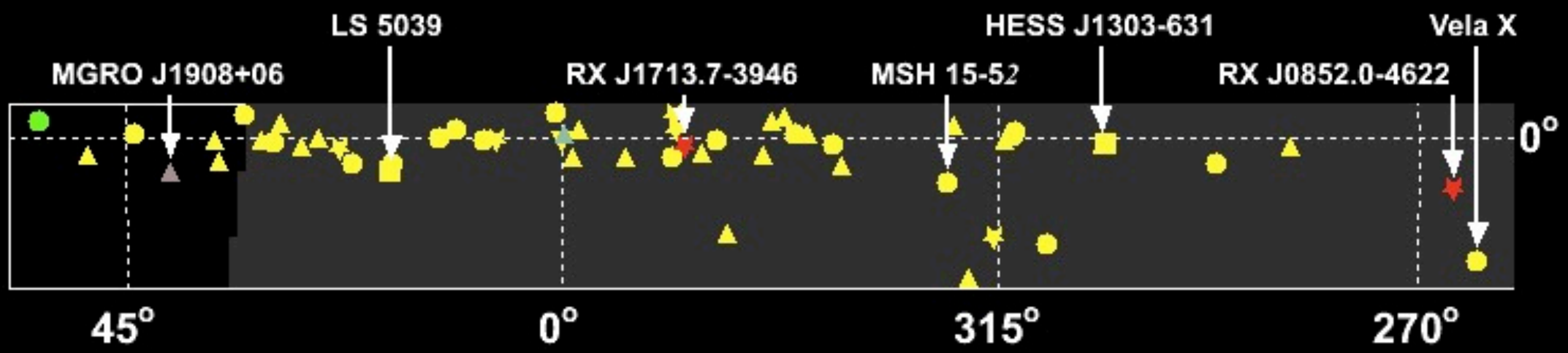
TACTIC

HESS

CANGAROO-III

2010:
113 TeV sources
109 ACT discoveries
72 Gal. / 41 EG





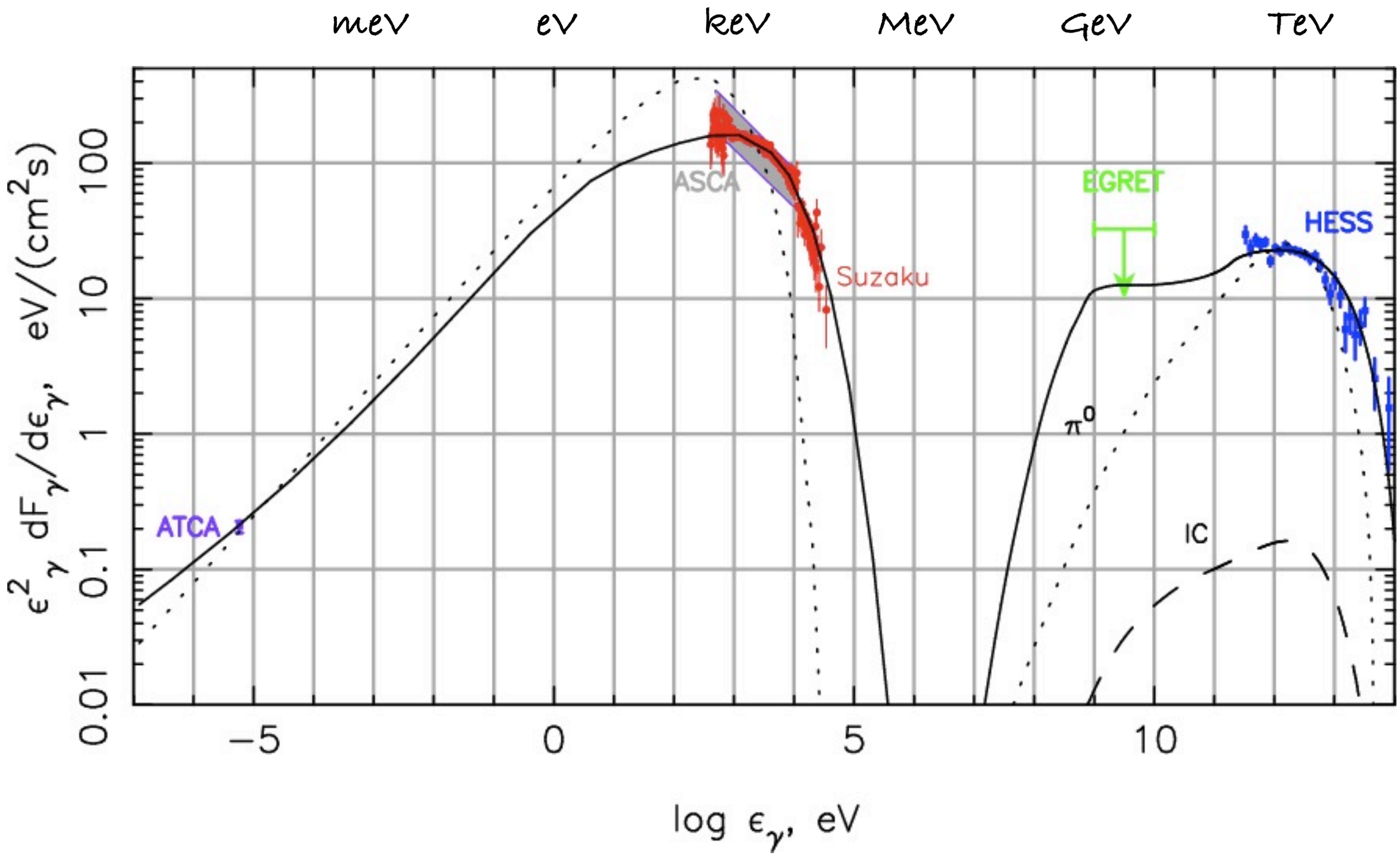
TeV Astronomy Highlights

Supernova remnants:	Nature 432 (2004) 75
Microquasars:	Science 309 (2005) 746
	Science 312 (2006) 1771
Pulsars:	Science 322 (2008) 1221
Galactic Centre:	Nature 439 (2006) 695
Galactic Survey:	Science 307 (2005) 1839
Starbursts:	Nature 462 (2009) 770
	Science 326 (2009) 1080
Active Galactic Nuclei:	Science 314 (2006) 1424
	Science 325 (2009) 444
EBL:	Nature 440 (2006) 1018
	Science 320 (2008) 752
Dark Matter:	Phys Rev Letters 96 (2006) 221102
Lorentz Invariance:	Phys Rev Letters 101 (2008) 170402
Cosmic Ray Electrons:	Phys Rev Letters (2009)

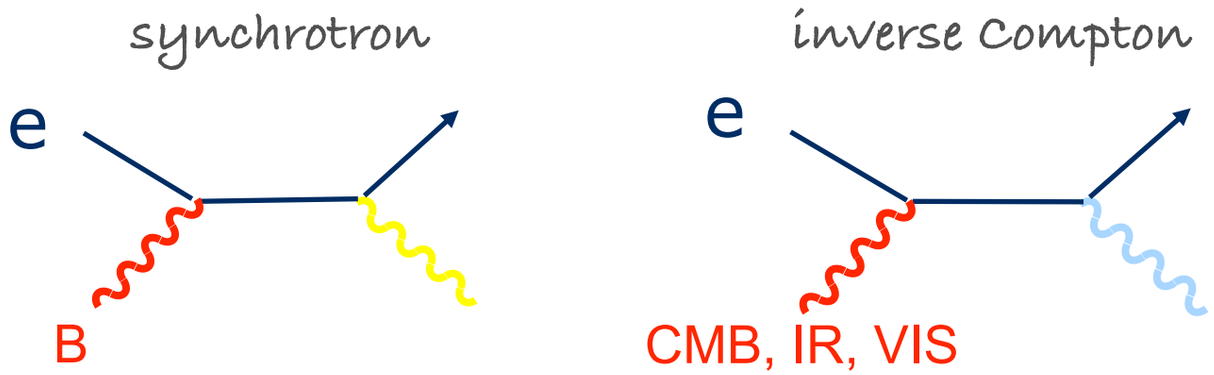
Results from HESS, MAGIC and VERITAS

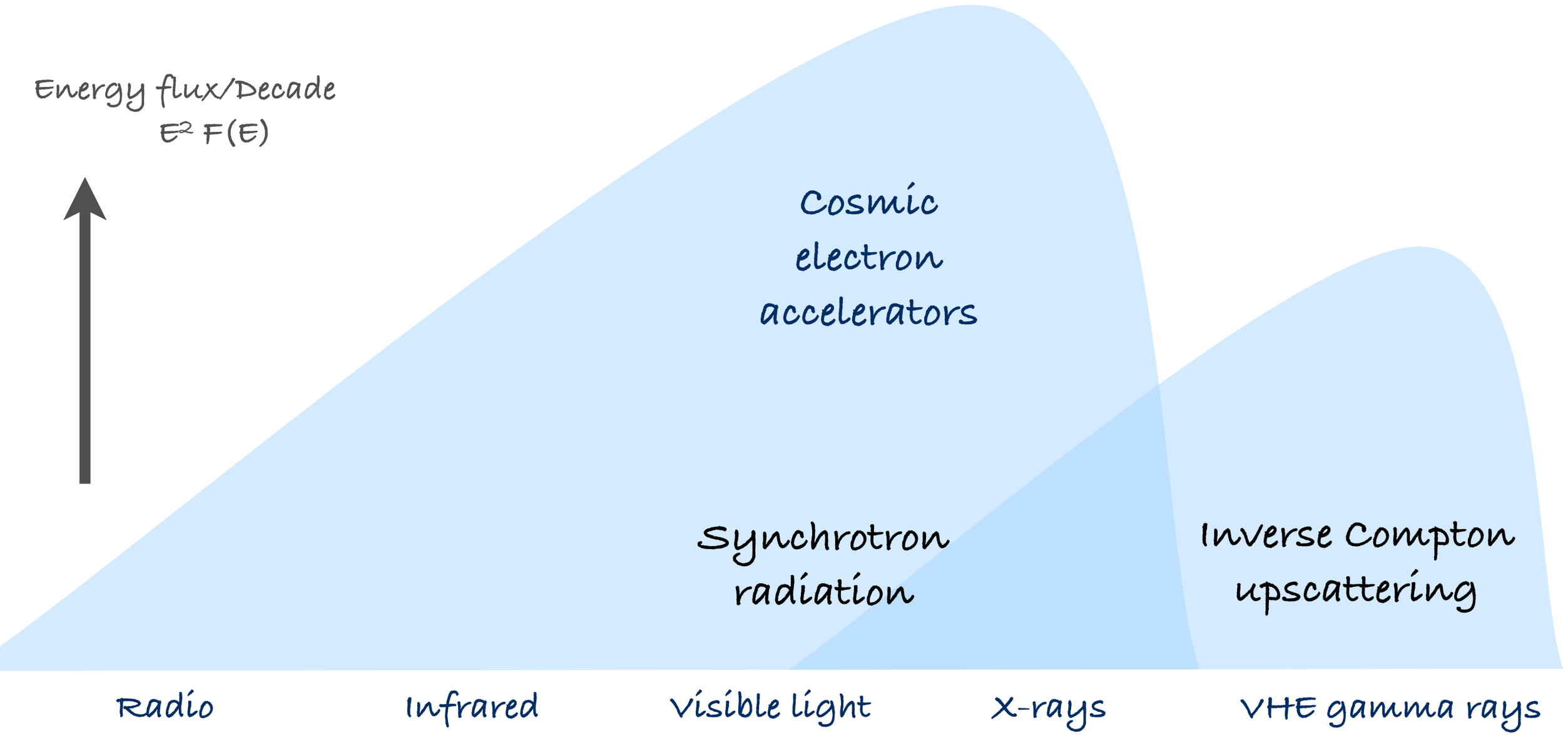
Descartes Prize for HESS

Supernova Remnant RX J1713.7-3946



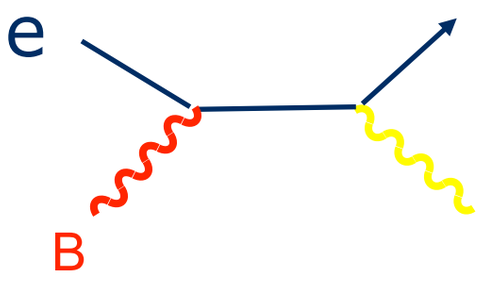
From particles to radiation



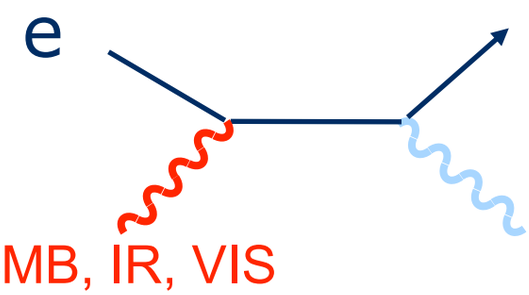


From particles to radiation

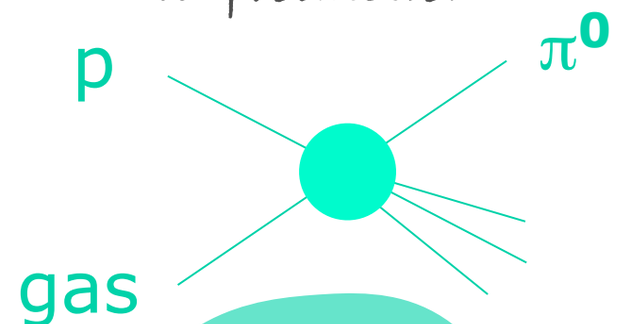
synchrotron



inverse Compton



π^o production



Energy flux/Decade
$E^2 F(E)$

Cosmic electron accelerators

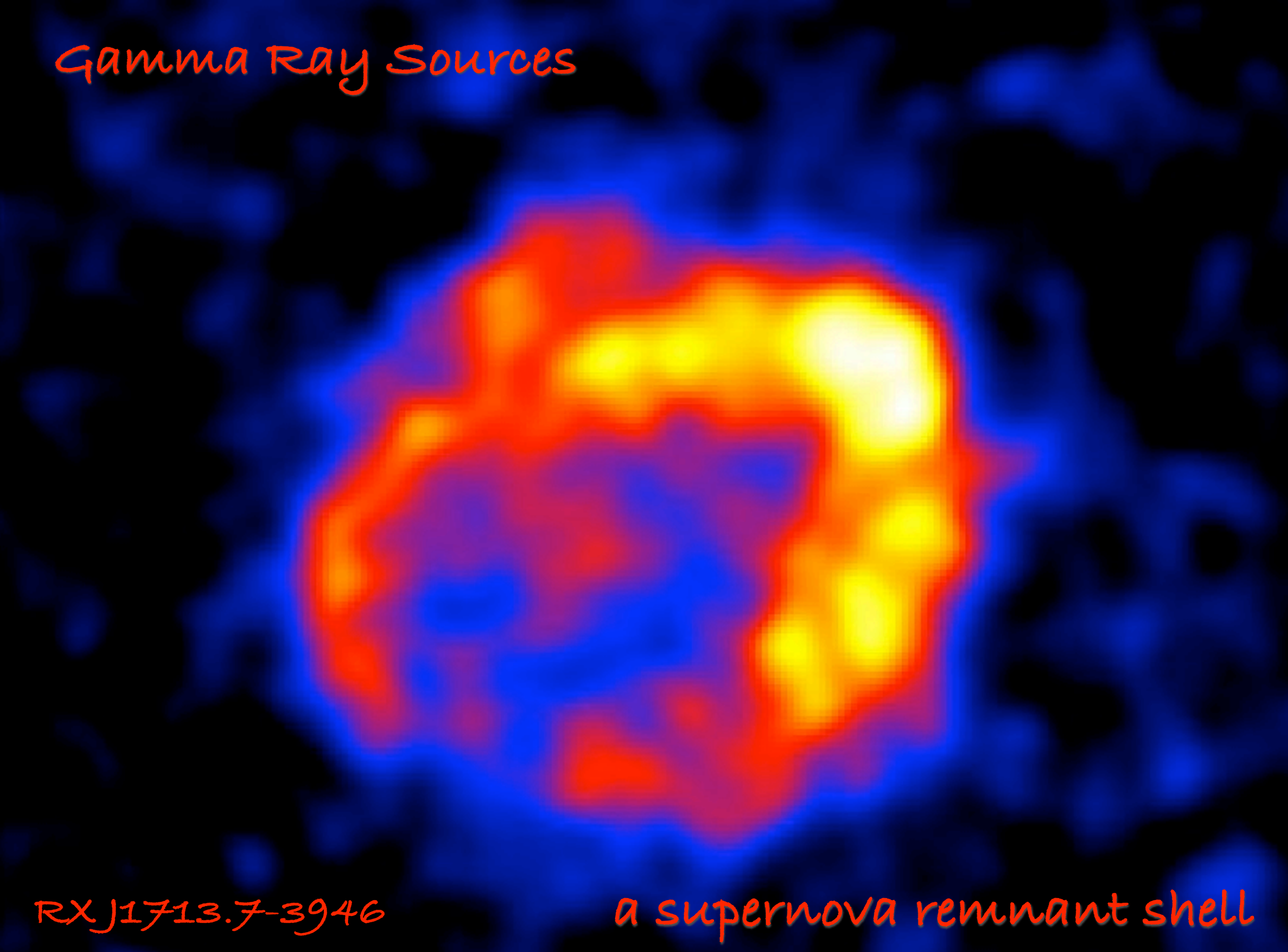
Synchrotron radiation

Cosmic proton accelerators

Inverse Compton upscattering

Radio | Infrared | Visible light | X-rays | VHE gamma rays

Gamma Ray Sources

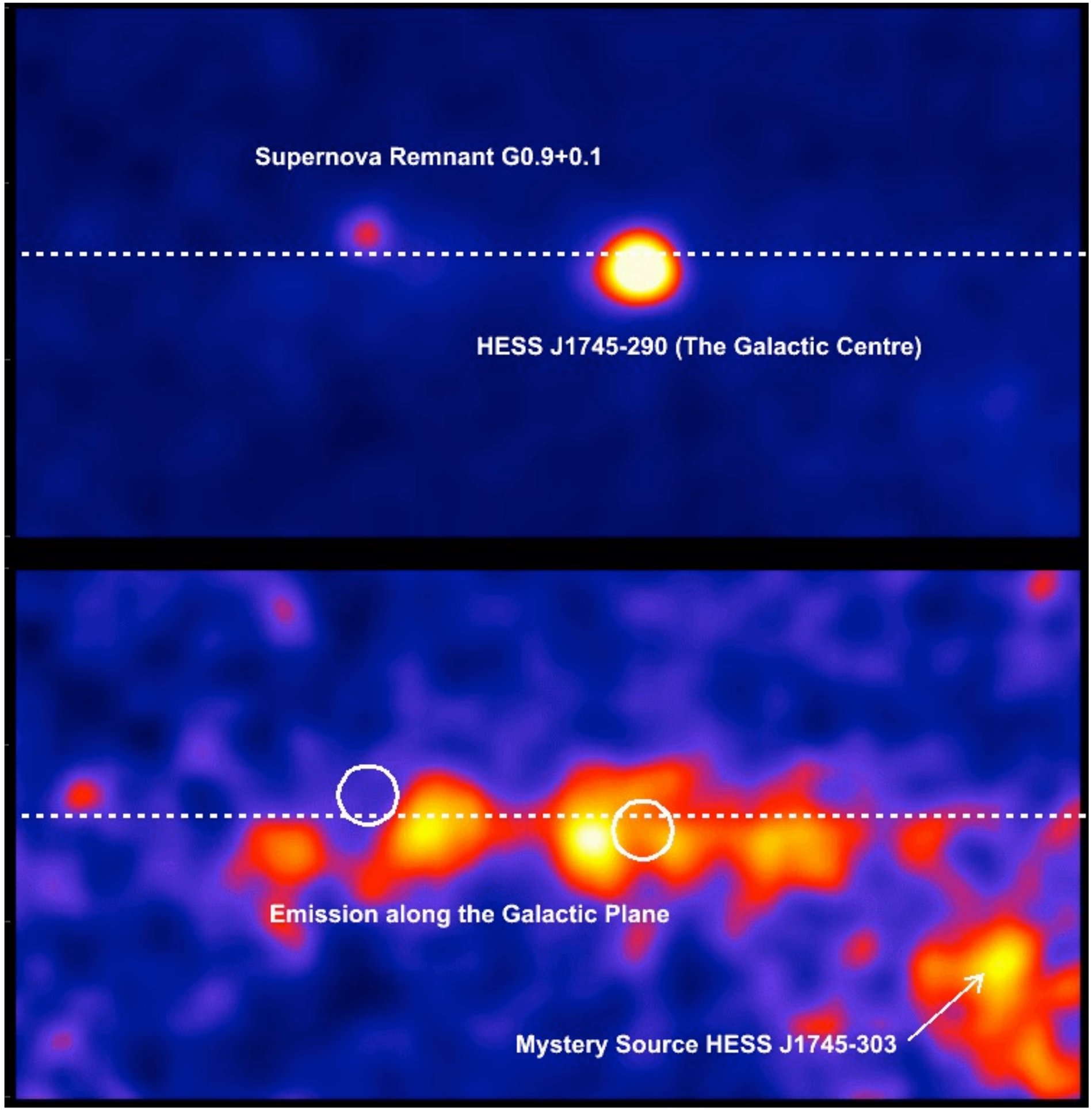


RX J1713.7-3946

a supernova remnant shell

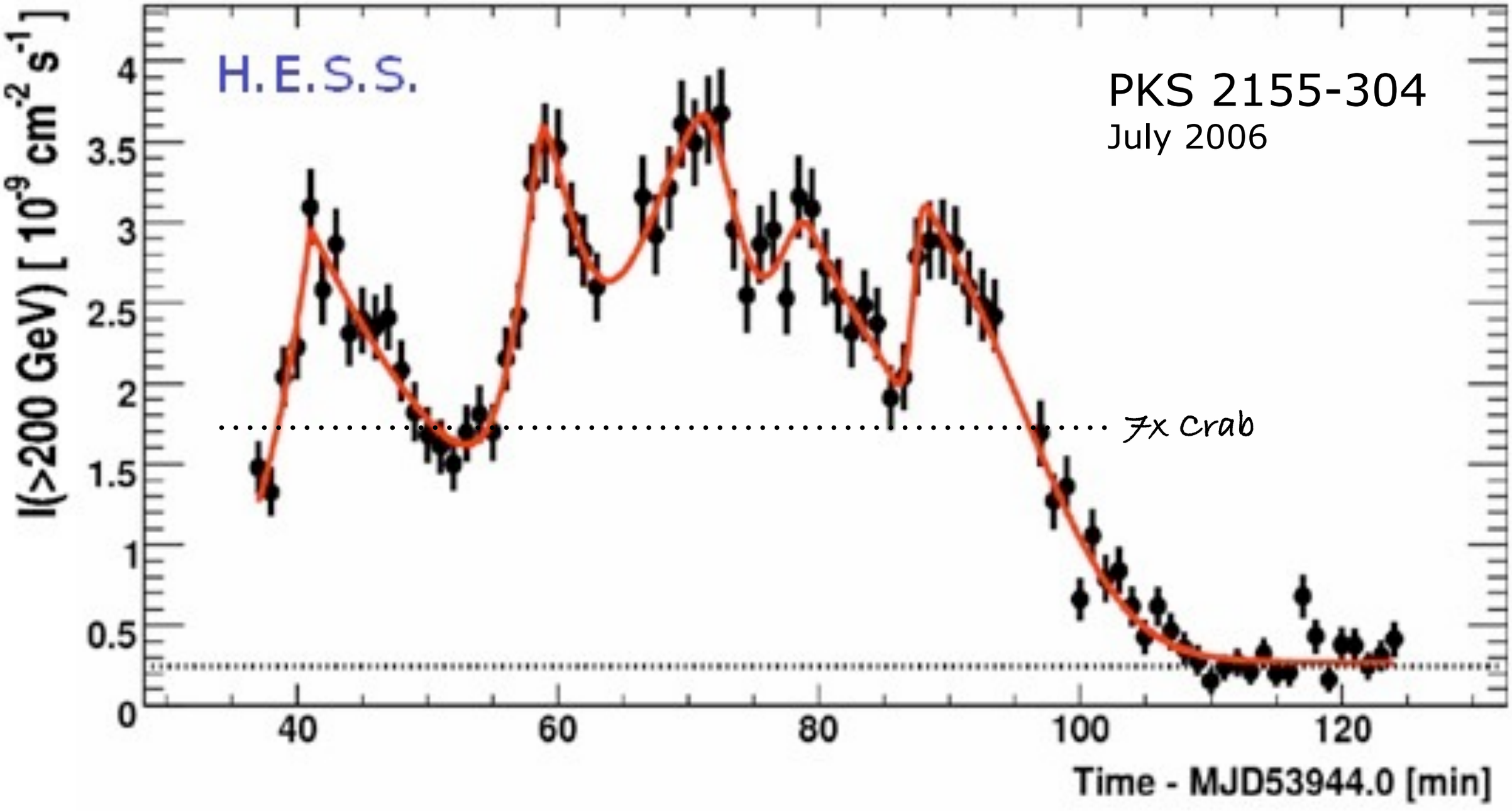
HESS:

gal. centre



CRs with

mol. clouds



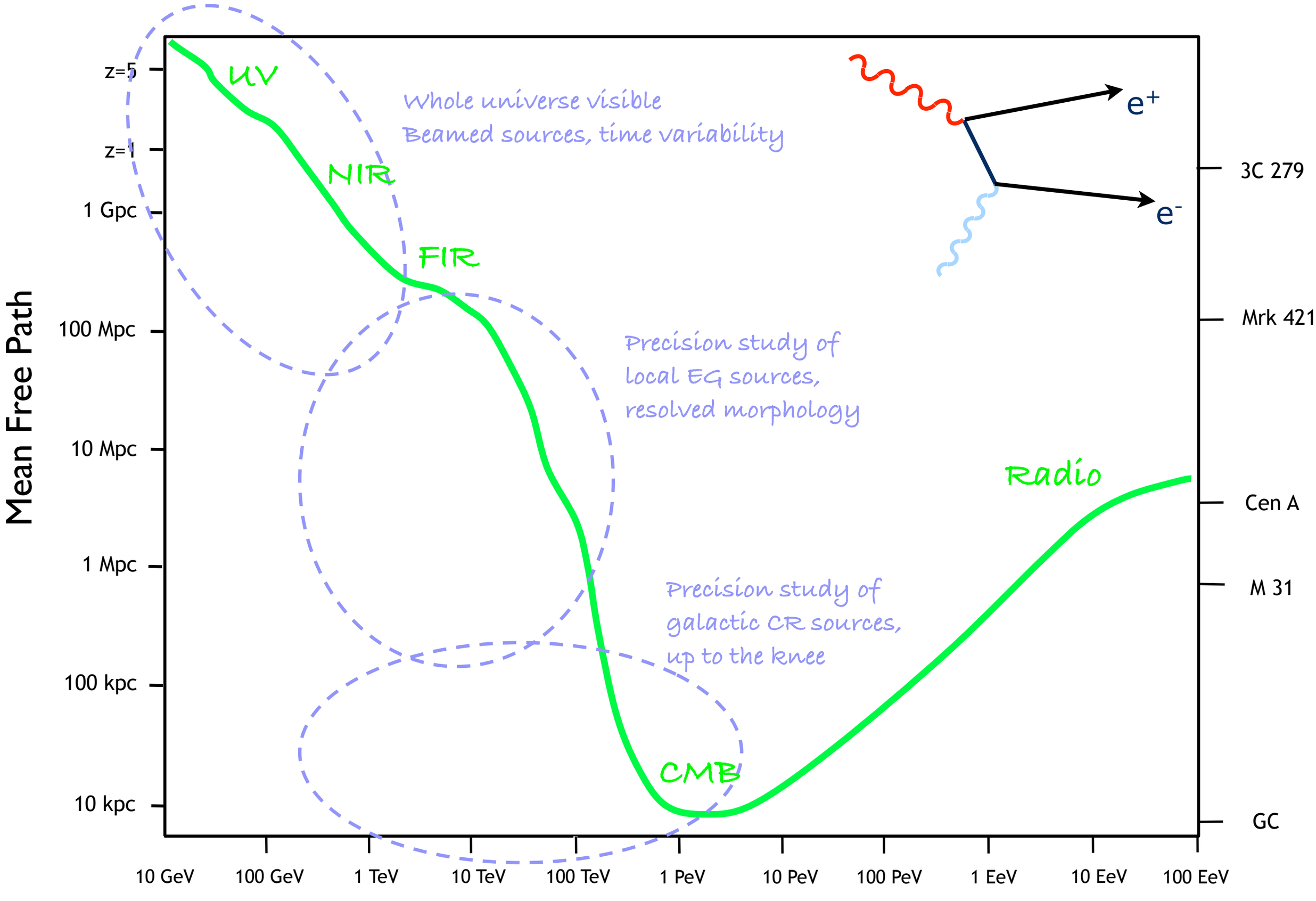
BL Lac object $z = 0.116$

bursts on 200 s scales

$\Gamma \geq 100$ are required

The Gamma Ray Horizon

$\gamma_{TeV} + \gamma_{IR} \rightarrow e^+e^-$



Scientific Objectives:

Cosmic energetic particles

Origin of the galactic cosmic rays

Also UHECR signatures

Role of ultra-relativistic particles in

in clusters of galaxies, AGN, Starbursts…

The physics of (relativistic) jets and shocks

Fundamental Physics

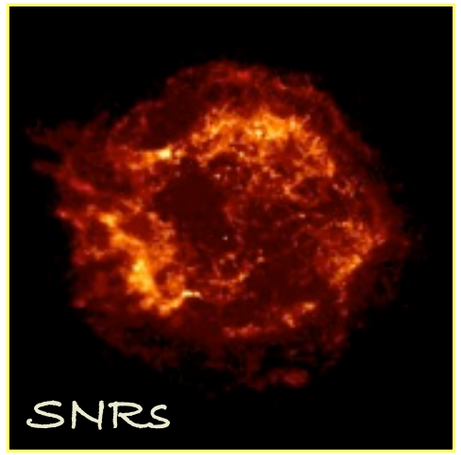
Dark Matter annihilation / decay

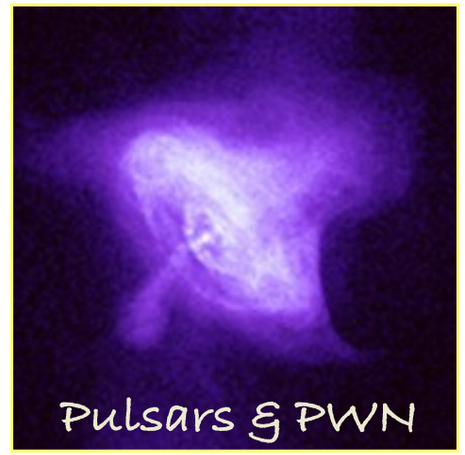
Lorentz Invariance violation

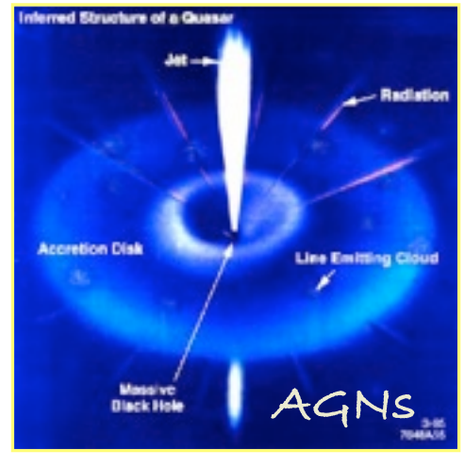
Cosmology

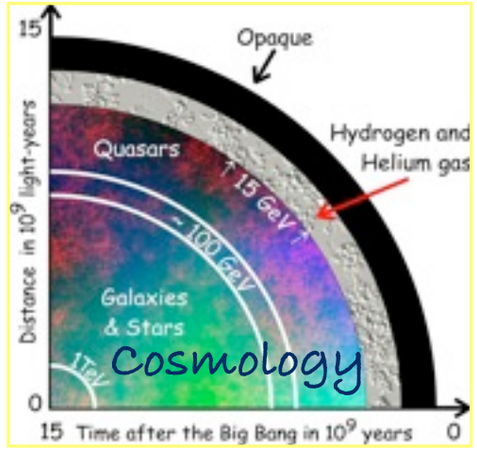
cosmic FIR-UV radiation,

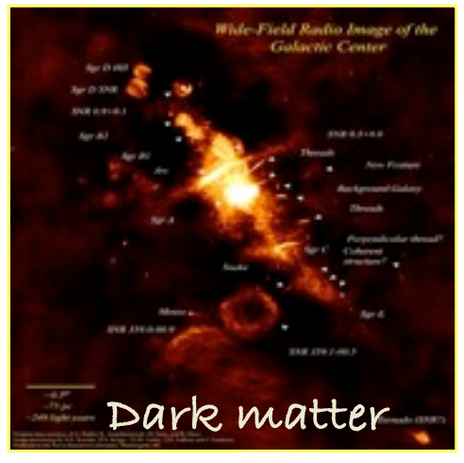
cosmic magnetism

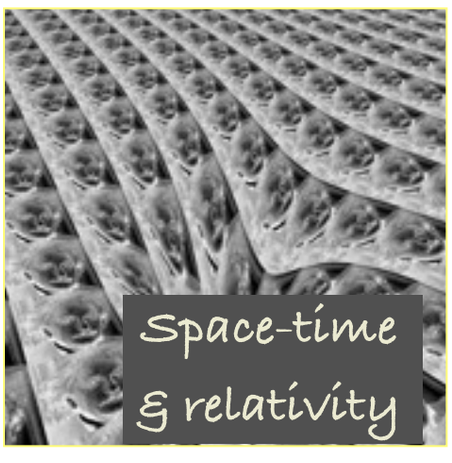












How to do even better with Ch. telescopes ?

A future Cherenkov observatory needs:

for E > TeV:

bigger collection area

(i.e. large array of telescopes, wider FOV)

more events

for E < TeV:

better background rejection

(i.e. large array of telescopes, wider FOV for multiple shower images)

better events

cherenkov telescope array

… an advanced facility for ground-based gamma-ray astronomy

CTA is the global next generation project.

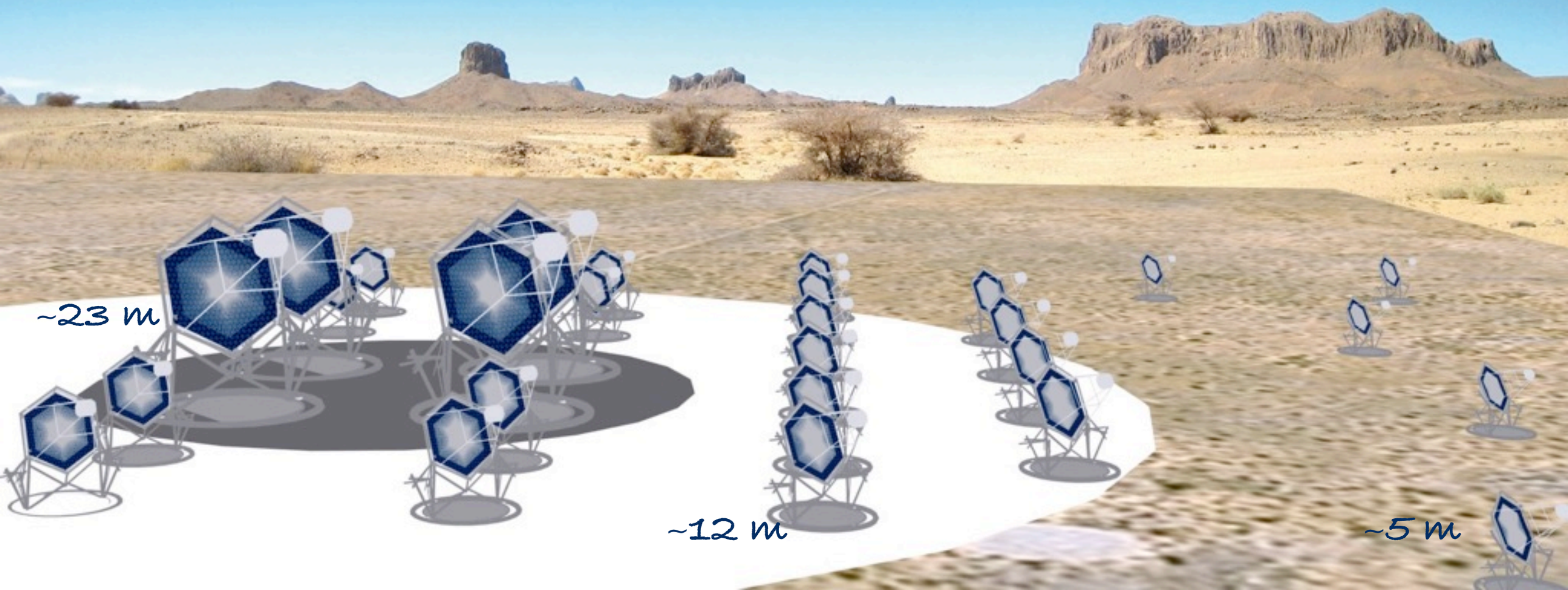
A precise and sensitive probe of the extreme universe,
with huge potential for extreme astronomy and
fundamental physics with TeV photons

The Cherenkov Telescope Array

- A factor 10 more sensitive than current instruments
- 30 GeV - 500 TeV
- substantially better angular and energy resolution
- wider field of view
- ≈100 Cherenkov telescopes

see arXiv:1008.3703

www.cta-observatory.org



Even higher energies ?

The Pierre Auger Observatory for Ultra-High Energy Cosmic Rays: $>10^{18}$ eV (... and photons ?)

Auger: unprecedented statistics and precision

≈ 3000 evts/yr with $E > 10^{19}$ eV

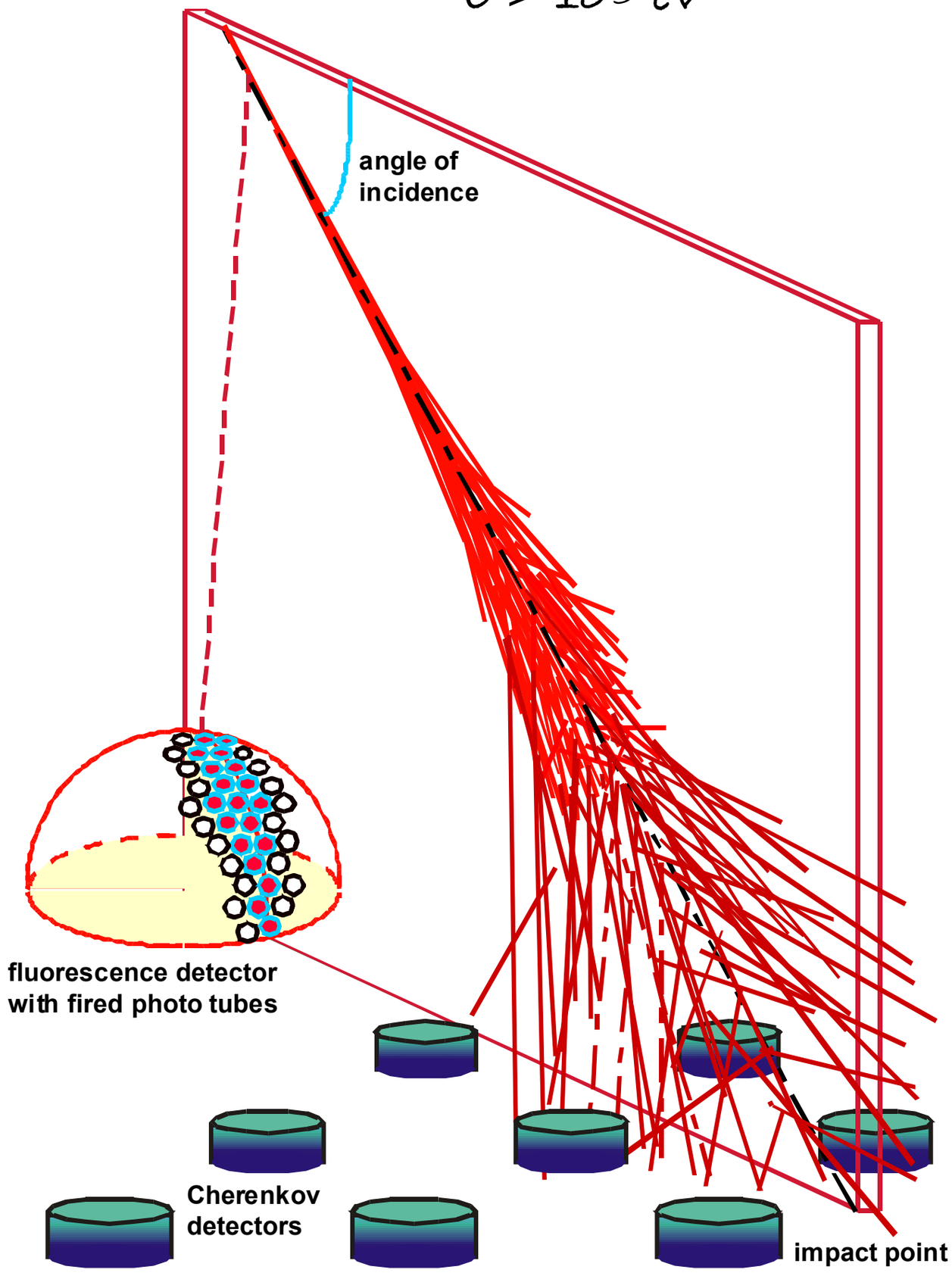
Hybrid Detector:

Array of 1600 water Cherenkov detectors
covering 3000 km²
duty cycle: 100%

Fluorescence telescopes
24 FDs (30°x30° each)
duty cycle: 10%

Better geometric reconstruction,
cross-calibration, control of systematics.

low-energy extensions:
HEAT & infill
$E \geq 10^{17}$ eV



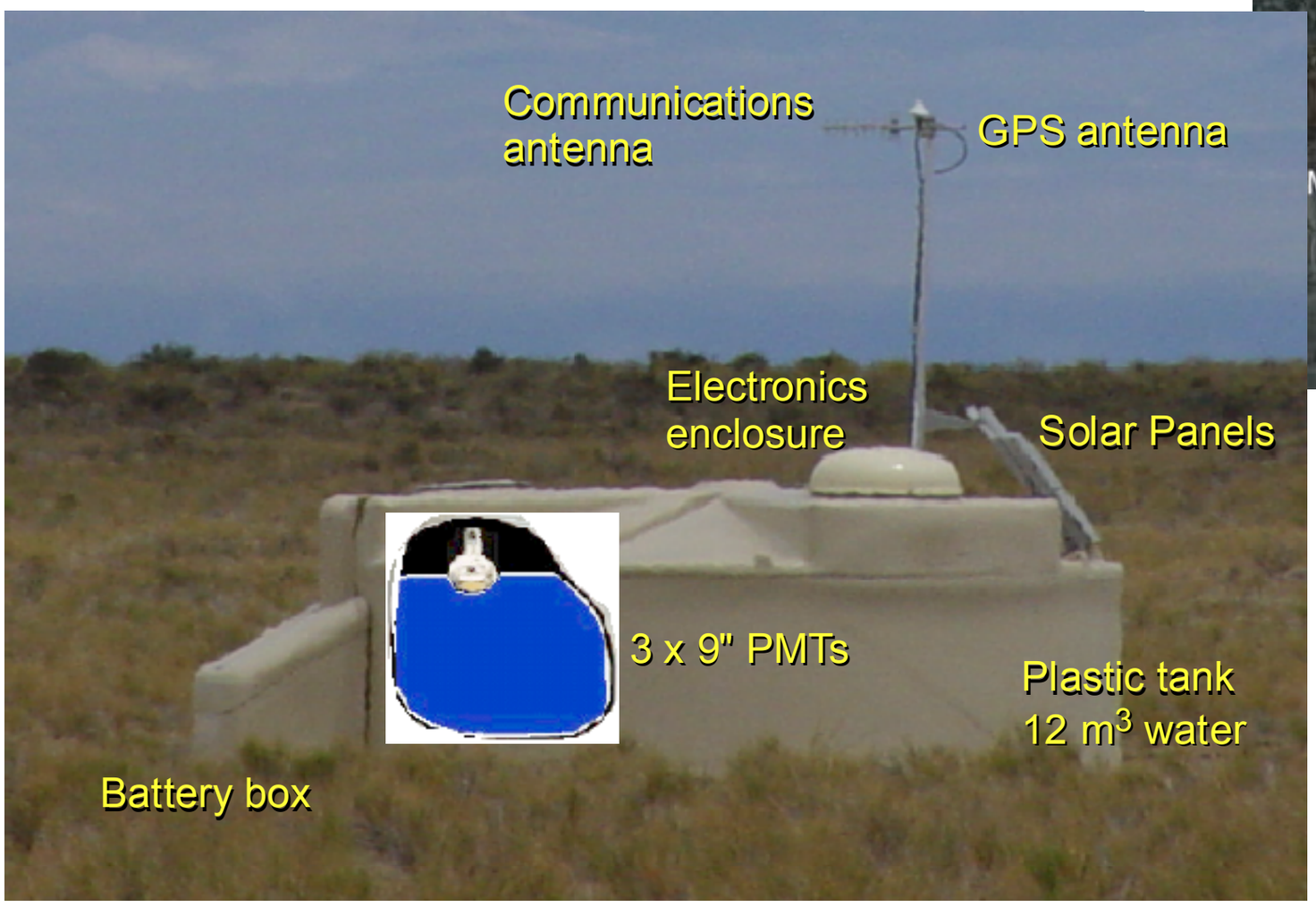
Auger array:

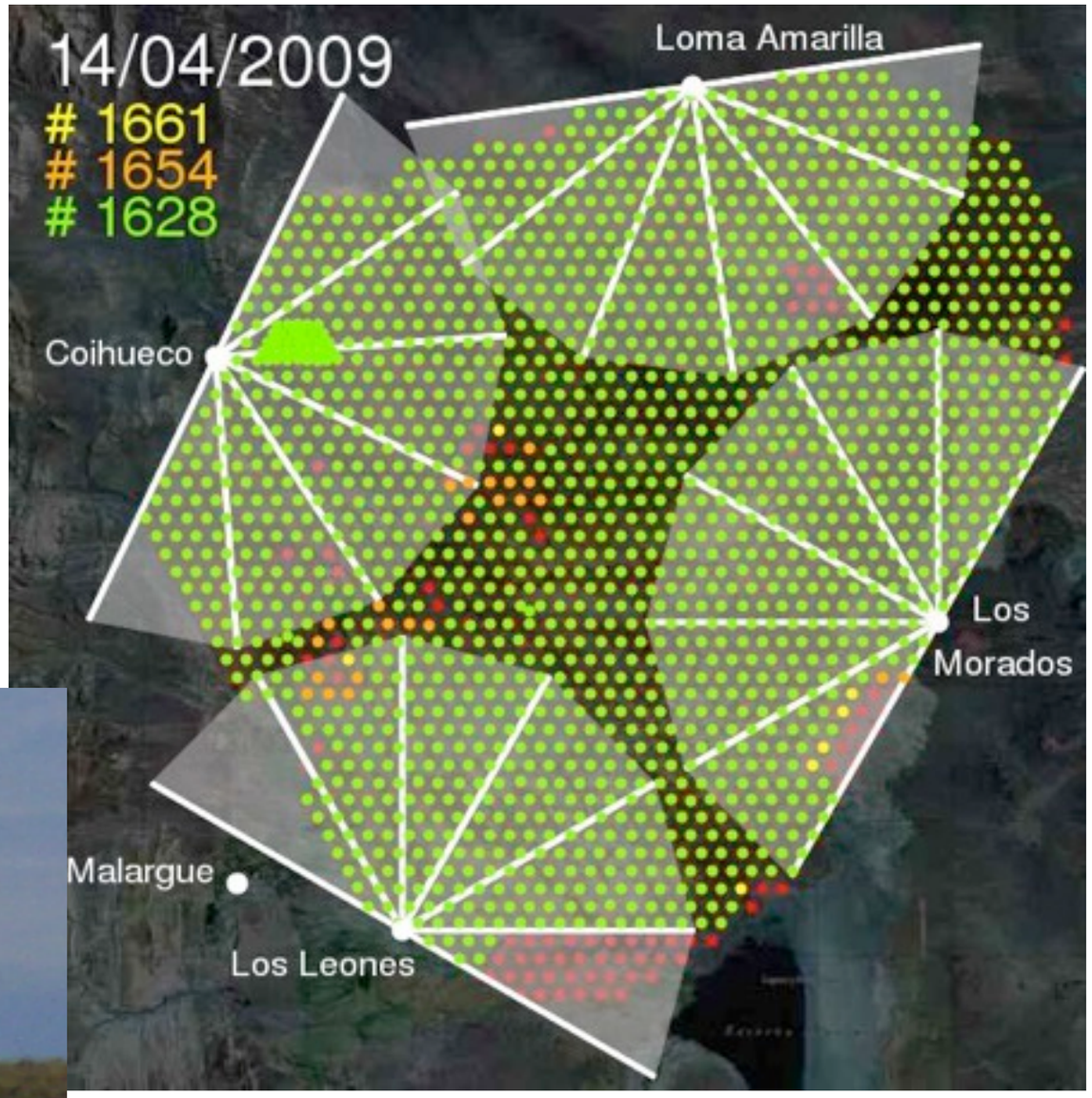
Auger detector:

3000 km^2

>1600 water Cherenkov det.

10 m^2 each, 1.5 km apart





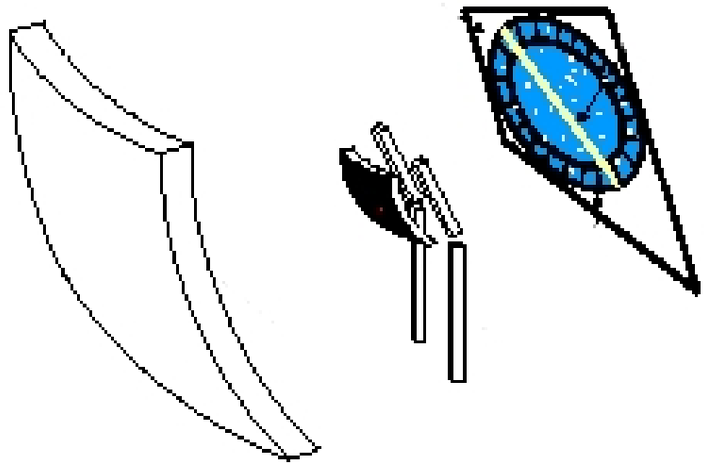
planned

tank deployed

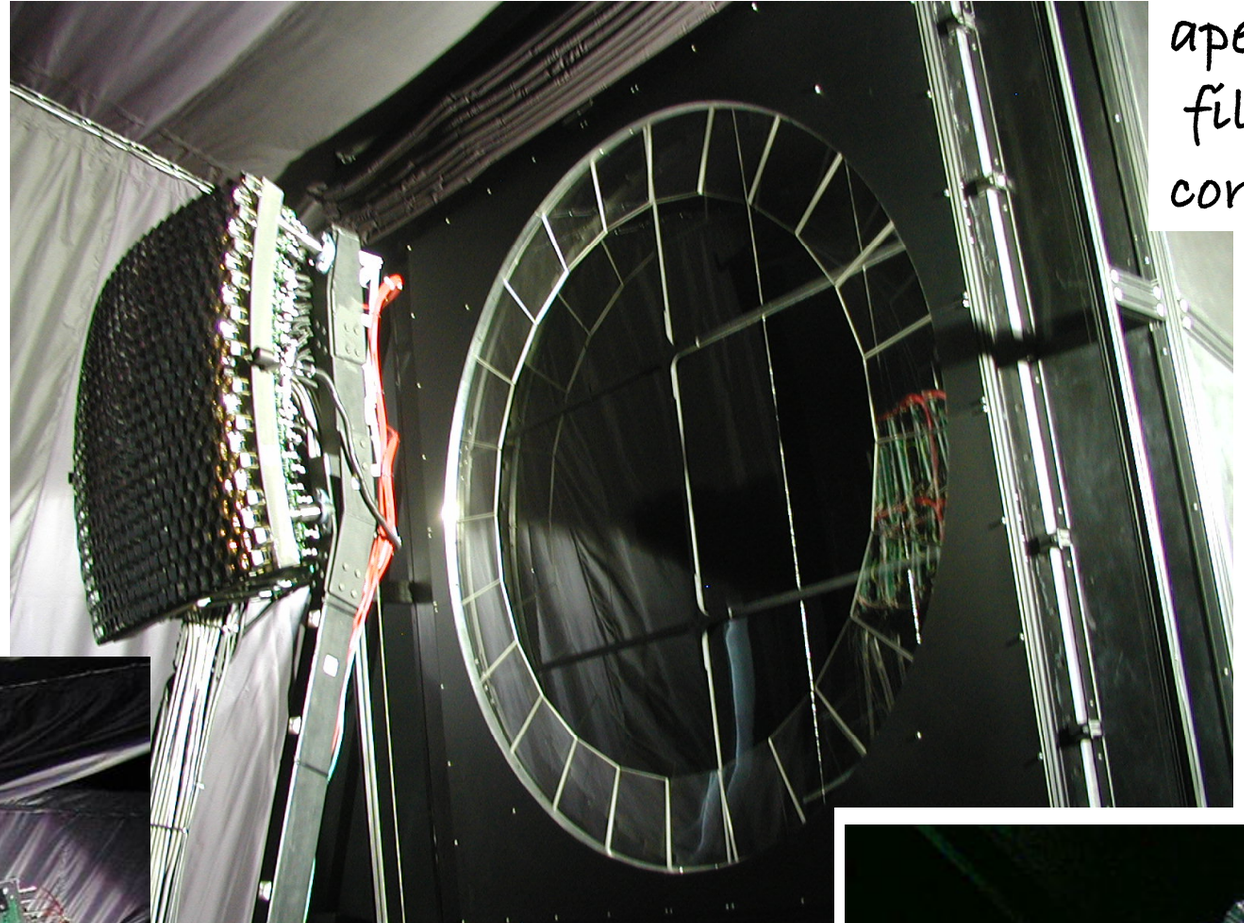
with water

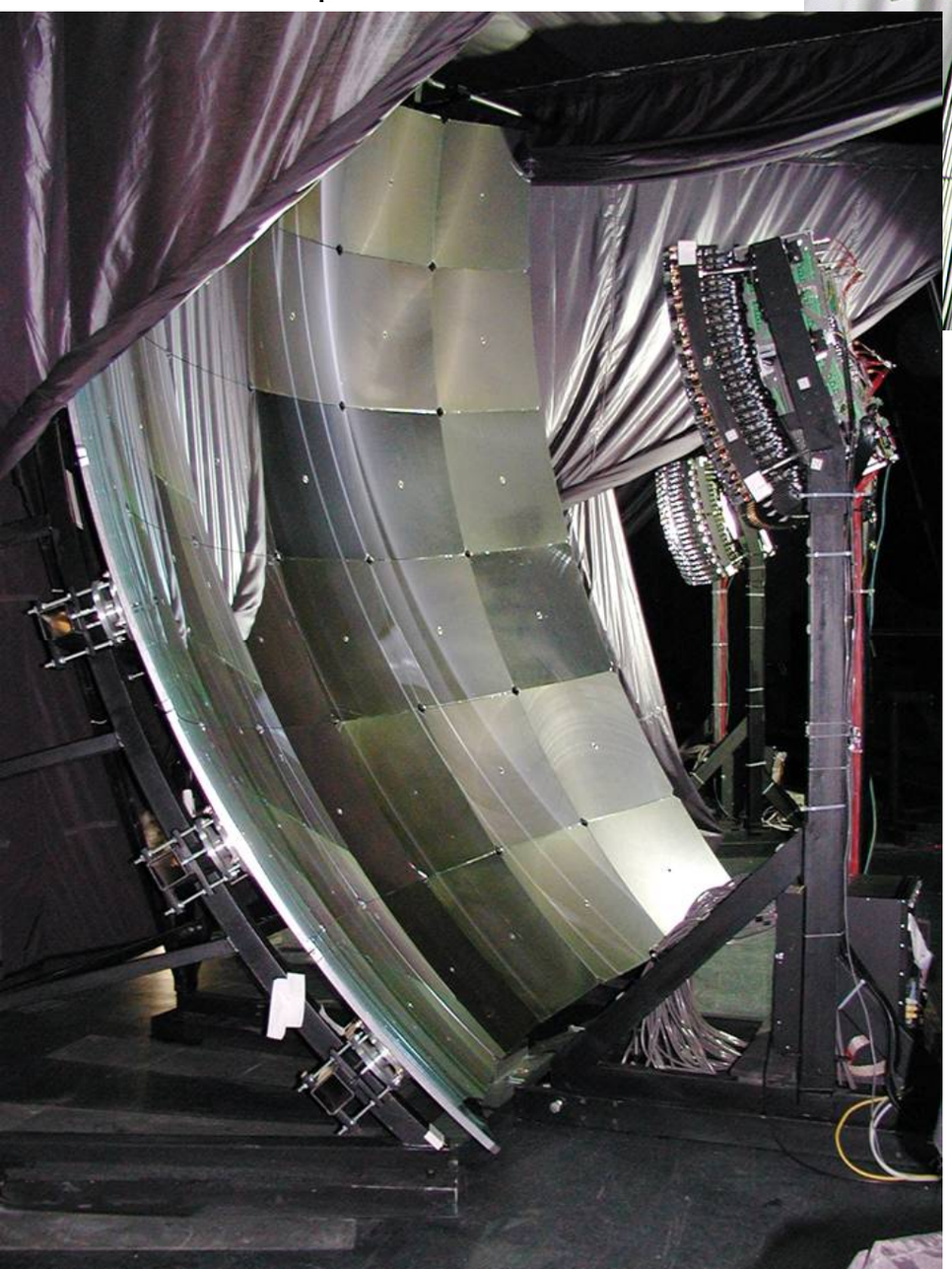
send data

FD telescope:



aperture with shutter, filter and Schmidt corrector lenses

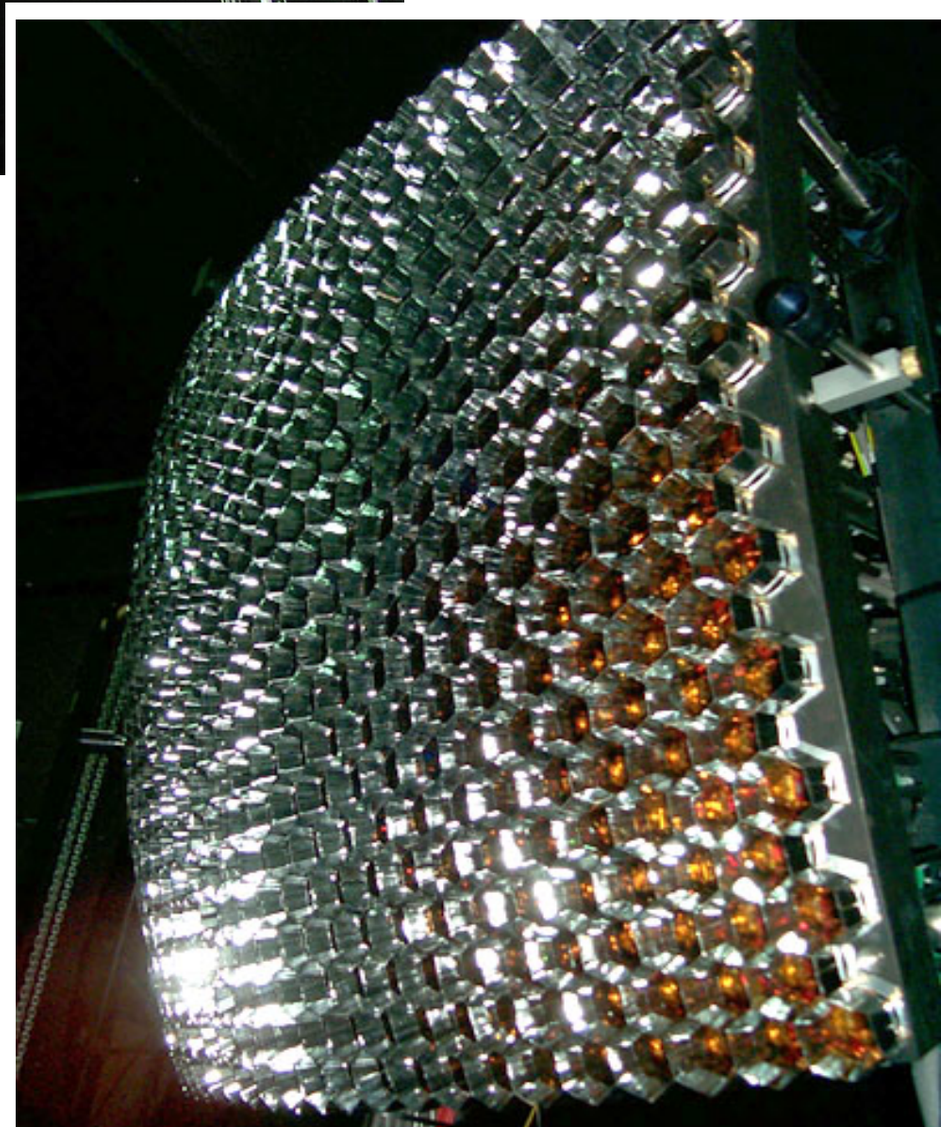




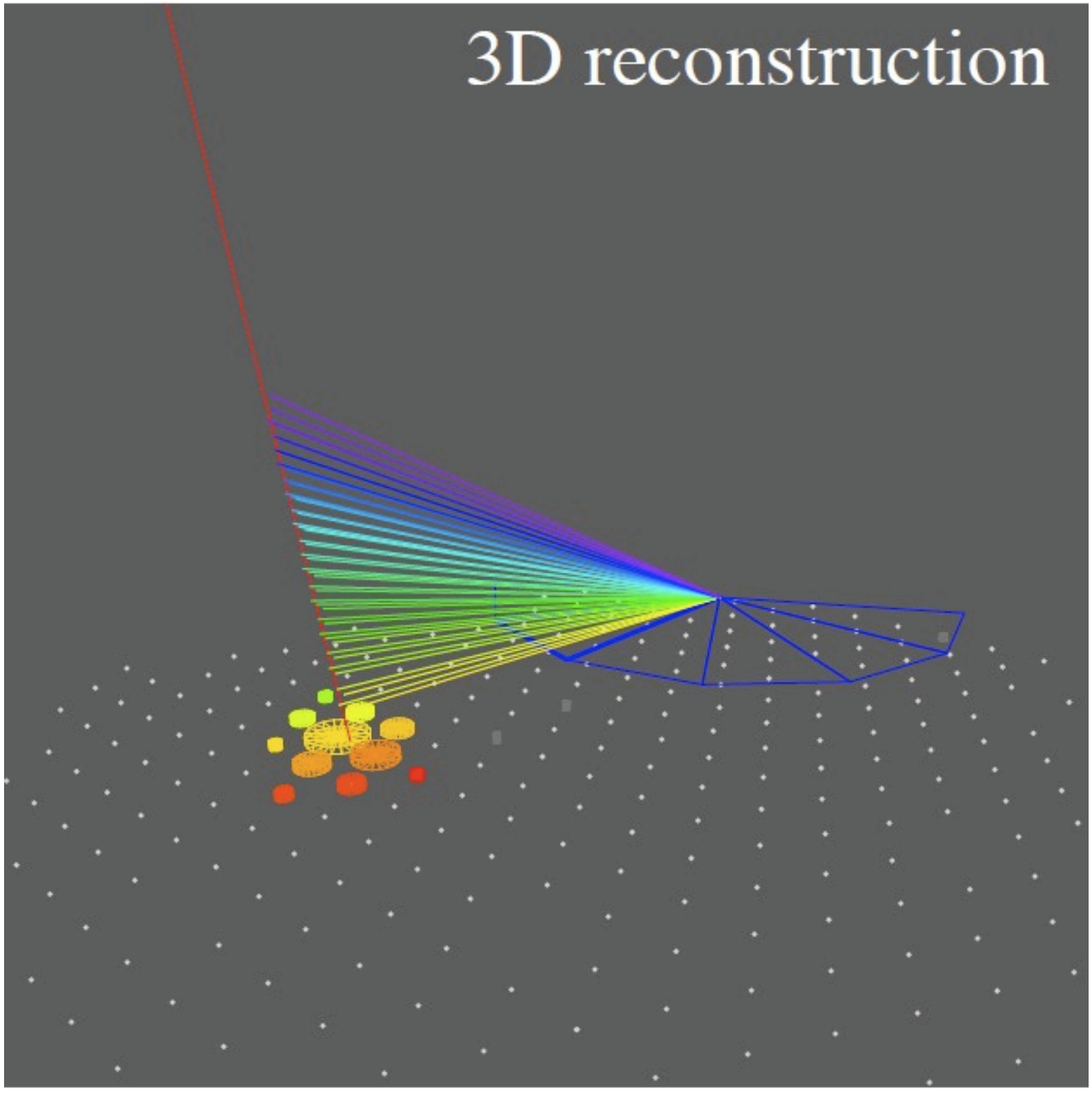
11 m² mirror (Aluminium)

440 PMT camera

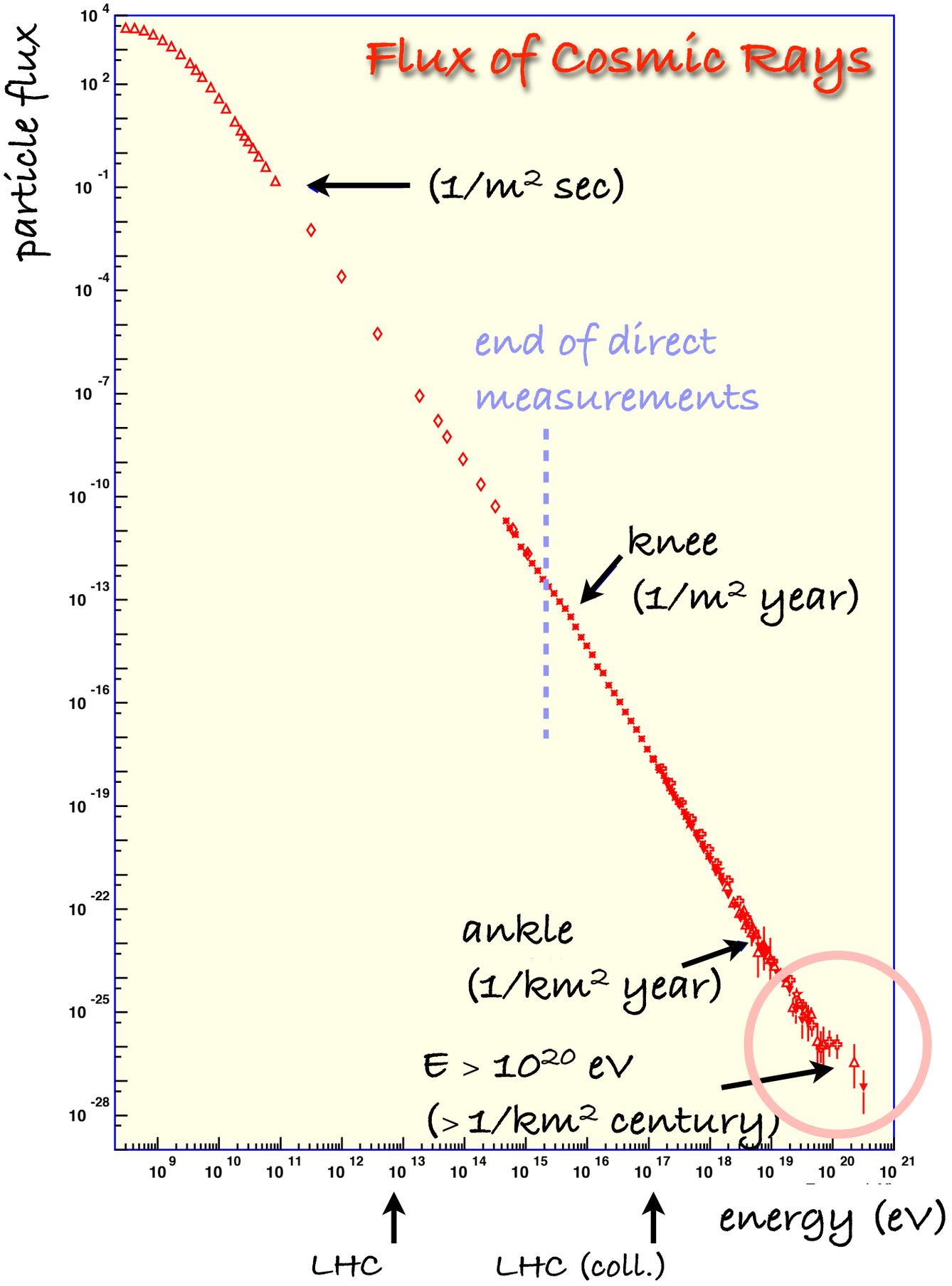
24 telescopes at 4 sites
30°x30° FOV, each



golden hybrid event



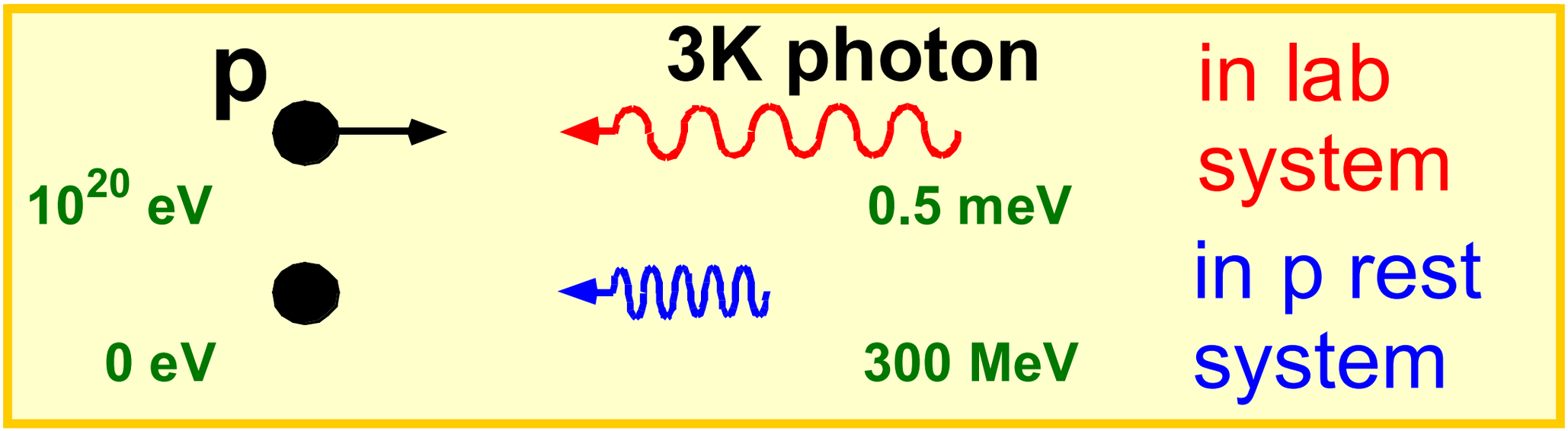
CR Spectrum



The Auger range ...
with a firm prediction of a spectral feature:
the GZK cut-off
due to interaction of CRs with CMBR

GZK Cut-off

Greisen (1966)
Zatsepin & Kuzmin (1966)



$p + \gamma_{3K} \longrightarrow \Delta^+ \longrightarrow p + \pi^0$ → γ Photo-pion production

$\longrightarrow n + \pi^+$ → ν

$^{56}Fe + \gamma \longrightarrow {}^{55}Fe + n$ Photo dissociation

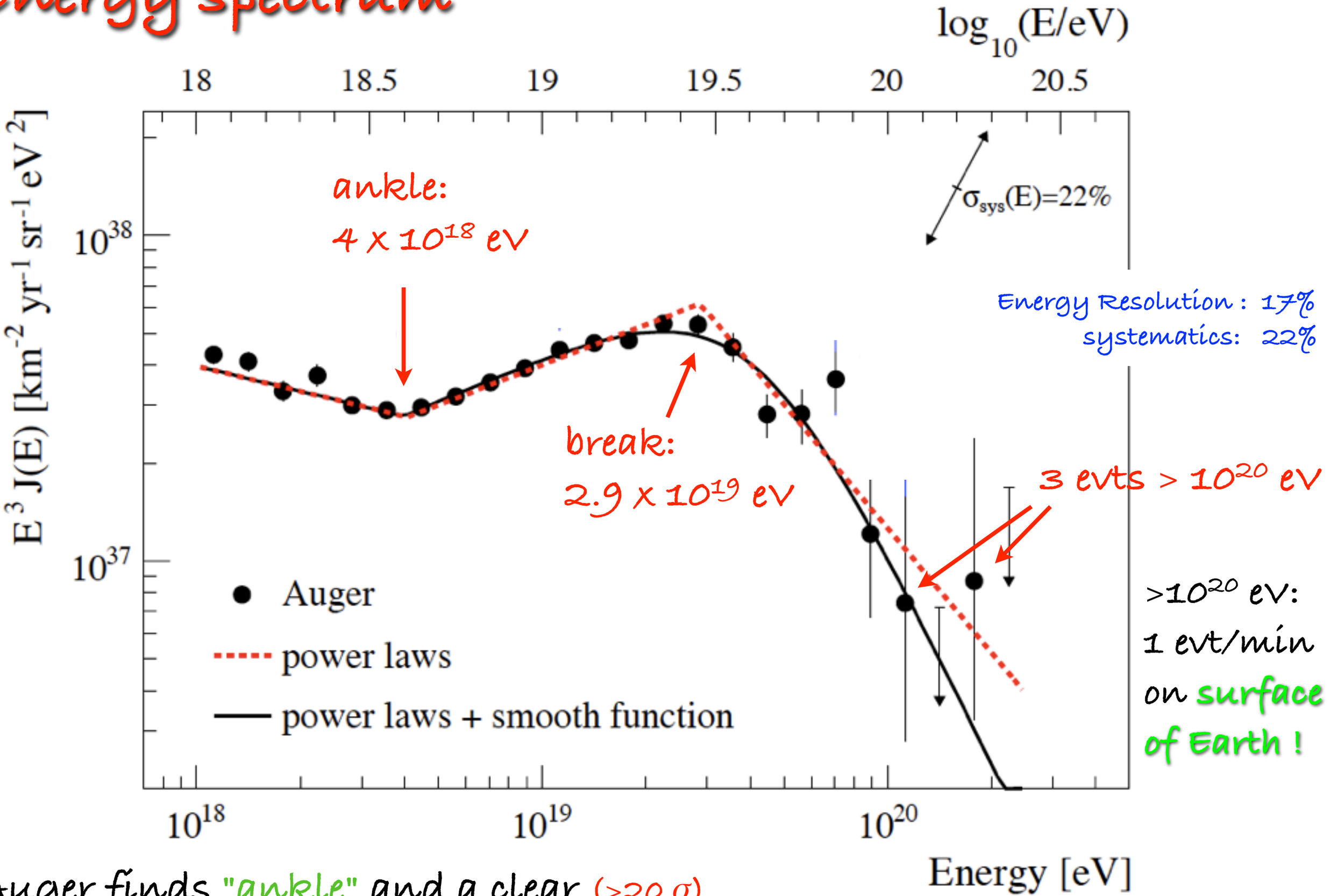
Universe becomes opaque for $E >$ few $\times 10^{19}$ eV.

beyond this: **Sources must be close !**

If sources are universal: **cut-off in CR spectrum.**

Test of Lorentz Invariance for $\gamma \approx 10^{11}$!

Energy spectrum



Energy Resolution : 17%
systematics: 22%

>10^{20} eV:
1 evt/min
on surface
of Earth !

Auger finds "ankle" and a clear (>20 σ)
spectral steepening at E ≈ 2.9 x 10^{19} eV.

12790 km² sr yr ≈ 2 full-Auger years
zenith angle: 0-60°

There is a cut-off roughly at the predicted energy !

Is it the GZK cut-off ? Spectrum is quite suggestive...

Alternatives:

- Also nuclear primaries would be absorbed (but not quite in the same way)
- mixed composition with similar cut-off ?
- maximum energy of accelerator ? .....

Need more information on mass composition to be sure.

if GZK cut-off then
- CRs are protons
- power-law spectrum at source $> 10^{20}$ eV
- sources are universally distributed
- Lorentz Invariance holds up to γ factors of 10^{11}

On average Fe showers have

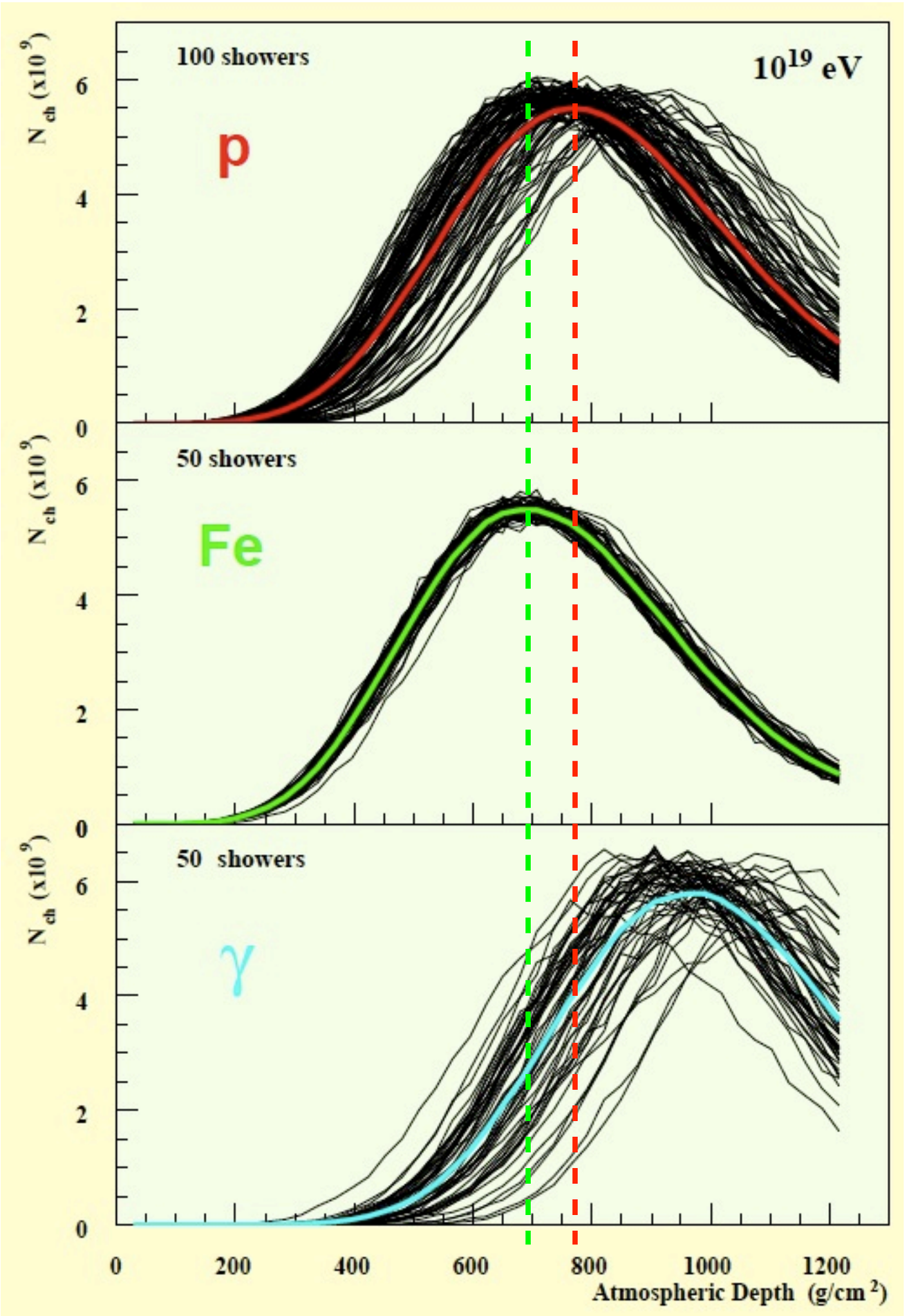
- higher 1st interact. and maximum
  (since σ_{int} larger)
- more secondaries
  (since $N_{sec} \sim \ln(E)$)
- more μ, less e,γ at ground
- smaller fluctuations
  (since superposition of 56 subshowers)

than p showers

difference p - Fe ≈
fluctuations in p

γ showers are more different.

- have (almost) no muons
- different longitudinal dist.

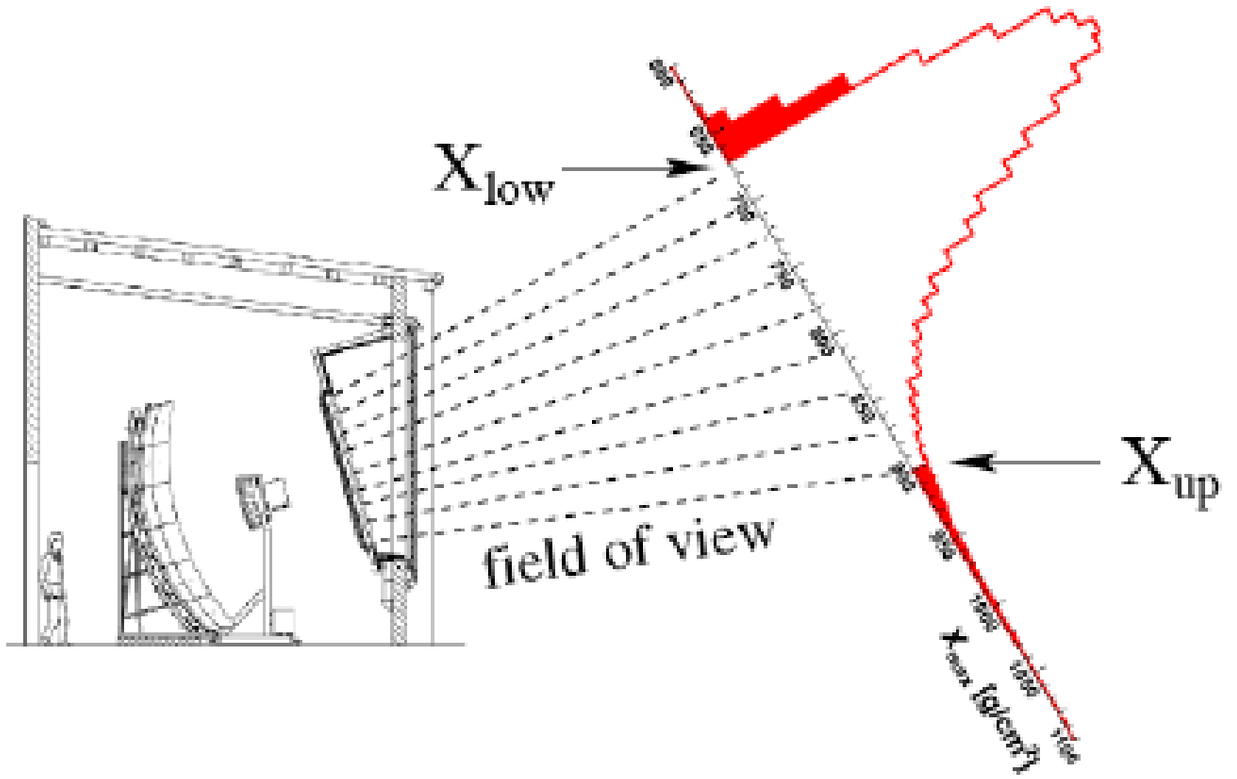


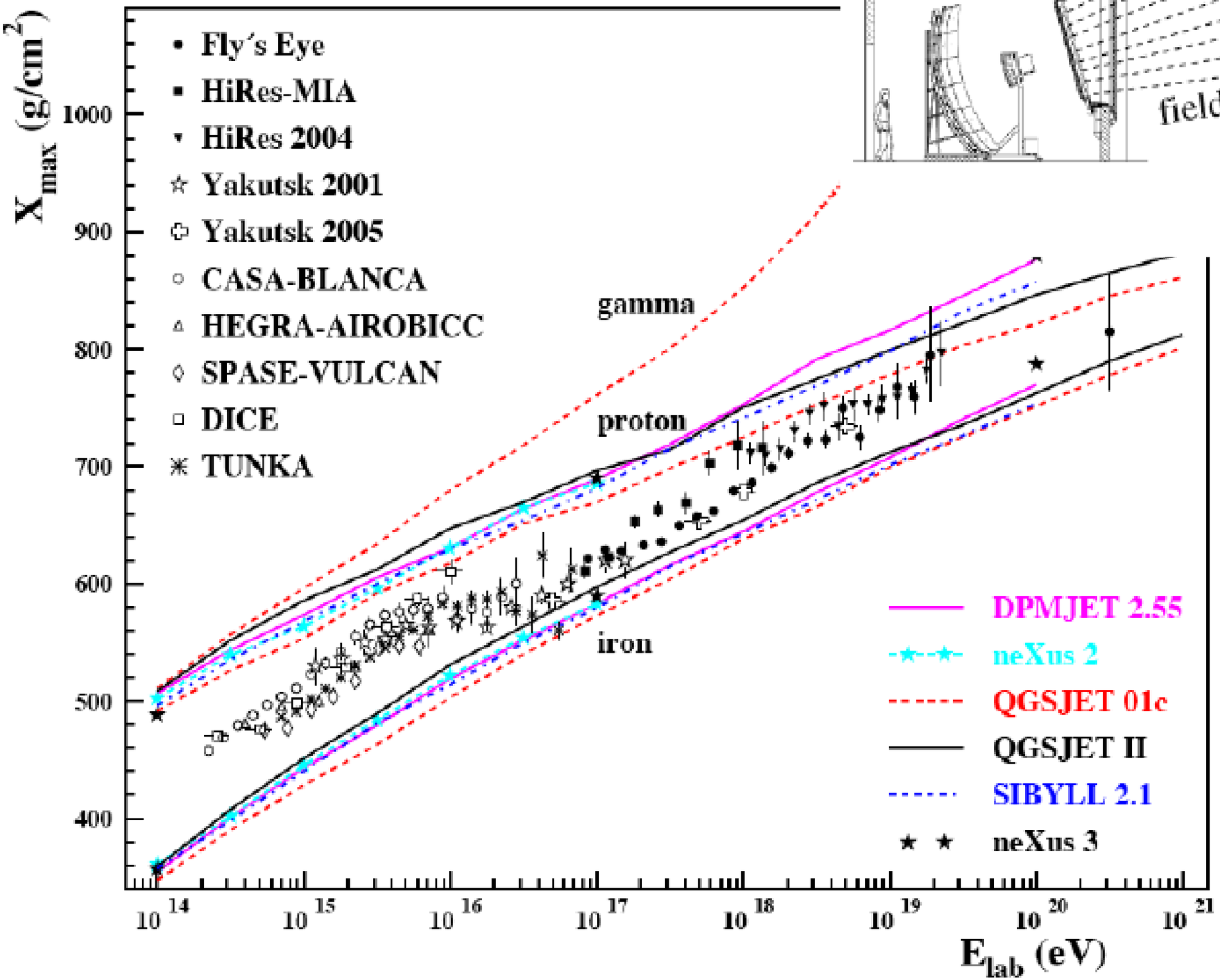
Photons

FD: measure X_{max}

photons maximise deeper than nuclei

protons maximise deeper than iron





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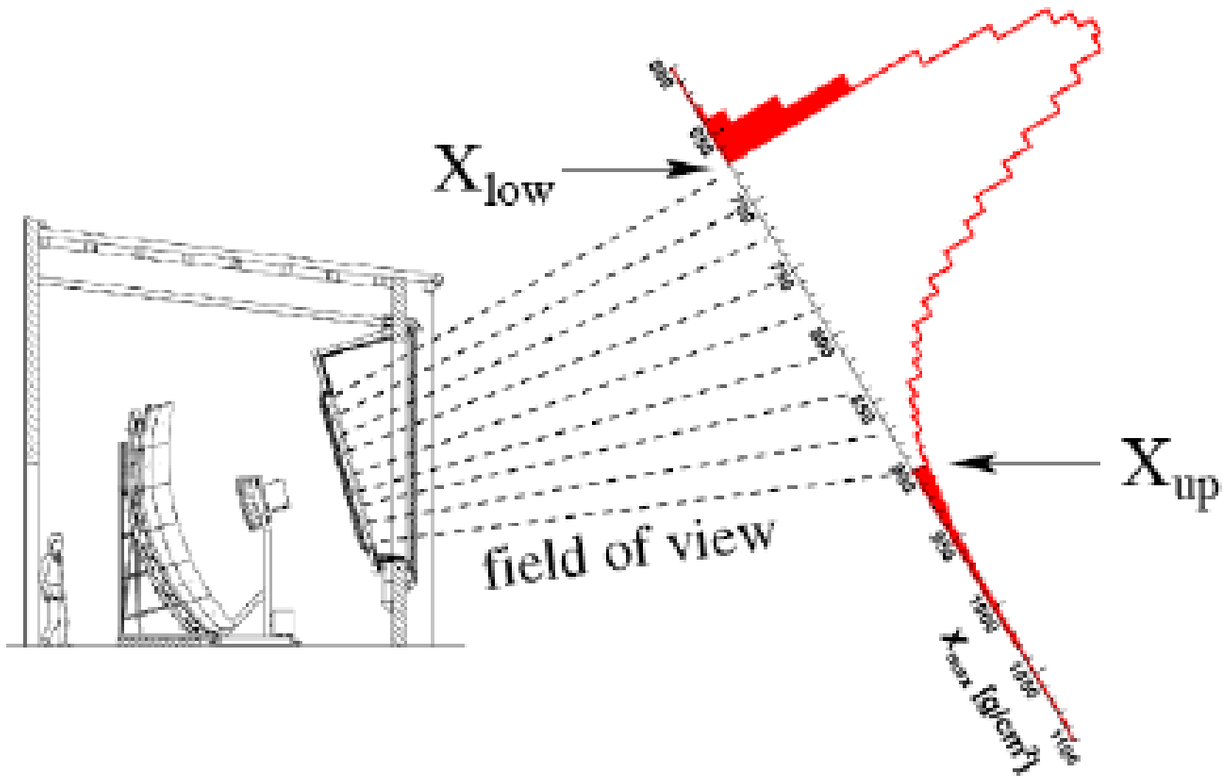
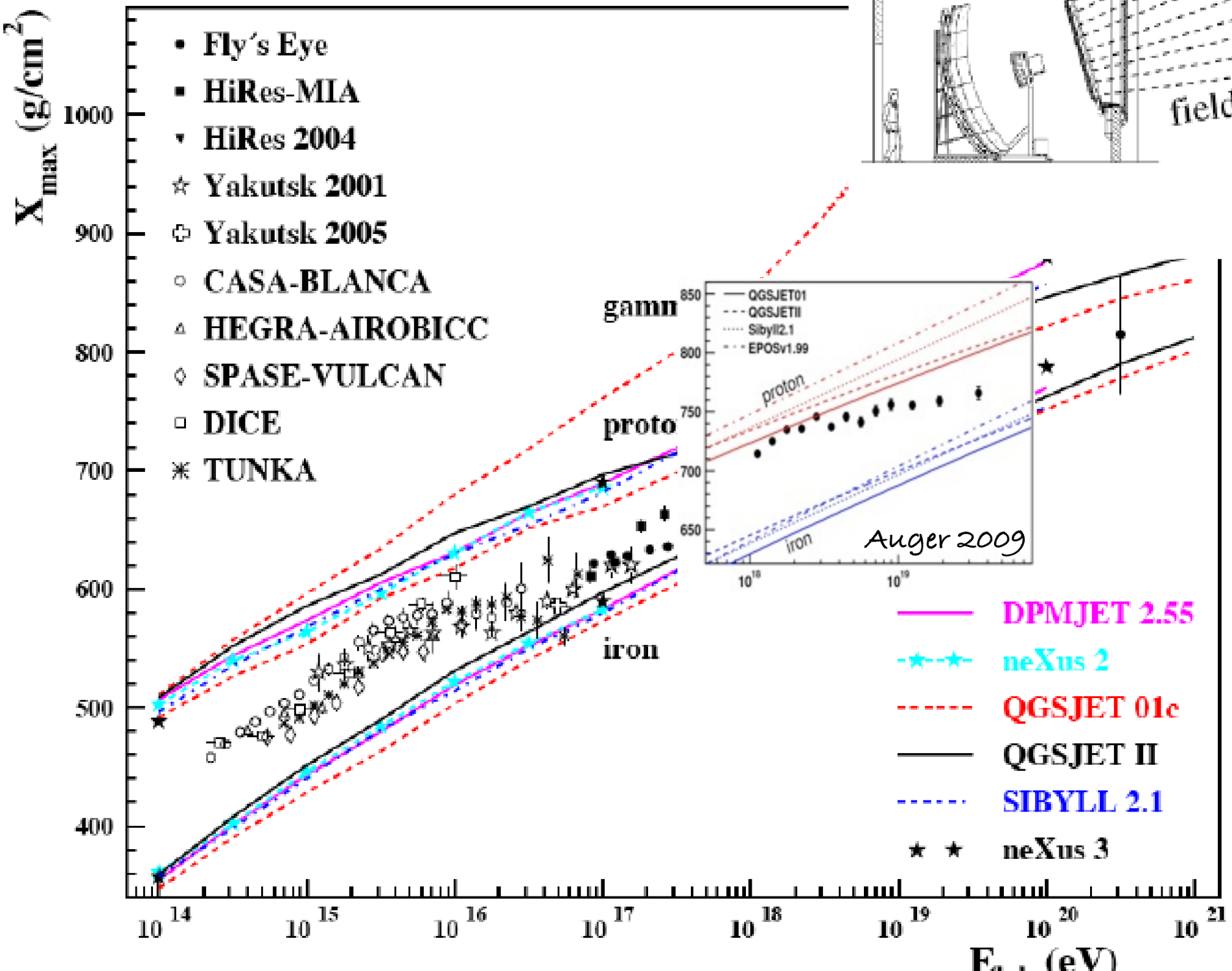
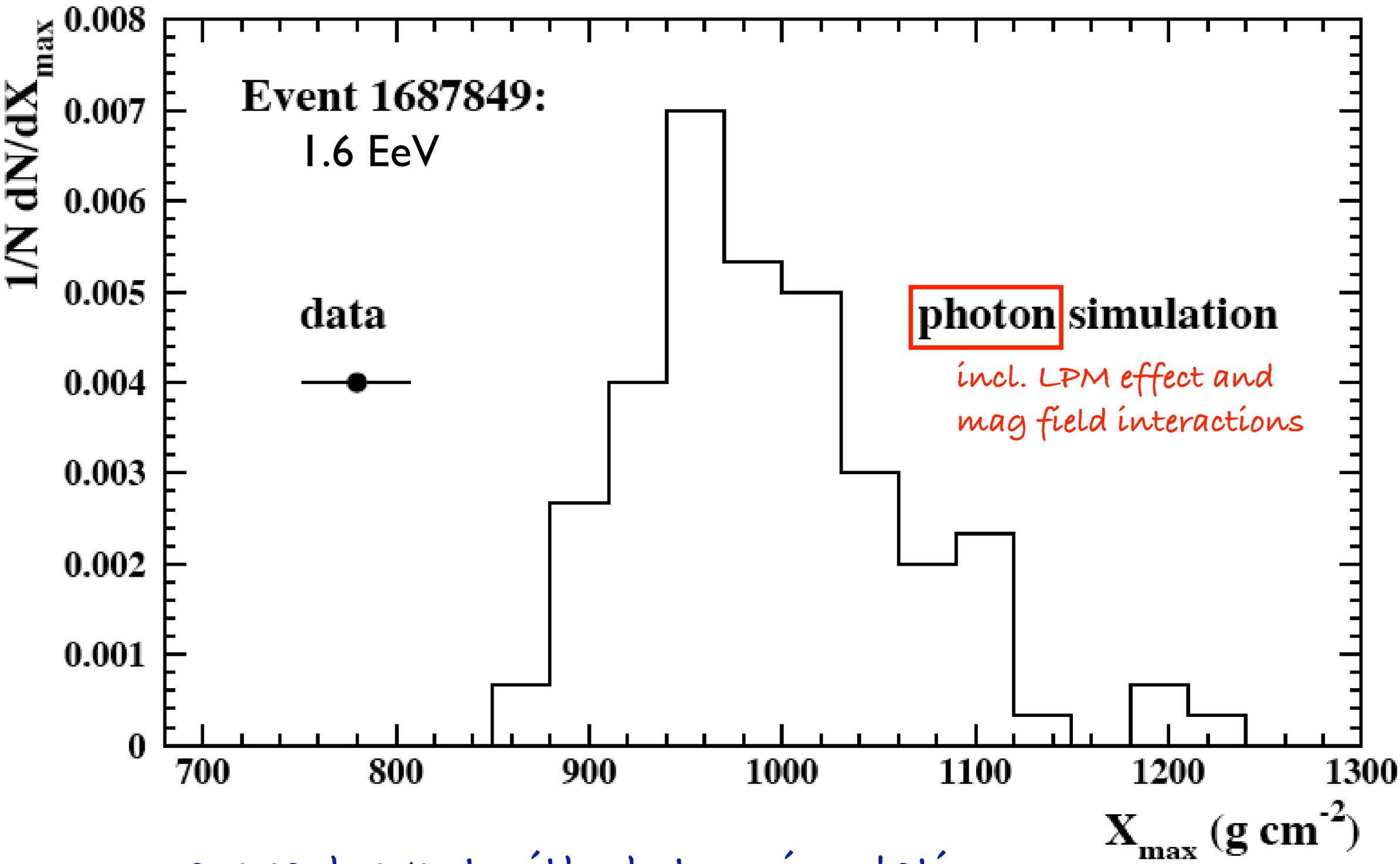
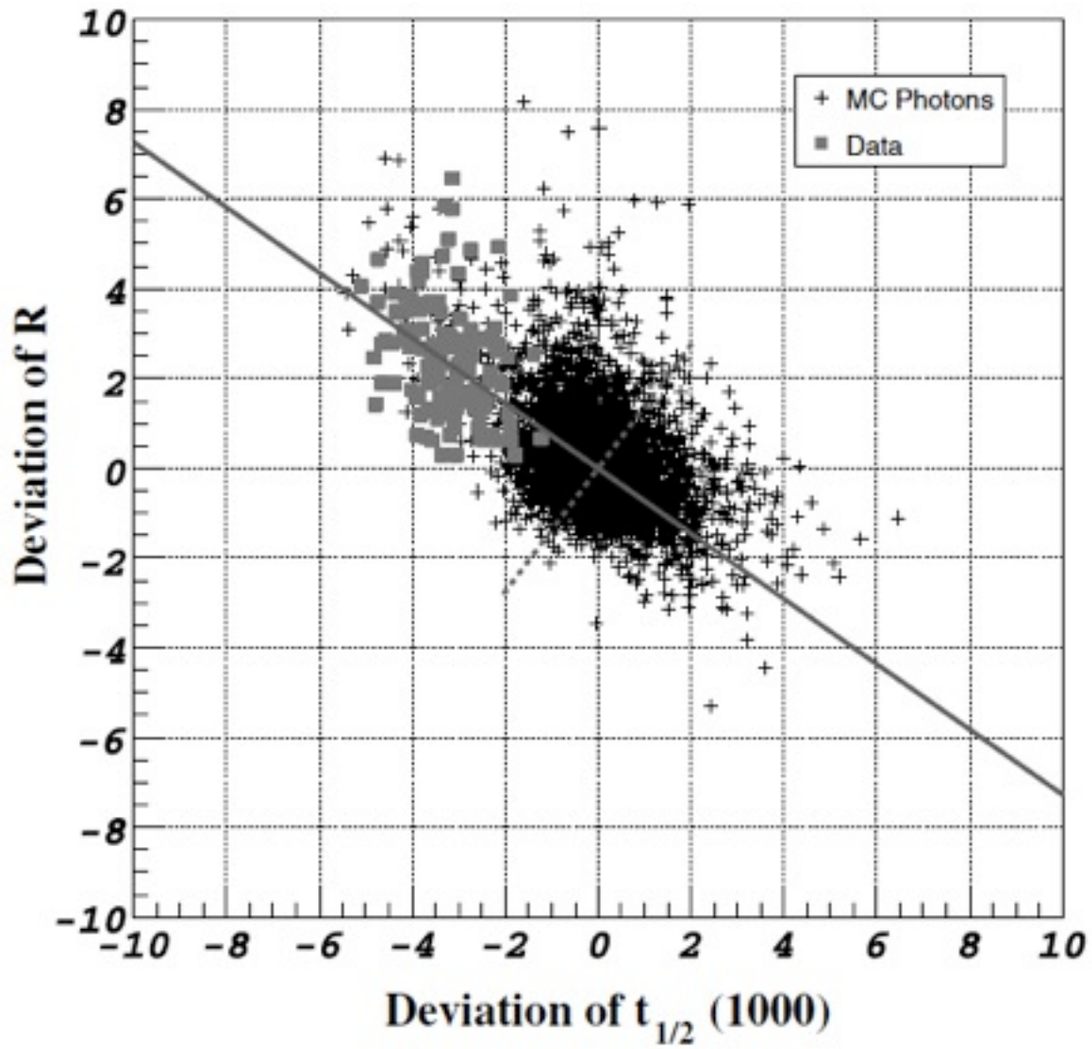


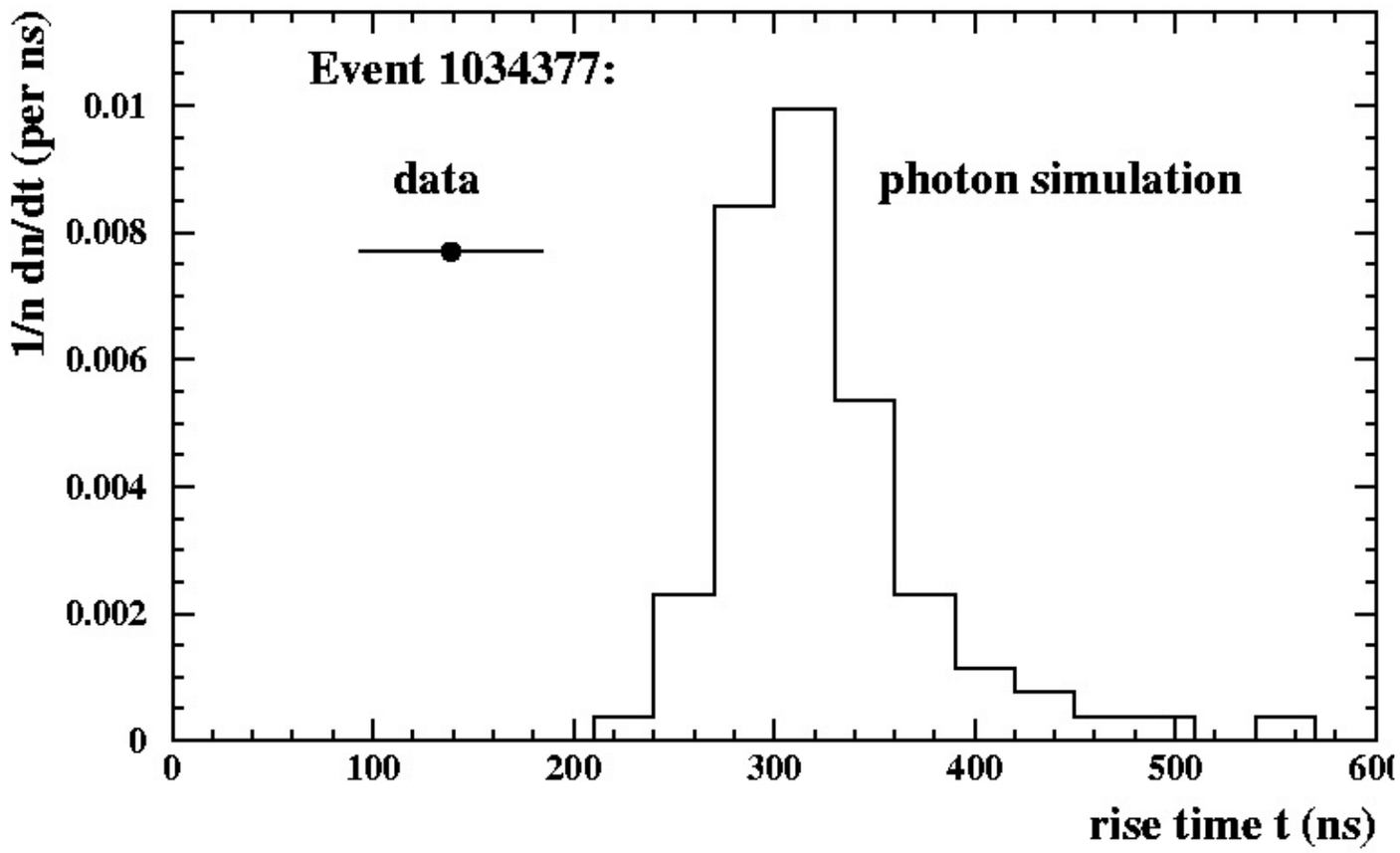


Hybrid events, $E>10^{19}$ eV



compare each event with photon simulations,
combine probabilities for all events

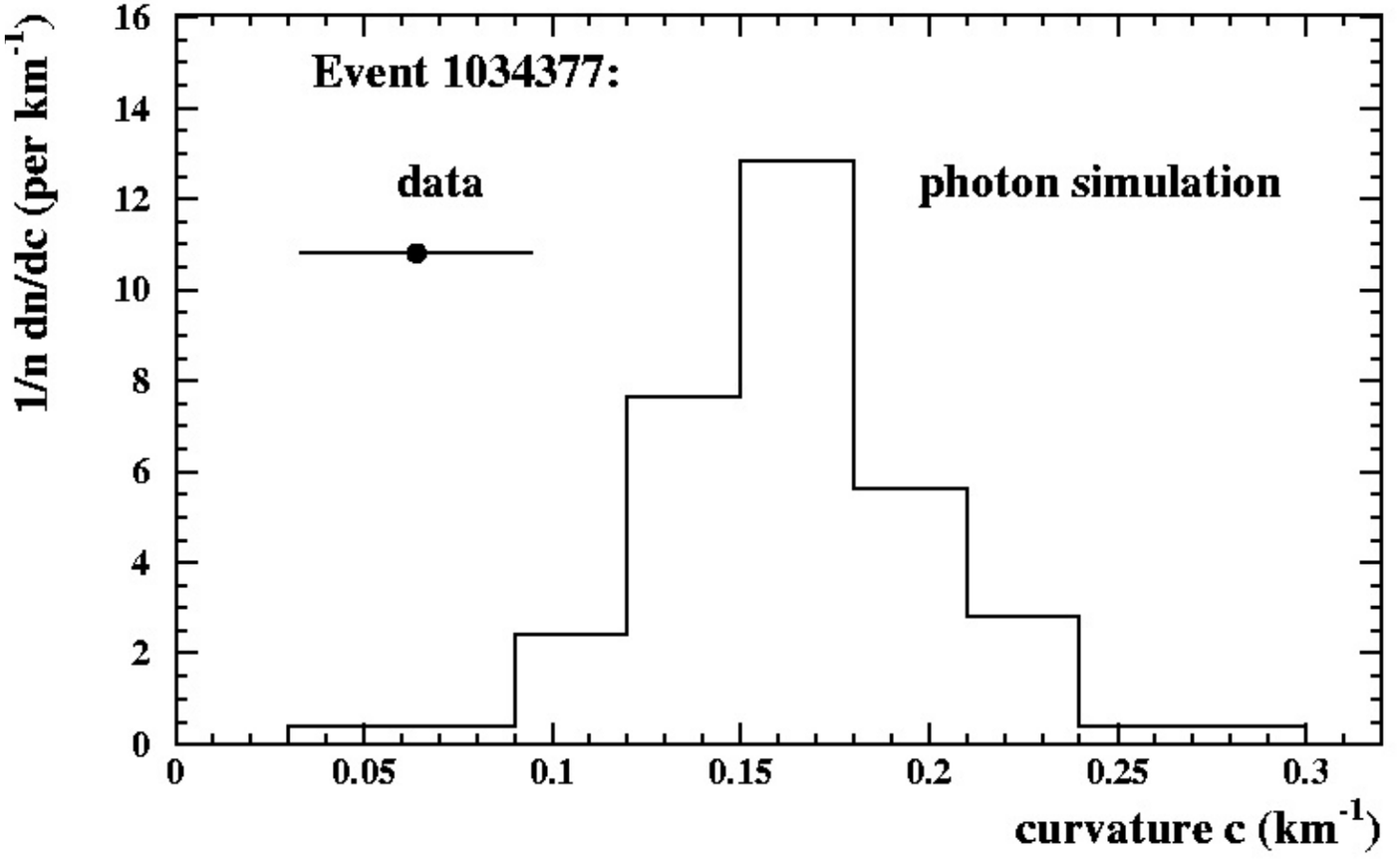


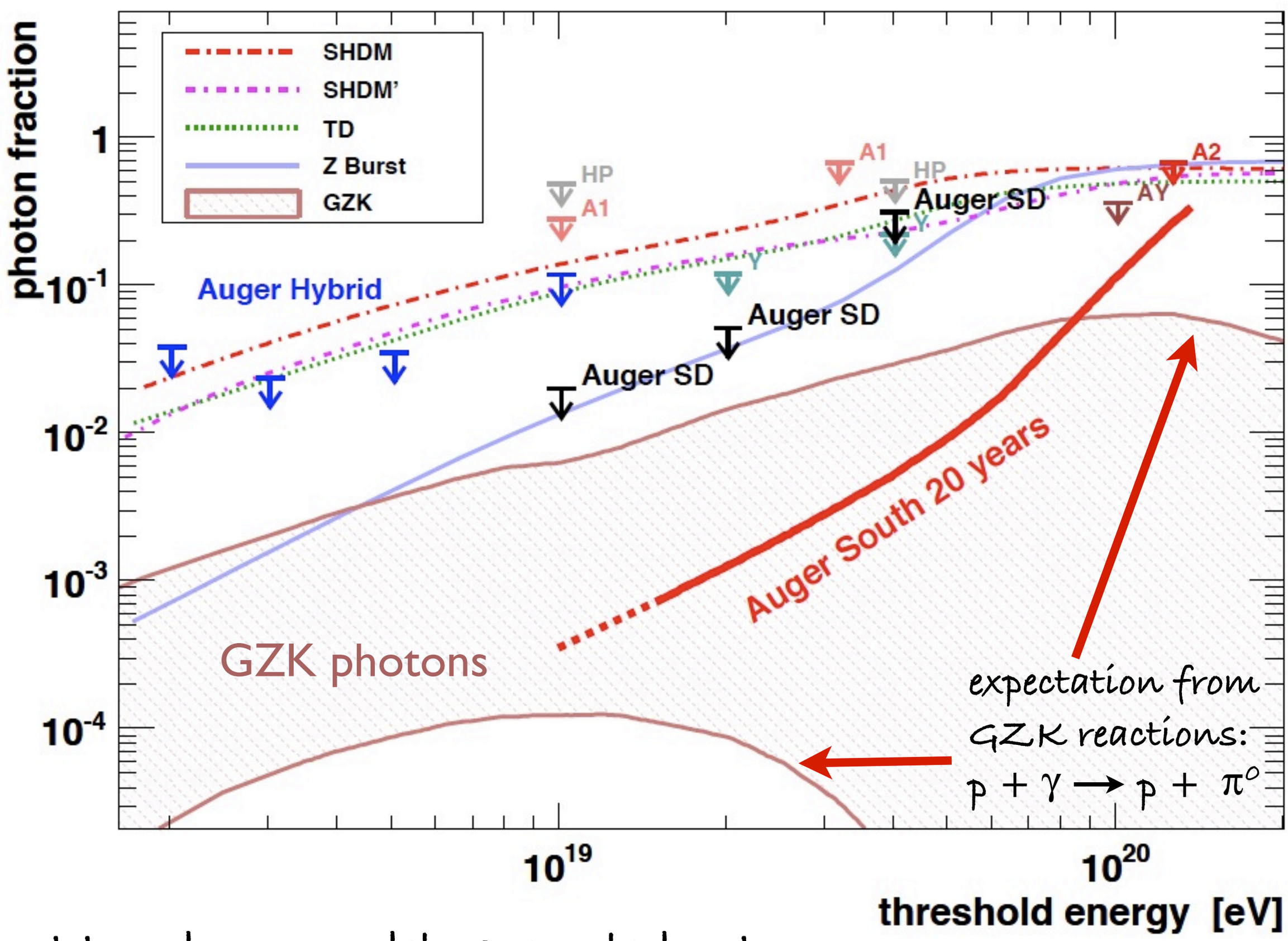


SD only variables:

- signal rise time
- curvature of shower front

SD: much larger statistics, but reconstruction not mass independent





most top-down models are ruled out,
limits improve with statistics.

Photons in Astroparticle Physics

play many roles as

probes, projectiles and targets

range from 10^{-6} - 10^{20} eV

pose many exciting questions for

research in the next decades ...