La Gamma Astronomie de très haute énergie au sol

(principes et méthodes de détection)

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OUTLINE

Part I:

- Ground systems: water and air Cherenkov systems
- Current experiments: methods, working principles and some results
- A multi-wavelength approach

Part II:

- The future challenges
- The CTA observatory

Cosmic radiation and non-thermal universe

- Cosmic Rays (CR) have non-thermal origin: their spectra do not show any « characteristic temperature » and a thermal emission mechanism to their energies does not exist.

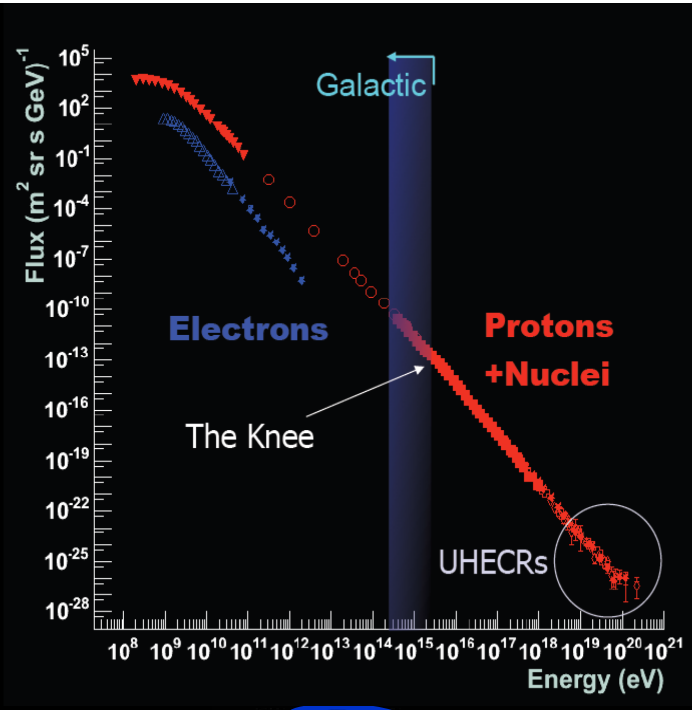
- Our Galaxy is filled up of ultra-relativistic particles:

  - energy density ~ 1eV/cm^3
    (~ e. d. of stars light, intergalactic magnetique fields , kinetidc e.d. of interstellar gas)

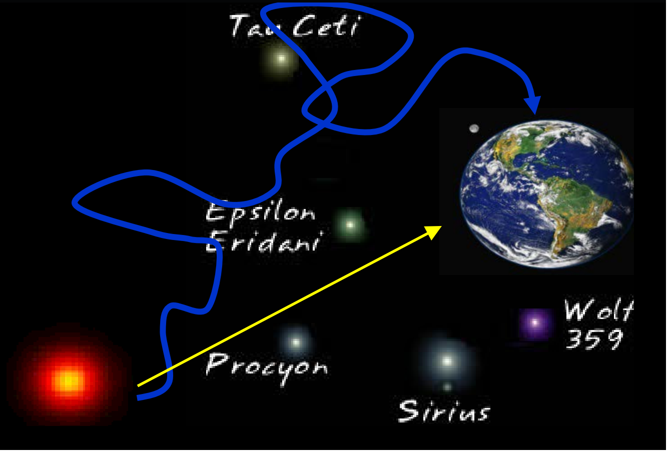
  - 99% protons + nuclei

  - of galactic origin at least up to ~ 10^{15} eV

  - charged CR are diffused by B (B_{IS}~ 3 mG)
    (directional information lost)

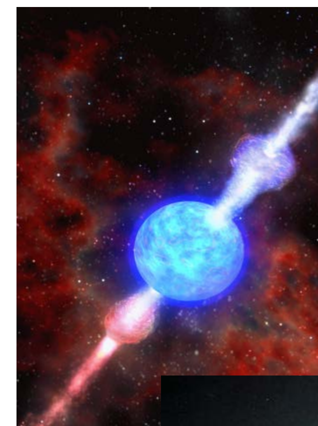


- The images of the CR accelerators are achieved by neutral (secondary) particles: ➔ Gammas (and Neutrinos) ➔ Astronomy



“High-energy gamma-ray created when cosmic rays interact with material near their acceleration sites.

Identifying the locations of cosmic ray accelerators by observing the spatial distribution and intensity of gamma rays across the sky.



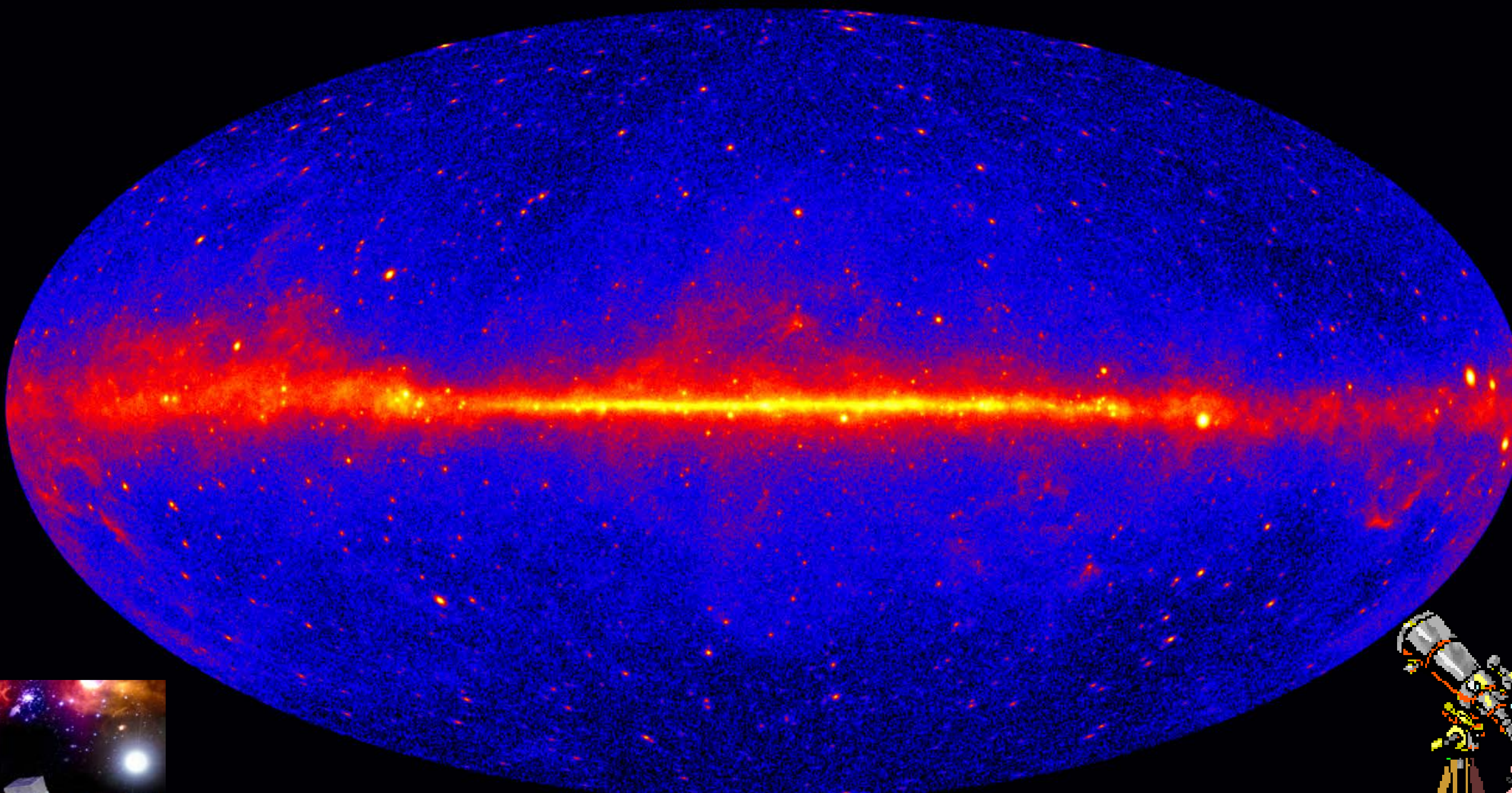
In addition, the time variability and energy spectra of the gamma-ray emission can be used to study the environment of the accelerators and the mechanisms of charged-particle acceleration. “

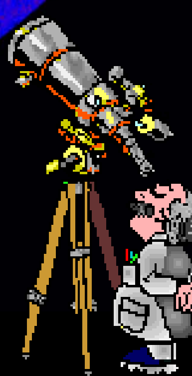
Radio Infrared Visible light X rays **Gamma rays**

$(10^9$ eV)

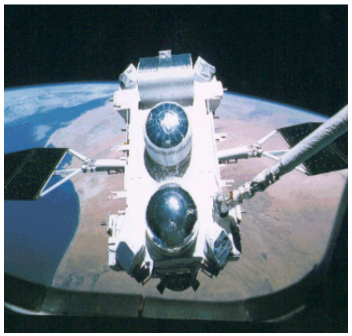
VHE

$(10^{12}$ eV)





- GeV gamma-ray Satellites: hard to launch large/heavy objects.



~ 1 m^2

γγγγγγγγγ
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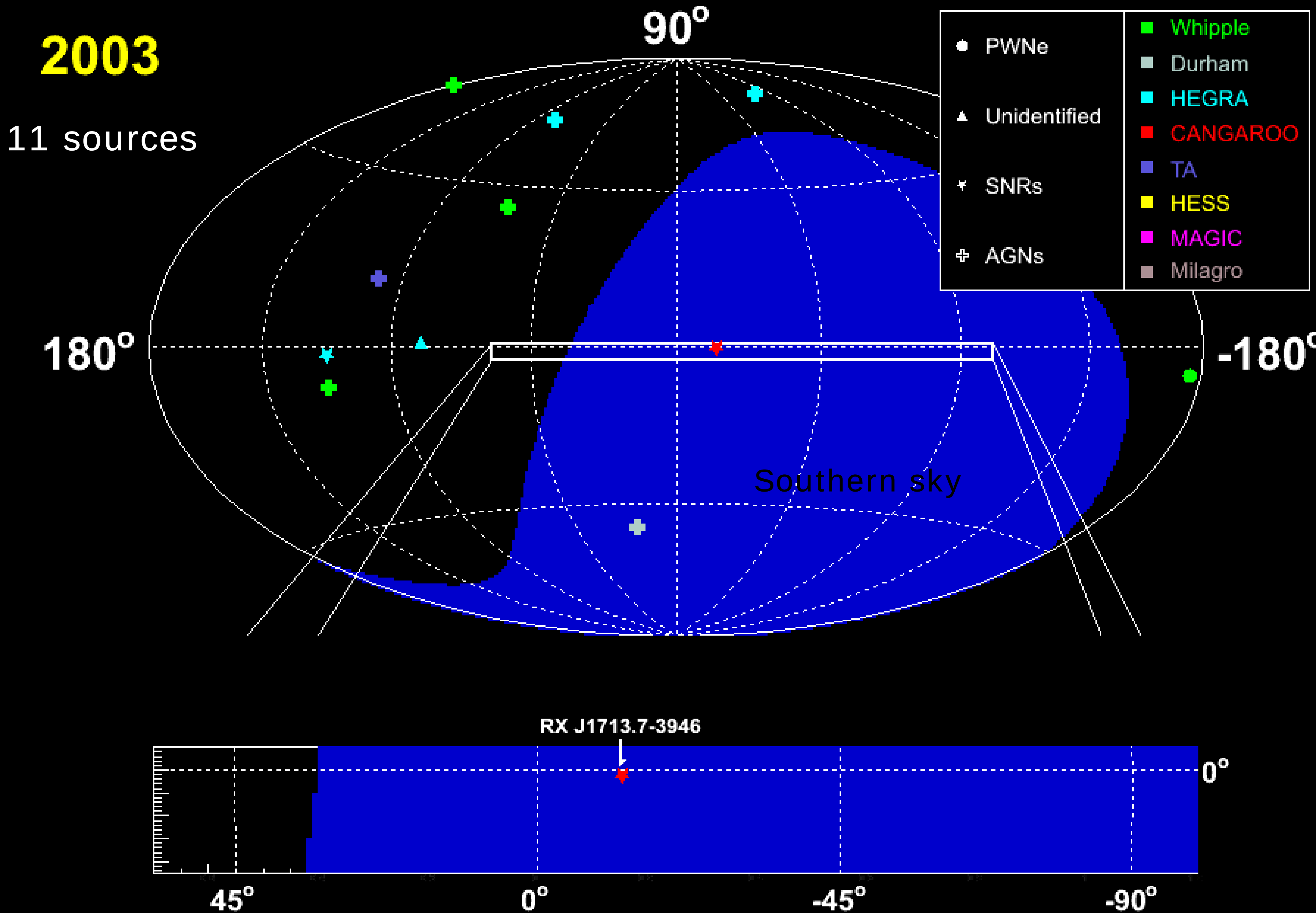
- TeV ground based (Cherenkov instruments): collection area much bigger than detectors; sensitive to fainter signals at higher energies.

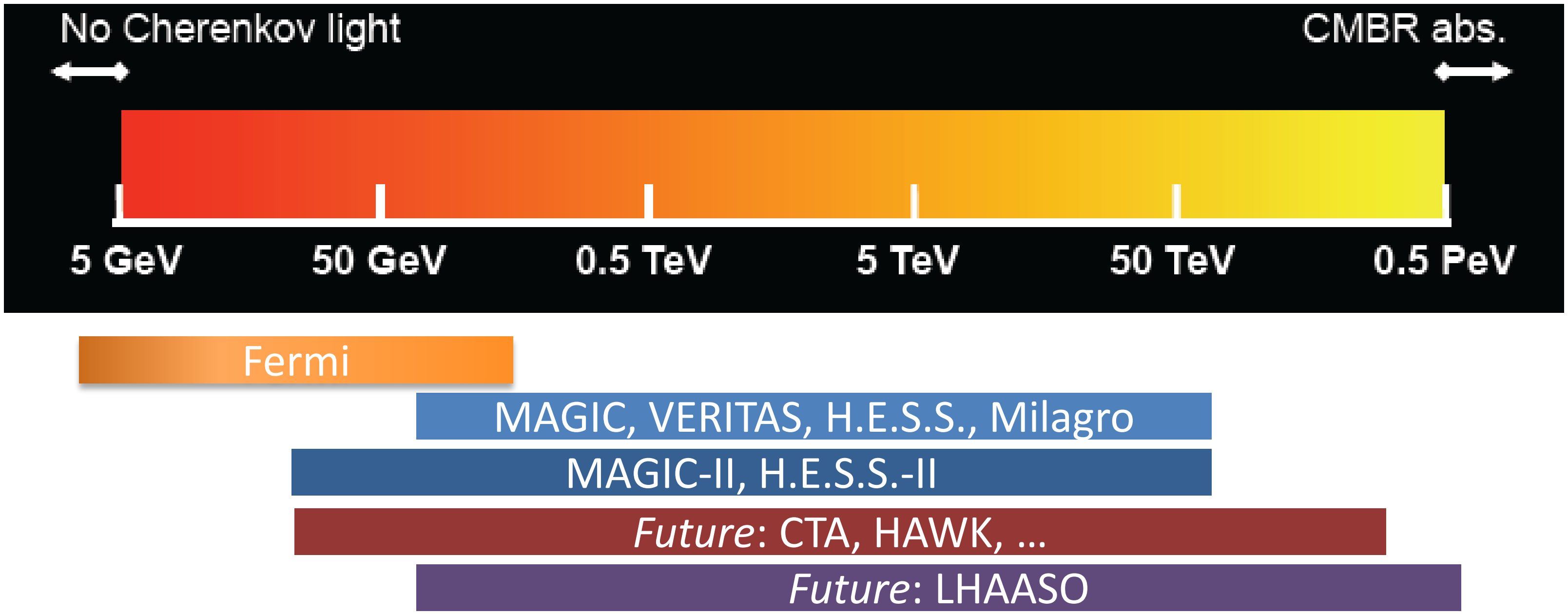
~ 10^5 m^2

γγγ

Visible light X rays Gamma rays VHE gamma rays



Ground based detectors

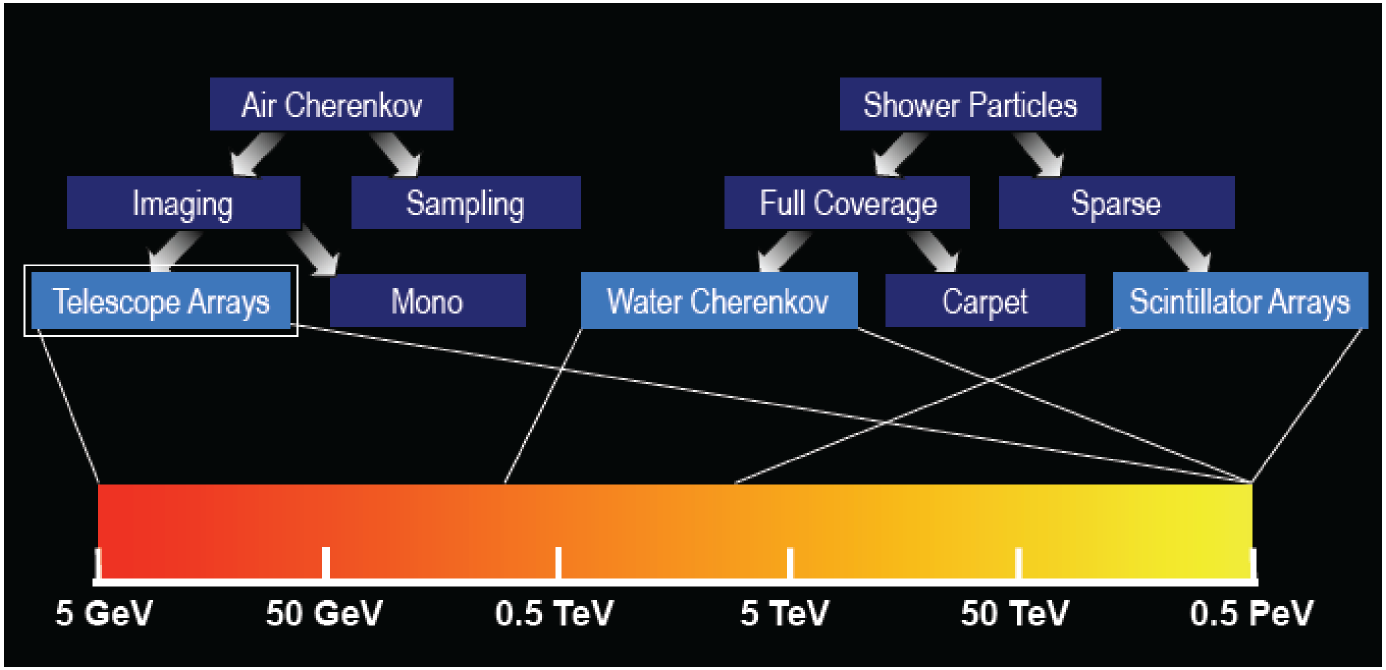


- 5 decades of energy are accessible from the ground for gamma-ray astronomy
- ~ 1 decade of overlap possible with satellites

Ground based techniques

- Many different approaches have been tried
- Major projects planned using three of them

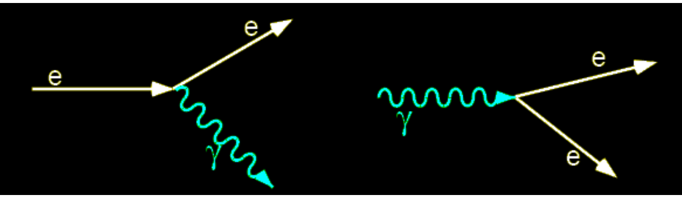
  All use ***air-showers***



In the following we focus on two currently successful examples:

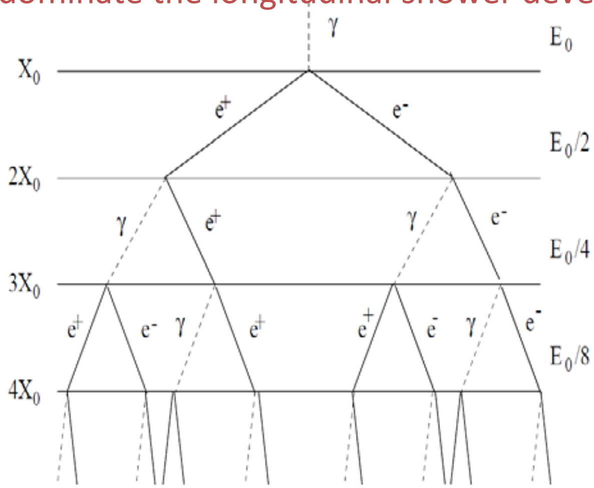
- "<u>Water Cherenkov Air Shower systems</u>".
- "<u>Imaging Air Cherenkov Telescopes</u>".

Air showers



Heitler Model:

Bremsstrahlung and pair-production dominate the longitudinal shower development

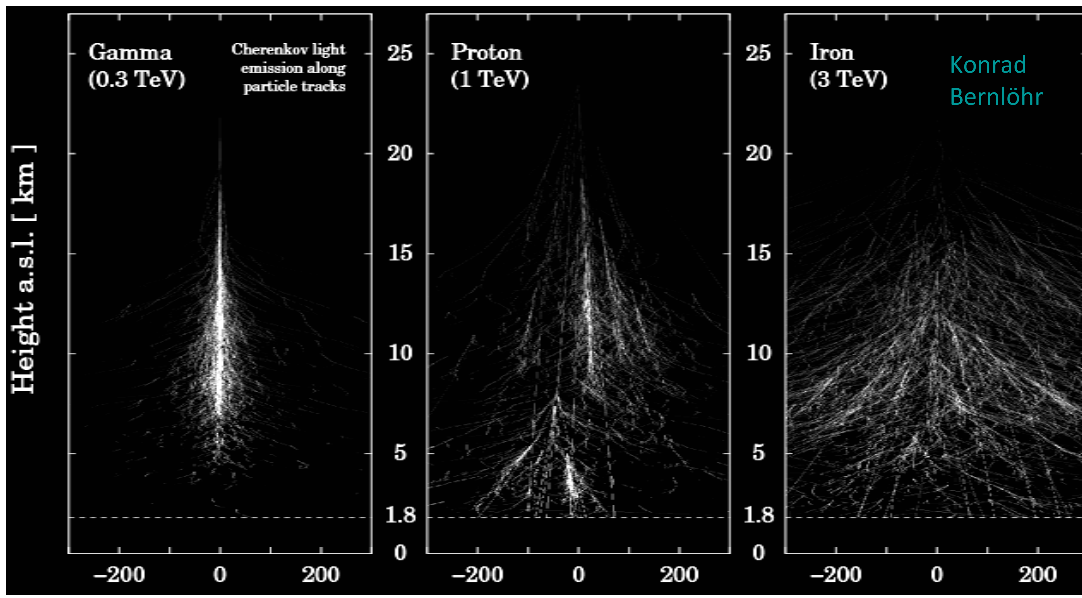


The atmosphere as a caloremeter:

- 1000 gr/cm² thick
- $\rho = \rho_0 \, e^{-h/h0}$, $h_0 \sim 8$ km

The electromagnetic shower:

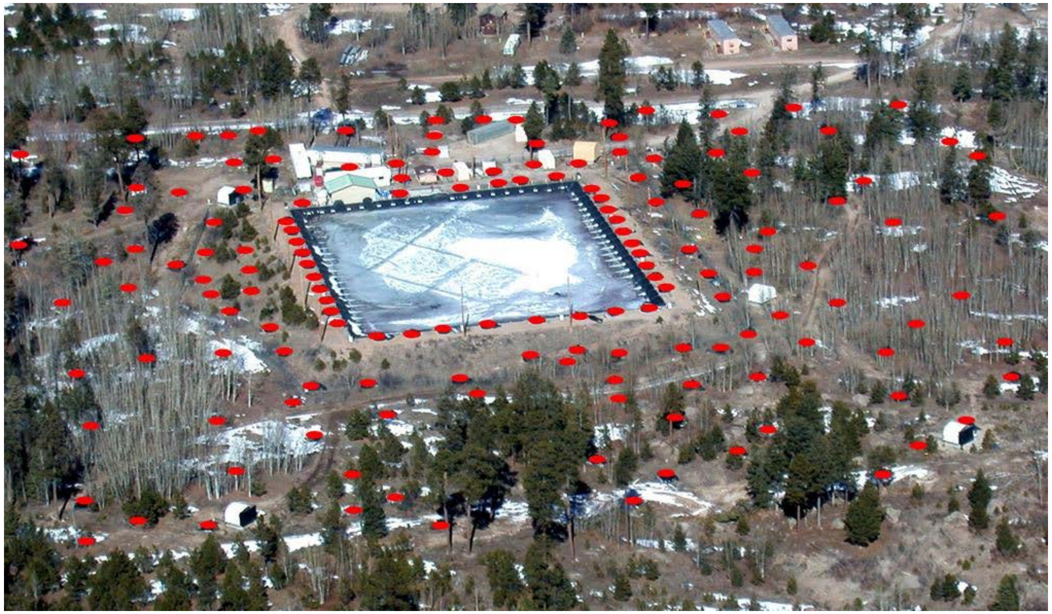
- $X_0 \sim 40$ gr/cm², $\lambda_{pair} \sim X_0$
- First interaction @ ~20 km
- Maximum shower evolution @ ~ 10 km (for a 1 TeV photon)
- $X_{MAX} \sim \log(E_0)$
- The number of electrons at the maximum of the shower is proportional to the gamma primary energy



Shower morphology (and imaging):

- Gamma-showers more compact
- Proton-showers more disrupted and sub-structured

Water Cherenkov air shower system, e.g. MILAGRO



- Altitude of 2630 m above sea level (near Los Alamos)
- A central water reservoir covering ~4000 m^2
- Surrounded by an array of 175 water tanks covering ~34,000 m^2 (the outrigger array)

In operation in 2000.
The outrigger array completed in 2003.
Operations ceased in April of 2007.

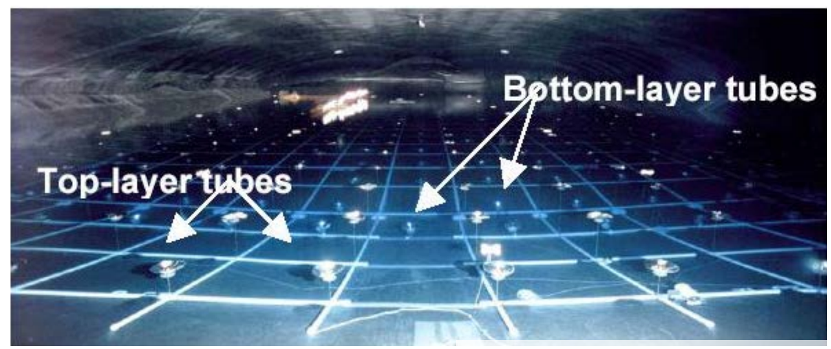
- Angular reconstruction accuracy 0.5°-1.4°
- Most of the effective area at TeV energies
  - ~10^5 m^2 @ 10 TeV
  - ~10 m^2 @ 100 GeV
- Median energy of triggers ~few TeV (for a Crab-like source)

Performance:
-Wide field of view (~2 sr)
-High duty cycle (~90%)
- Good for unbiased whole-sky searches, observations of large-scale features & anisotropies, monitoring for transient emissions (flares, GRBs).
Crab-like source: Milagro ~8σ/sqrt(year)

Water Cherenkov air shower system, e.g. MILAGRO

The central detector:

- 24-million liter of highly purified water reservoir.
- 80m x 50m with a depth of 8m at the center.
- Two layers of 20cm photomultiplier tubes (PMTs).
  The top layer of 450 PMTs is under 1.5 meters of water
  The bottom layer of 273 PMTs is under 6m of water.
  Both layers are on a 2.8m x 2.8m grid.
- The reservoir is enclosed with a light-tight cover.

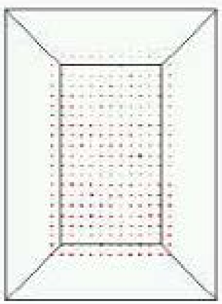


The Outrigger Array:

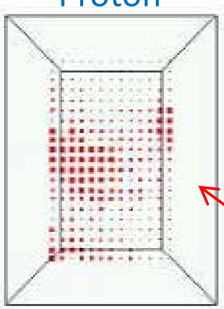
- Each water tank has an area of $8m^2$ and a depth of $\sim$1m.
- A single PMT is mounted at the top looking down into a TYVEK lined water volume.

Water Cherenkov air shower system, e.g. MILAGRO

Gamma-ray



Proton



- ***Air Shower Layer (+ outrigger array)**:*
  - *Triggering*
  - *Direction Reconstruction*

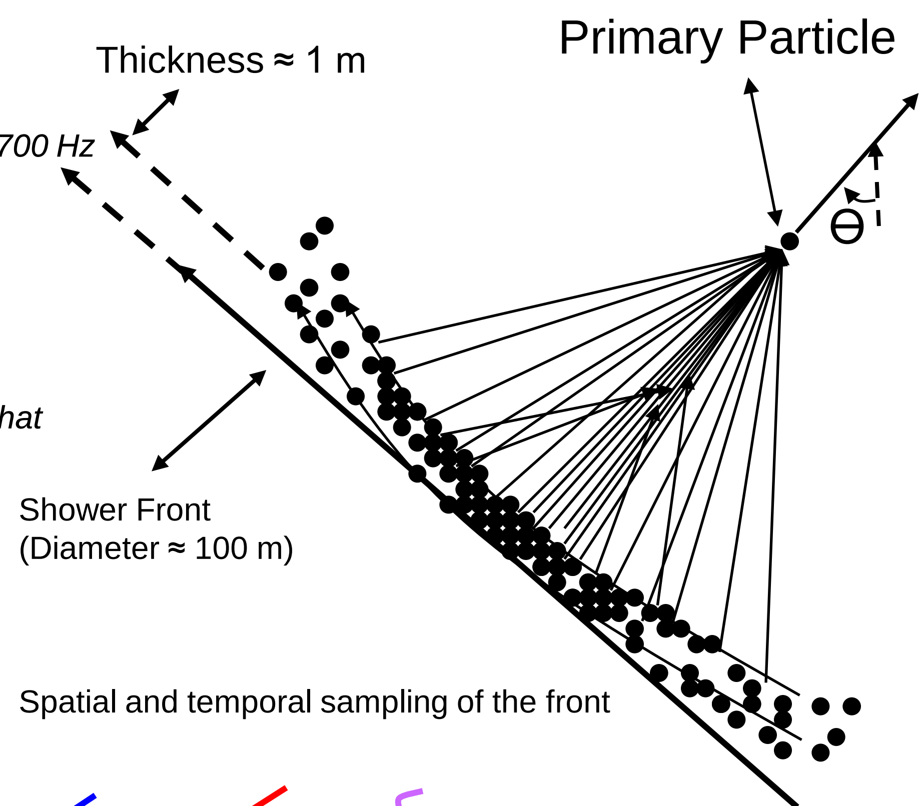
Trigger rate (before background rejection) is ~1700 Hz

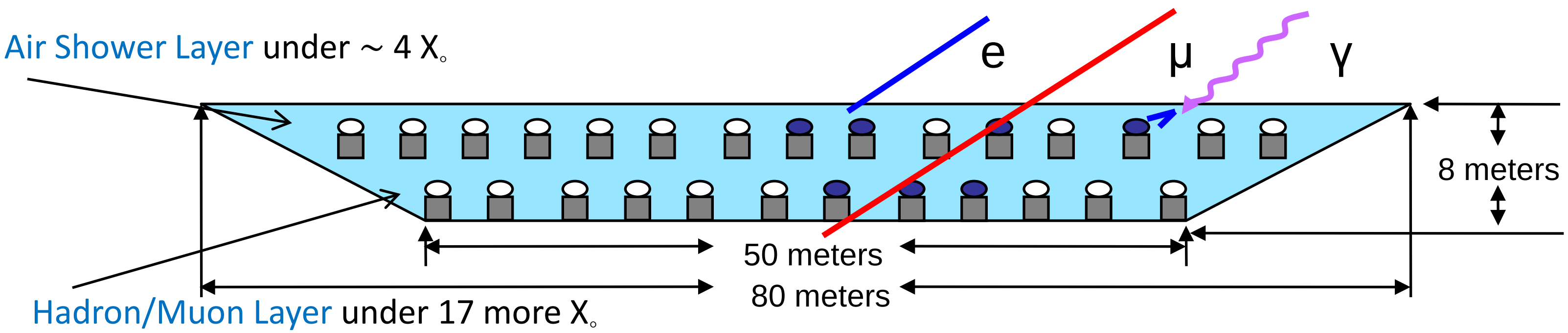
- ***Hadron/Muon Layer**:*
  - *Background Rejection*
  - *Energy Reconstruction*

Air showers induced by hadrons contain a penetrating component (muons and hadrons that shower in the reservoir)…..

μ as low as 1.2 GeV can penetrate and shower near the muon layer

Red areas proportional to the PEs

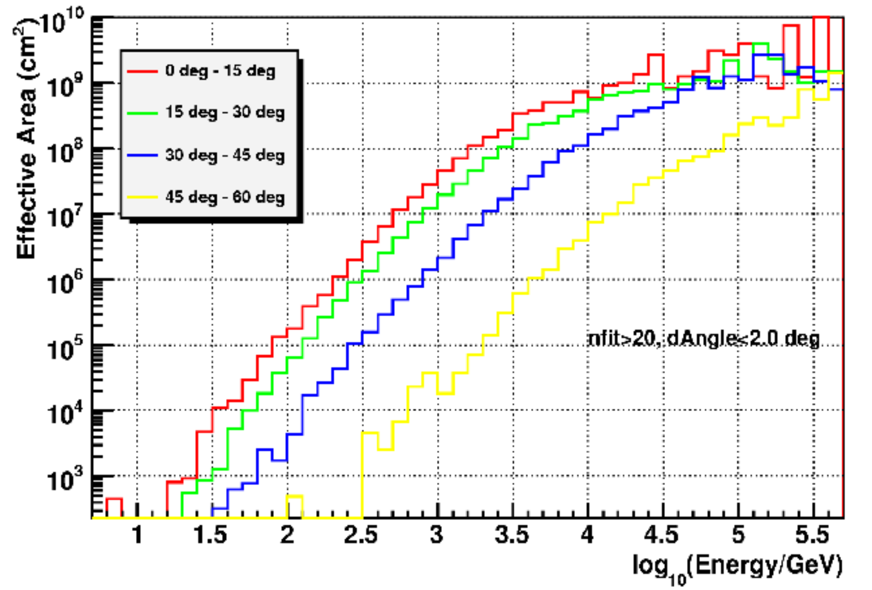




Water Cherenkov air shower system, e.g. MILAGRO

Movies:
1) 2 TeV Gamma Shower evolution.
2) 2 TeV Proton Shower evolution.
3) 2 TeV Gamma Shower entering MILAGRO
4) (same from bottom)
5) 2 TeV Proton Shower entering MILAGRO

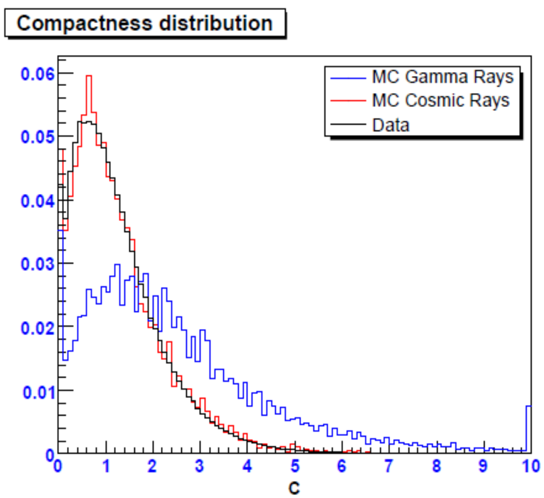
http://umdgrb.umd.edu/cosmic/milagro.html



Gamma-Hadron Separation:

- Using Monte Carlo simulations, a muon and/or a hadron that enters the pond: 80% of all proton showers and only 6% of gamma ray induced air showers that trigger Milagro.

- A compactness parameter about the clumpiness in the muon layer is used.

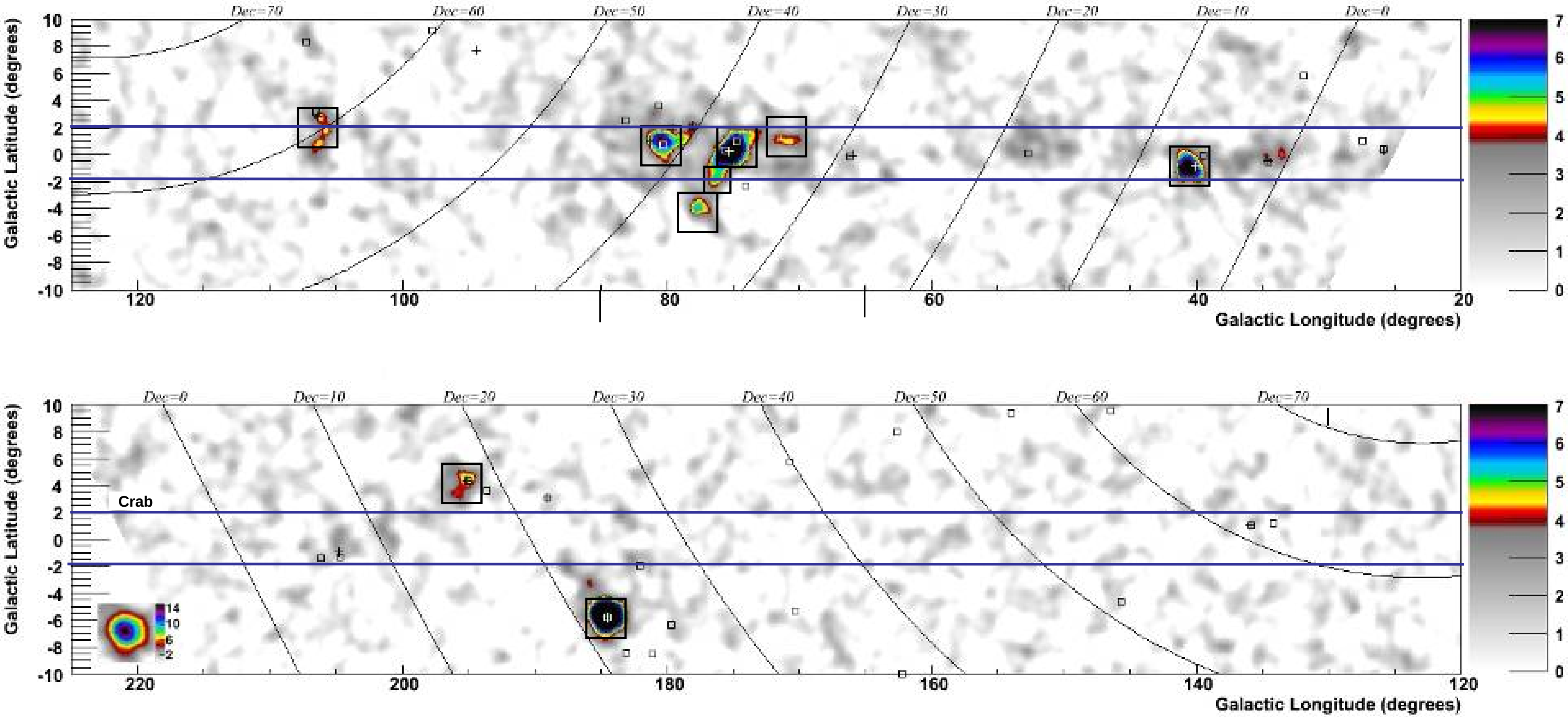


Gamma efficiency and resolutions:

- Shower front is fit to a plane to reconstruct the direction (AS layer + outrigger): ΔAngle.

- Rather broad energy response: no well defined energy threshold;
- Median triggered Gamma energy (function of the zenith angle) ~ 3.5 TeV (95% of a -2.4 spectrum between 0.4 and 70 TeV)

Some MILAGRO results

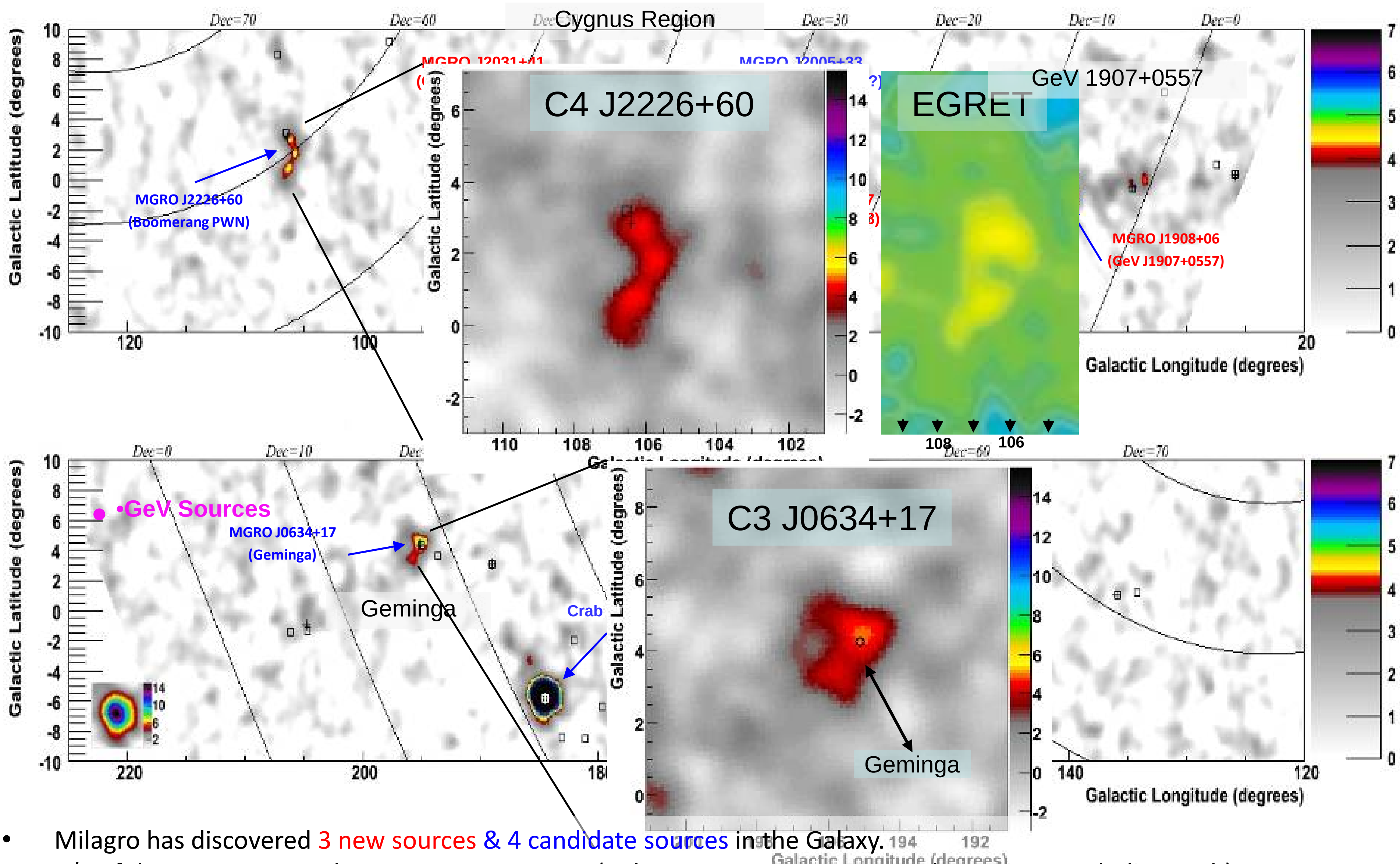


- Mapping of the diffuse Galactic gamma-ray emission at TeV energies.
- Discovery of a new (slightly extended) source (MGRO J2019+37) of TeV gamma rays embedded in the Cygnus Region.
- 14 out of 34 Fermi-LAT counterpart PWN observed by Milagro.

[…]

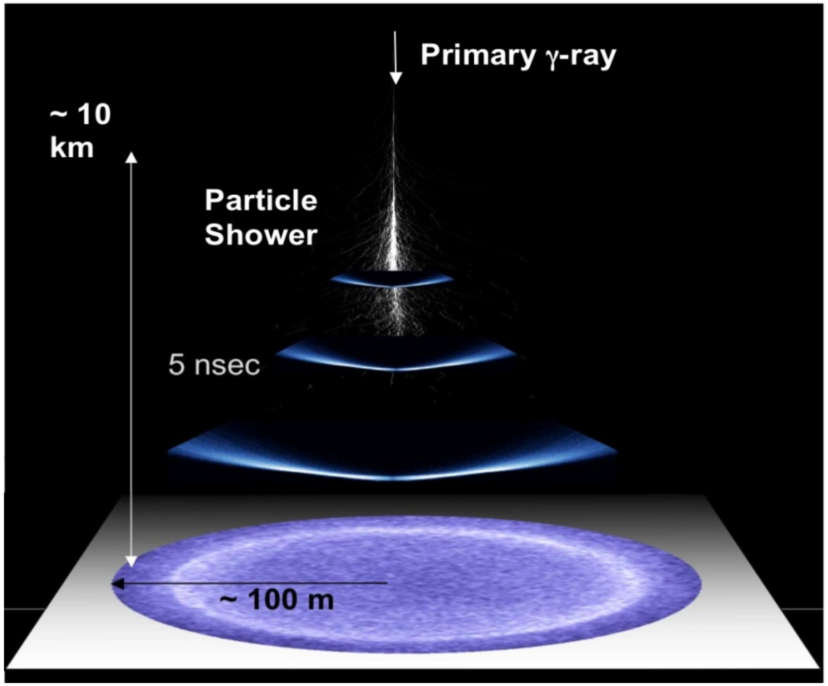
… More listed in http://umdgrb.umd.edu/cosmic/results.html

Some MILAGRO results



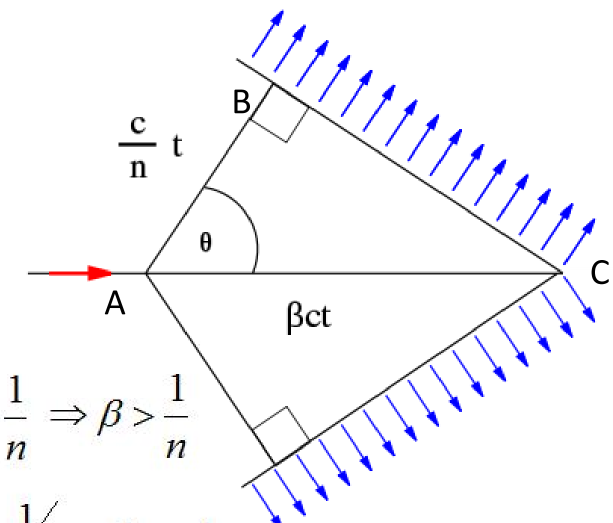
- Milagro has discovered 3 new sources & 4 candidate sources in the Galaxy.
- 5/7 of these TeV sources have GeV counterparts (only 13 GeV counterparts in this region - excluding Crab)

Detection based on Cherenkov radiation



Cherenkov radiation is emitted when a charged particle (such as an electron) passes through a dielectric medium at a speed greater than the phase velocity of light in that medium. The charged particles polarize the molecules of that medium, which then turn back rapidly to their ground state, emitting radiation in the process.

Cherenkov Effect



$$v > \frac{c}{n} \Rightarrow \frac{v}{c} > \frac{1}{n} \Rightarrow \beta > \frac{1}{n}$$

$$\cos\theta = \frac{AB}{AC} = \frac{1/n}{\beta} = \frac{1}{n\beta} = \frac{1}{n}$$

Opening angle for Cherenkov light:

θ = arccos(1/nβ), for β = v/c ~ 1:

1.4° in air at sea level, decreasing with altitude *(n = 1.00029 at sea level)*;

42° in water

Cherenkov radiation: arrival time

- Pile-up at Cherenkov "shoulder" at ~120-150 m: … forming the light ring in the pool

-> *Close to shower axis*:

Travel time for Cherenkov photons is

$t_2 \sim h / (c/n) \sim 20\ \mu s$

Travel time difference between photons from the top and bottom of the shower is

$t_2 - t_1 \sim (n - 1) \times L / c \sim 3e\text{-}4 * 5e3/3e8 \sim 5\ ns$

Last emitted photons arrive first !

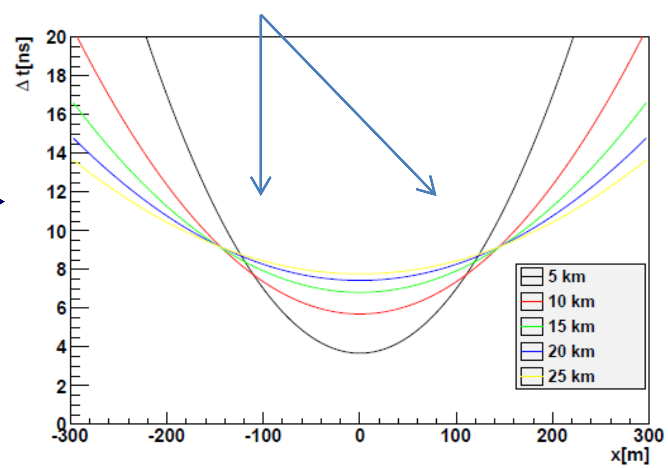
-> *Far from shower axis*

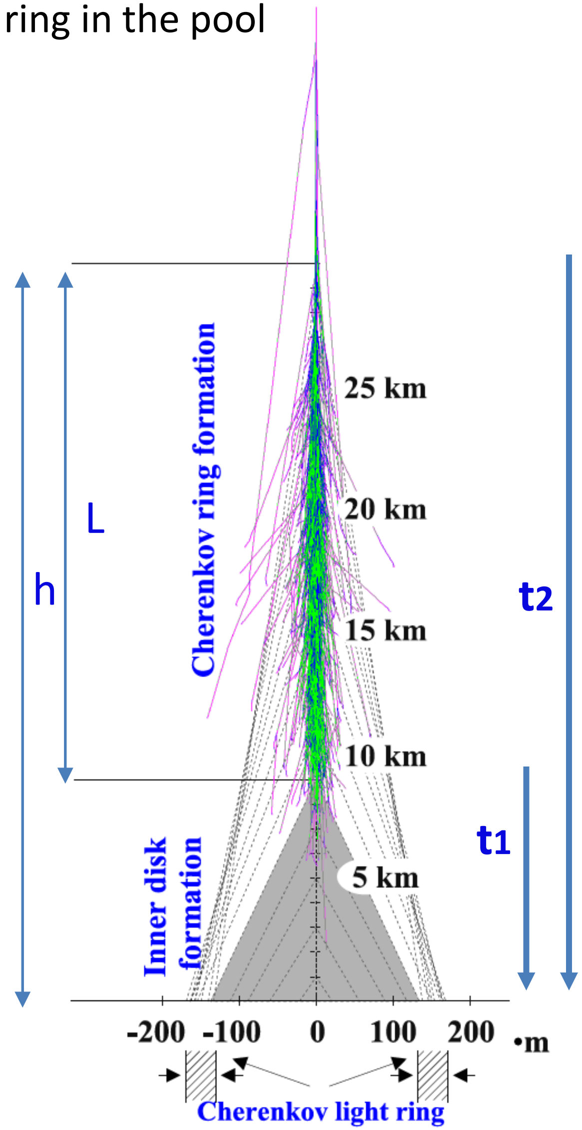
Path length difference dominates over refractive index effect

First emitted photons arrive first

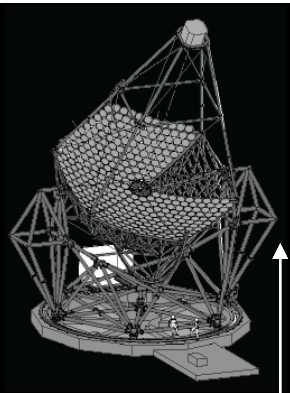
-> *Smallest time-spread at "shoulder"*

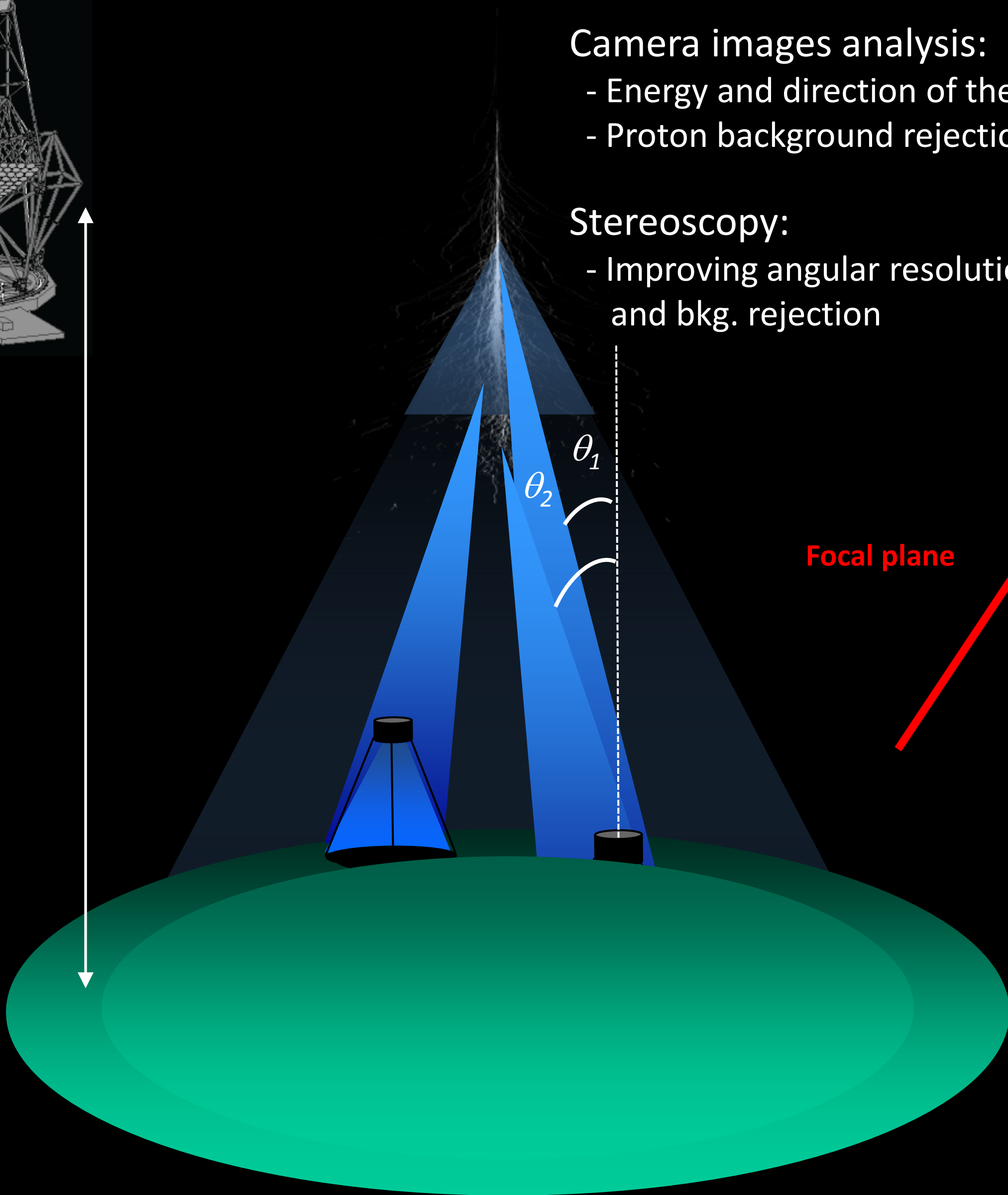
The time difference between the projected arrival time of the primary on the ground and the photons →





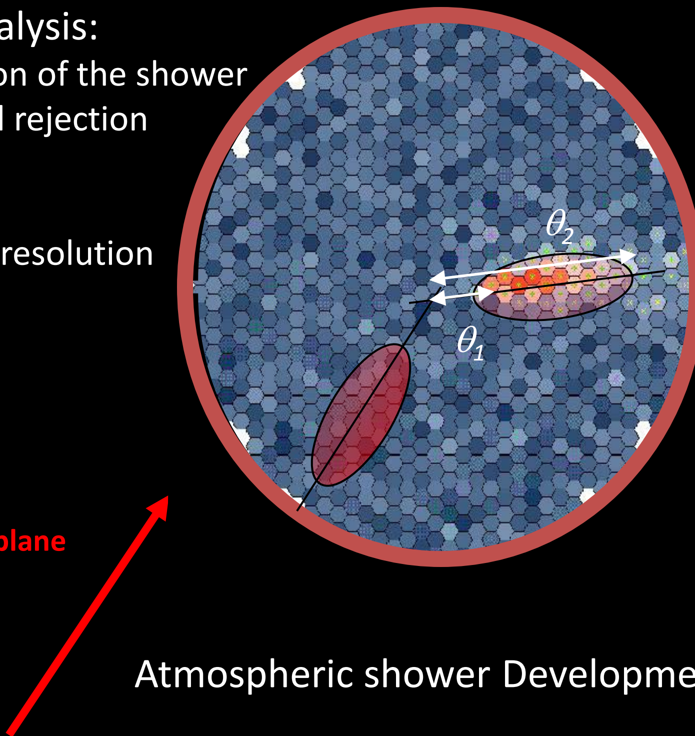
VHE γ-ray Imaging Air Cherenkov System





Camera images analysis:
- Energy and direction of the shower
- Proton background rejection

Stereoscopy:
- Improving angular resolution and bkg. rejection



Focal plane

Atmospheric shower Development:

- Cherenkov light cone: α=1° at 10 km
- Flash of “blue light “lasting 5 ns
- <u>Spectrum</u>: $dN/d\lambda \propto 1/\lambda^2$ → continues into UV but mostly absorbed in the atmosphere
- Pool surface of 100 m radius
- <u>Yield</u>: 30 photons/metre in air for one Z=1 charged particle at sea level ($\propto Z^2$)

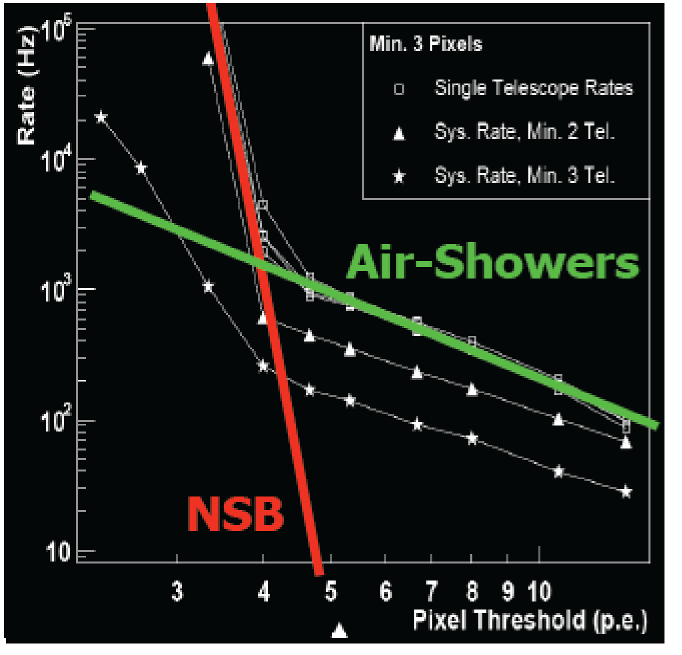
→ *Cherenkov yield ∝ total path length ∝ E0*

IACT: trigger

NSB (Night sky background):
Air-glow, stars, … ~1 photon every 10 ns
for a 100 m2 telescope with 0.15° pixels

Gate width:
Cherenkov pulse is a few nanoseconds wide
(impact dependant)
Telescope optics may introduce a few ns spread

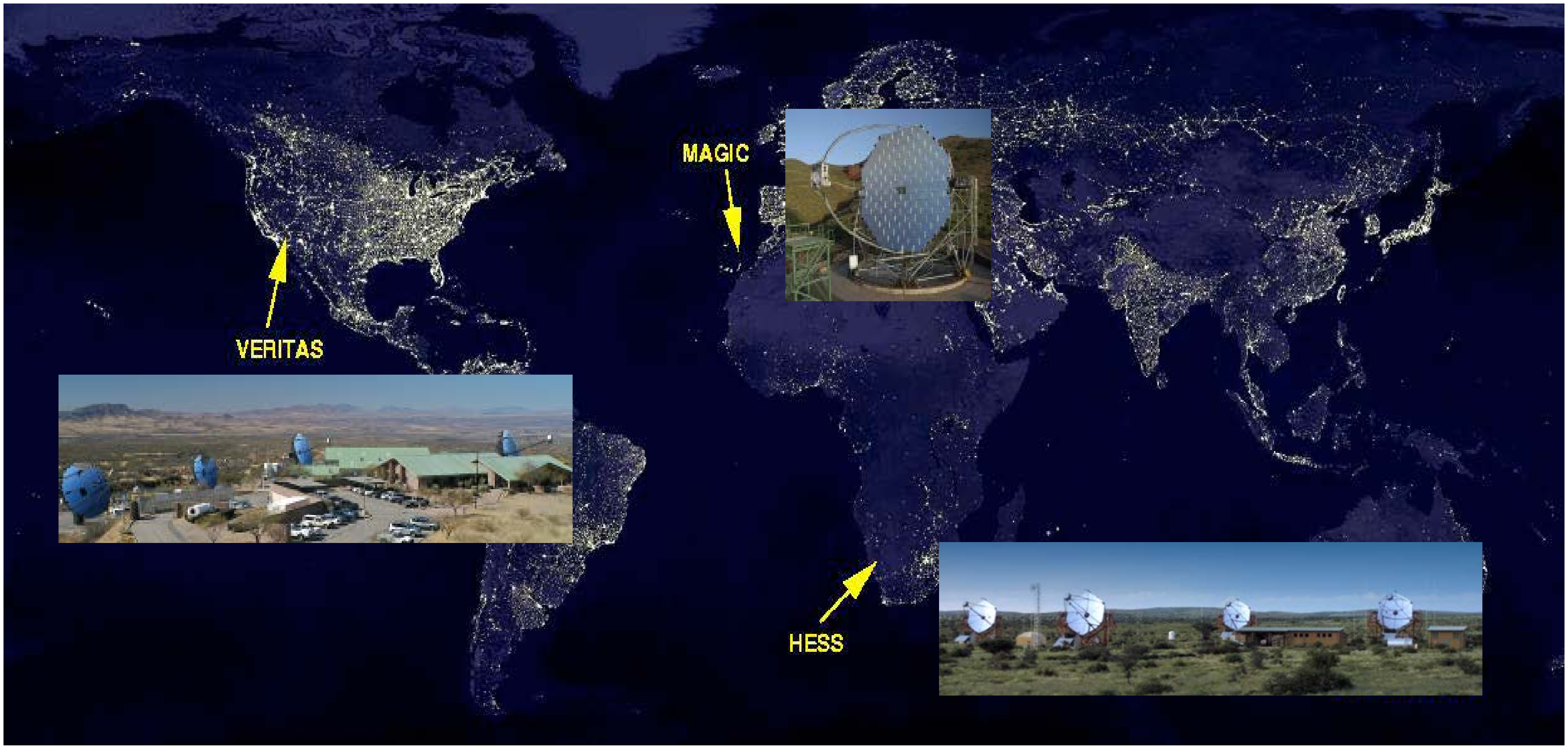
Cosmic ray trigger rate:
~ kHz for 100 GeV threshold, 5° field of view



Camera trigger:
Signal in ~ 3 neighboring pixels over threshold ~ 4 p. e.
within 1.3 ns -> leading to ~ 1.5 kHz single camera rate

The main VHE IACT

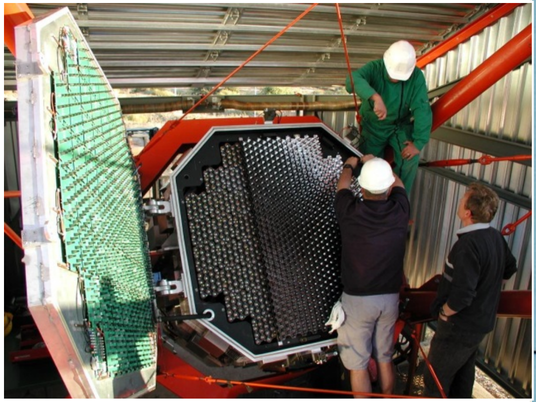
The current (succesful) generation of Imaging Atmospheric Cherenkov Telescopes



- A mature discipline
- Towards a new wavelength astronomy in the next decade

H.E.S.S.: High Energy Stereoscopic System

System of 5 telescopes on the Khomas island, in Namibia (1800 m)
(4 telescopes in operation since 2004):



- 13 m diameter mirror (*dish*): 107 m^2
- 15 m focal distance
- Camera with 960 pixels of 0.16°
- Good gamma-hadron discrimination
  (rejection factor ≈ 10000 for pointlike sources)

- Sensitivity within 100 GeV – 100 TeV
  (Crab nebula detected in 30 s and 1% du Crab in 25 h)

- Moon-free observations: ~1000 h / an
- 15% energy resolution

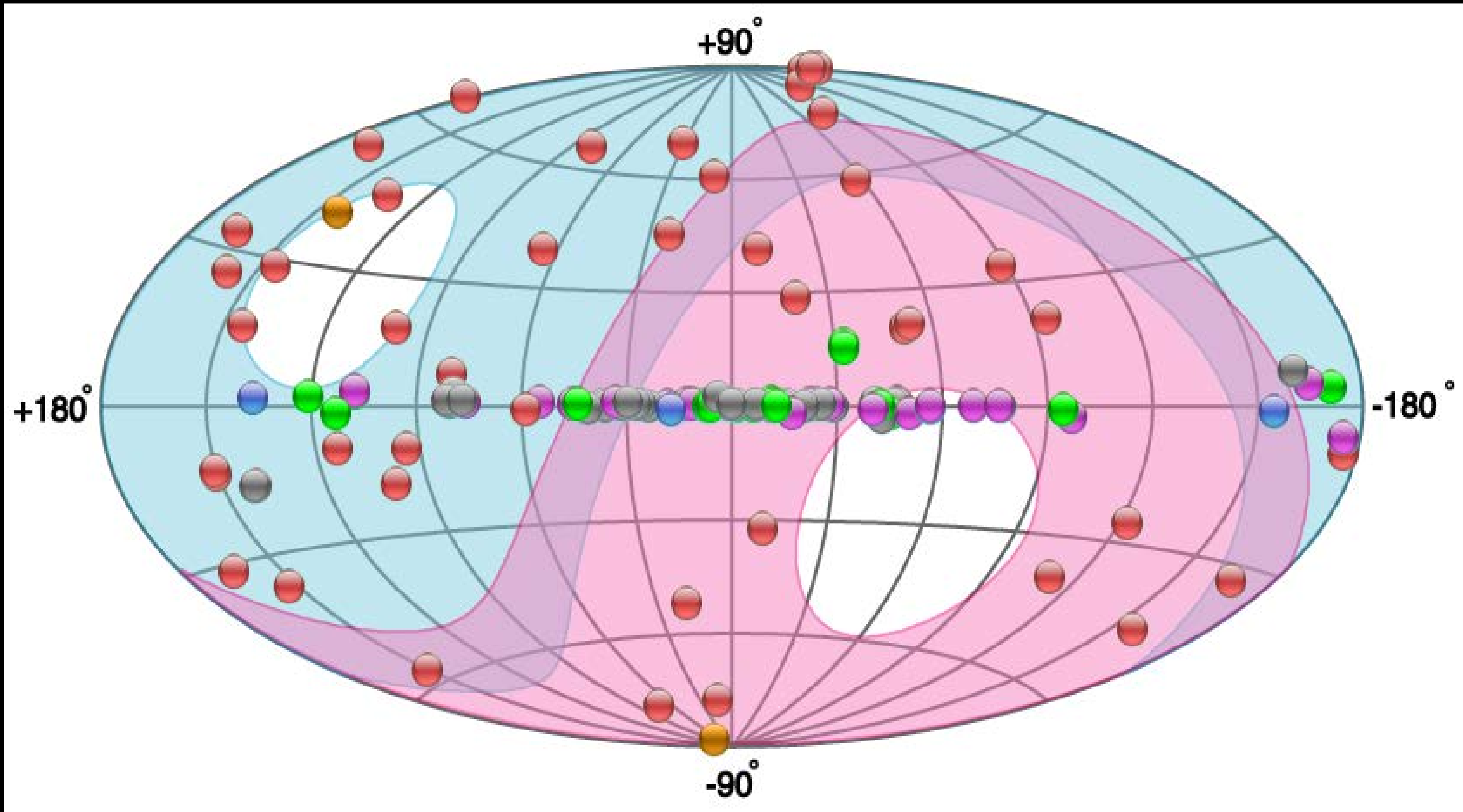
- 4' - 6‘ angular resolution **… but limited FoV** (5° diameter → sources need to be followed up

$$E_{\mathrm{seuil}} \propto \sqrt{\frac{\Omega \Delta t \phi_{\mathrm{nsb}}}{\mathrm{A}\epsilon}}$$

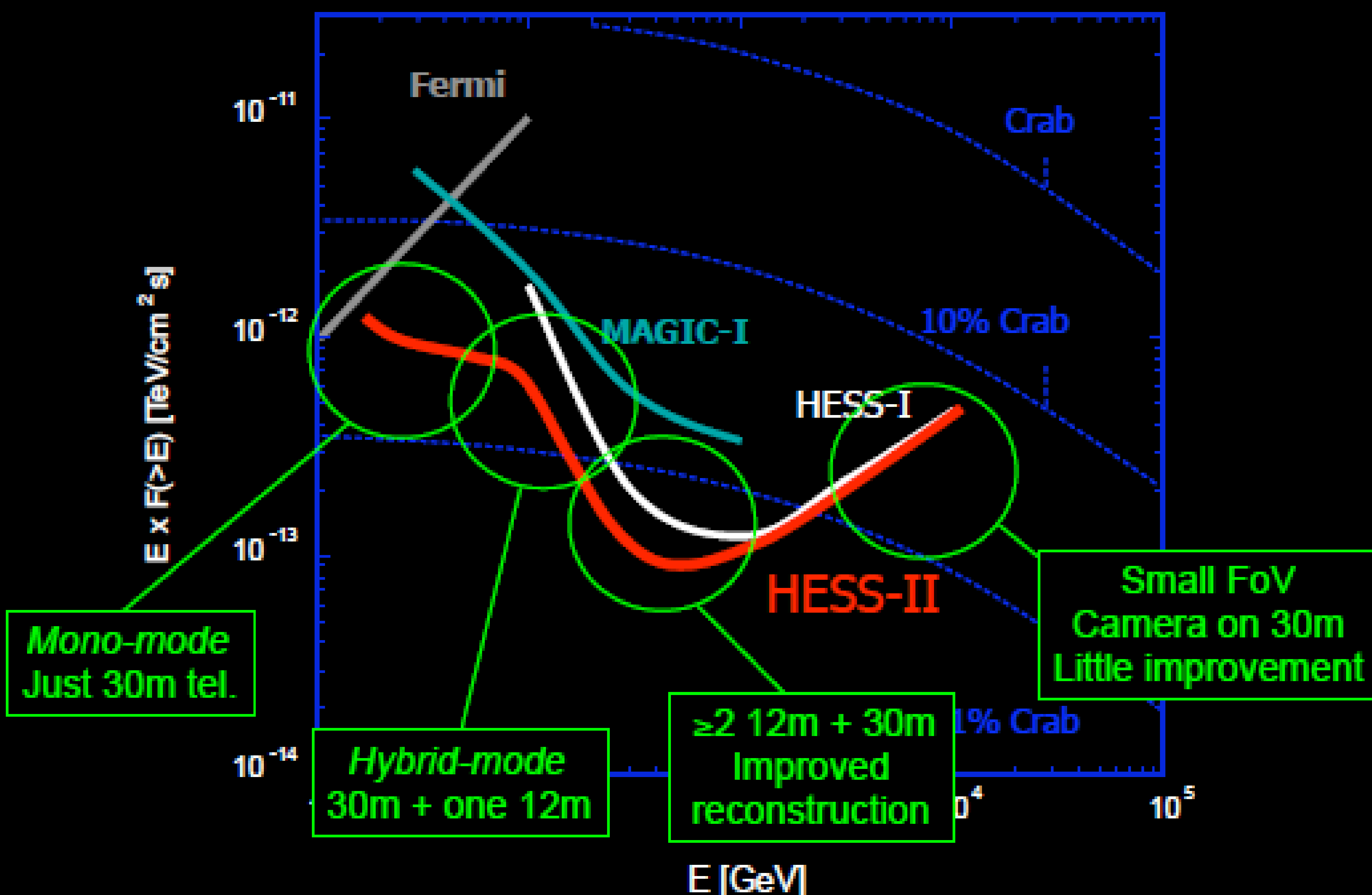
HESS 2 (5th telescope since 2013) :
- 2048 pixels (0.07°)
- 3.5° (f.o.v.)
- 30 m *dish*
- **Lower energy threshold**

Visible light X rays Gamma rays VHE gamma rays

> 100 VHE sources



Visible light X rays Gamma rays VHE gamma rays



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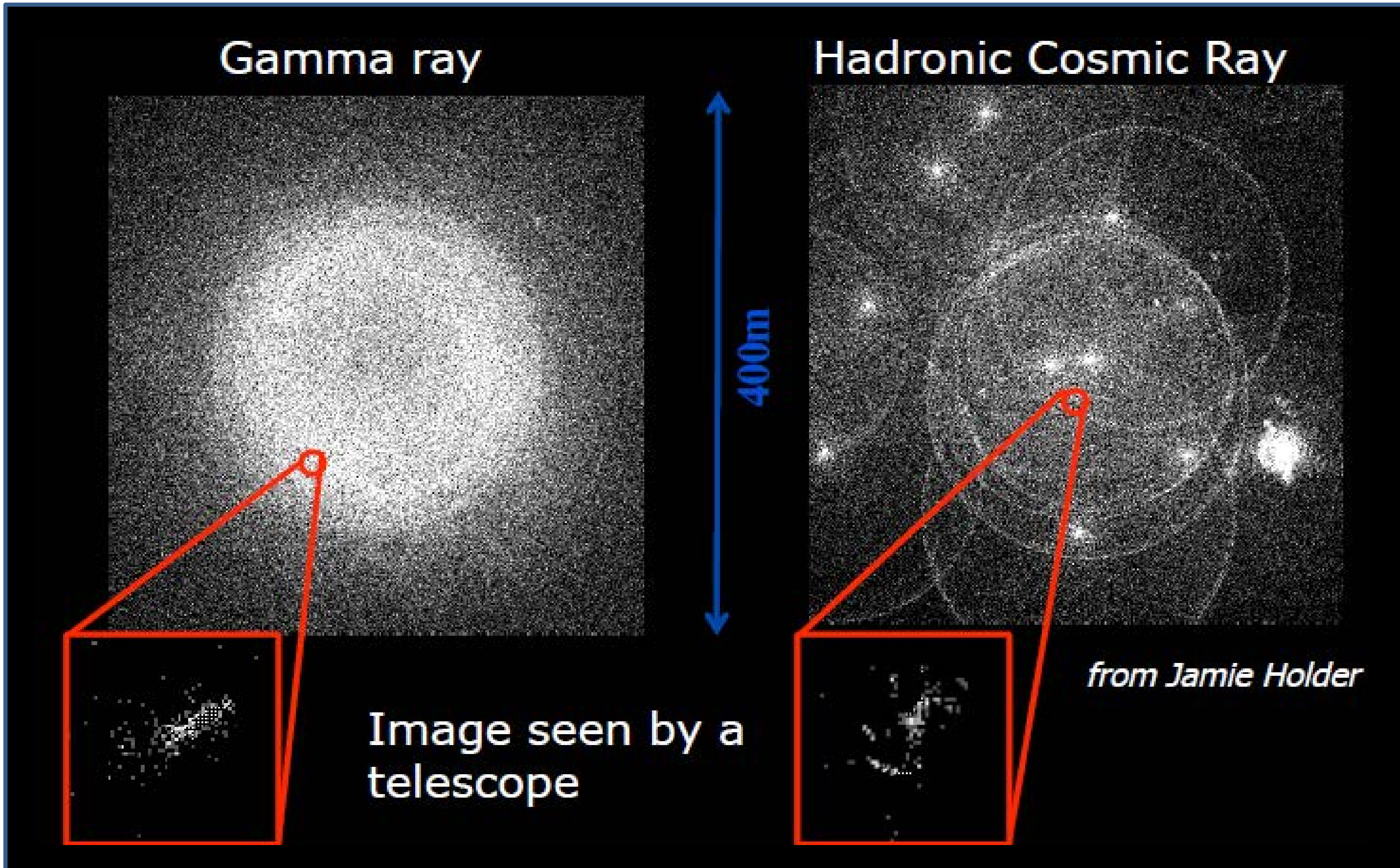
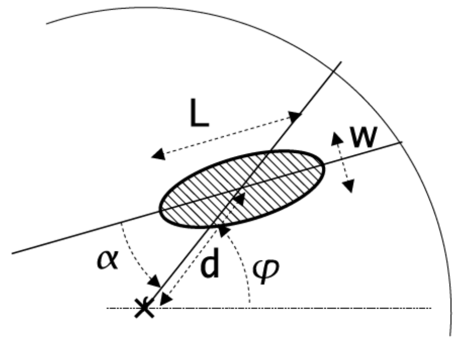


Background suppression and subtraction

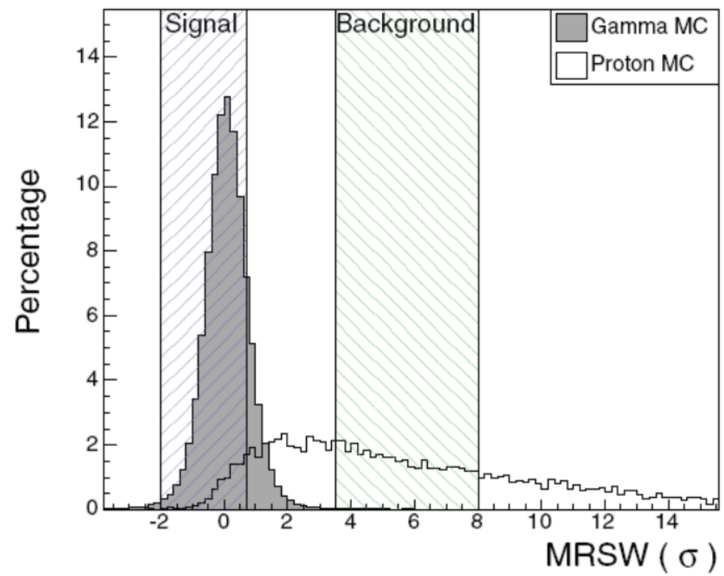
CERENKOV LIGHT IMAGES OF EAS PRODUCED BY PRIMARY GAMMA RAYS AND BY NUCLEI

A. M. Hillas

- length L and width w of the ellipse
- size (total image amplitude)
- nominal distance d (angular distance between the centre of the camera and the image centre of gravity)
- azimuthal angle of the image main axis ϕ
- orientation angle α



Main difference: Gamma-showers are narrower, e.g. Mean Reduced Scaled Width



Many other differences:
- Image Length
- Xmax
- Sub-structure
- Distribution on the ground
- Time structure

(Width - Expected Width) / (Expected Spread)

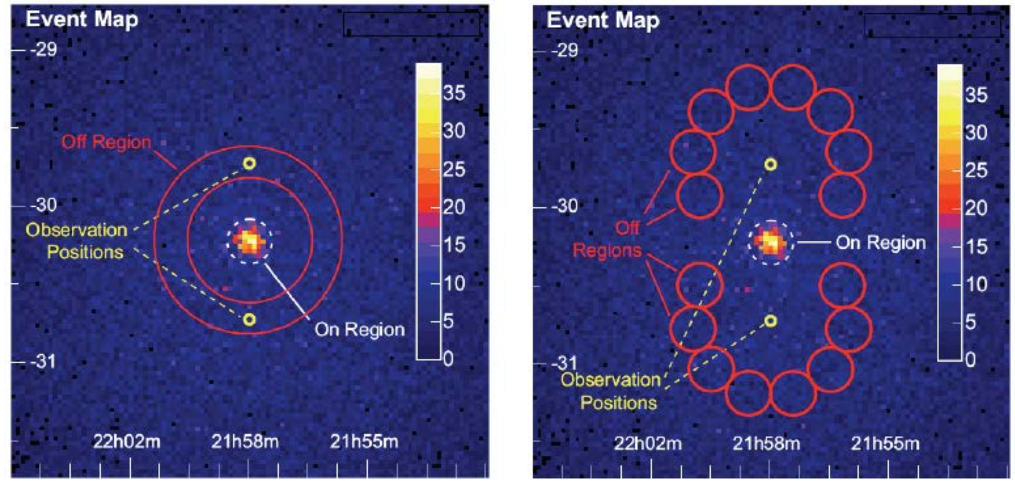
Functions of image size and impact distance

Background suppression and subtraction

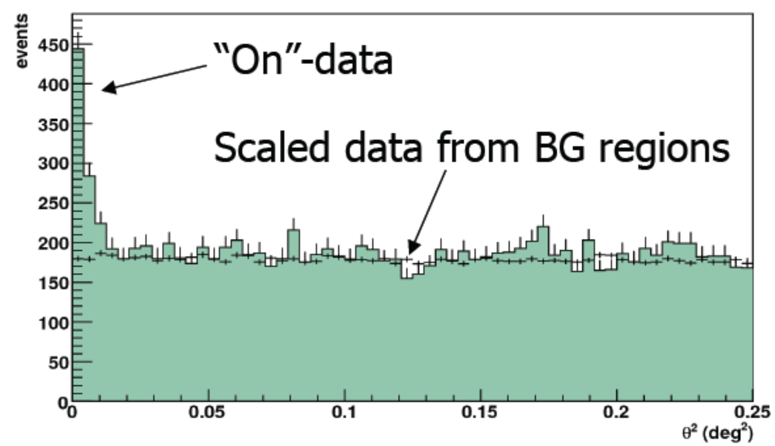
Can never get rid of all background

Residual background needs to be modelled and subtracted:

Different methods:
- On/Off, ring, reflected, …

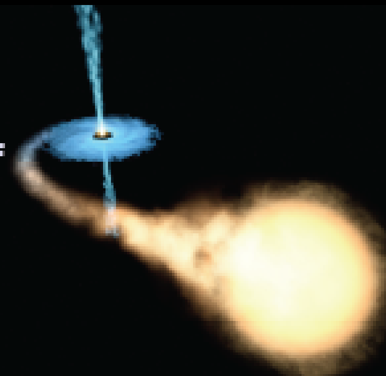


Generally :
  -Define off region larger than on-region
  -Geometric scaling factor
 - Subtract

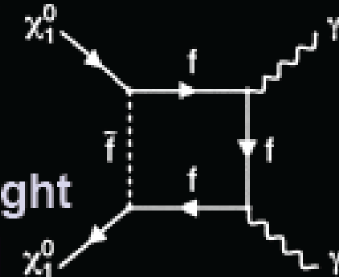


What we can learn using VHE Gamma rays?

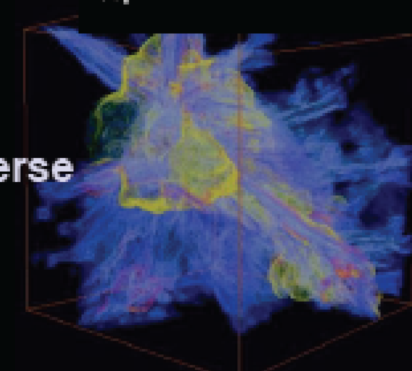
- High energy astrophysics
  - Acceleration, propagation and energy losses of ultra-relativistic particles in astrophysical environments
    - Specific question:
      - Where are the "cosmic rays" accelerated?

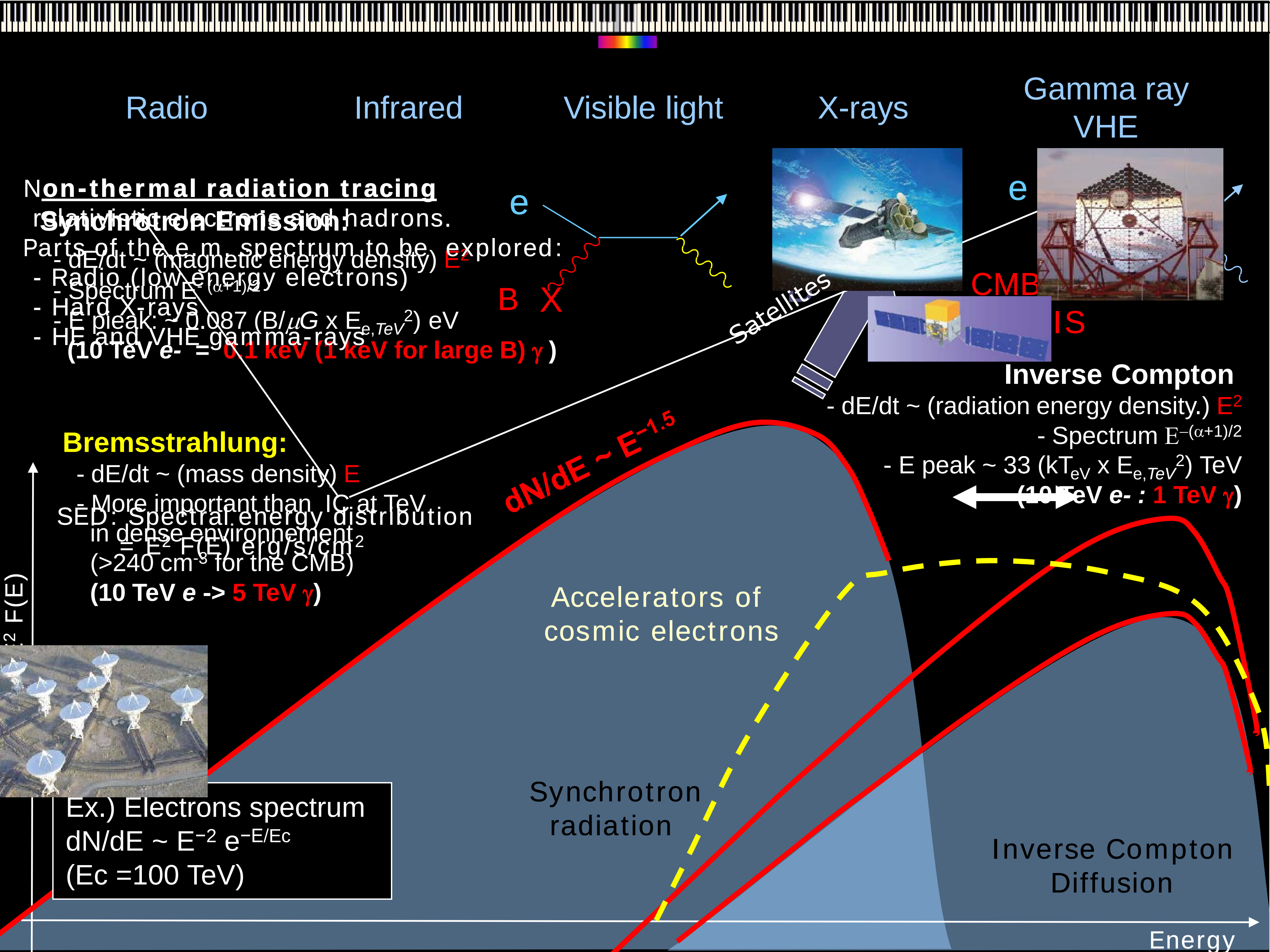


- Astroparticle Physics
  - Indirect search for Dark Matter
  - Search for energy dependence of the speed of light

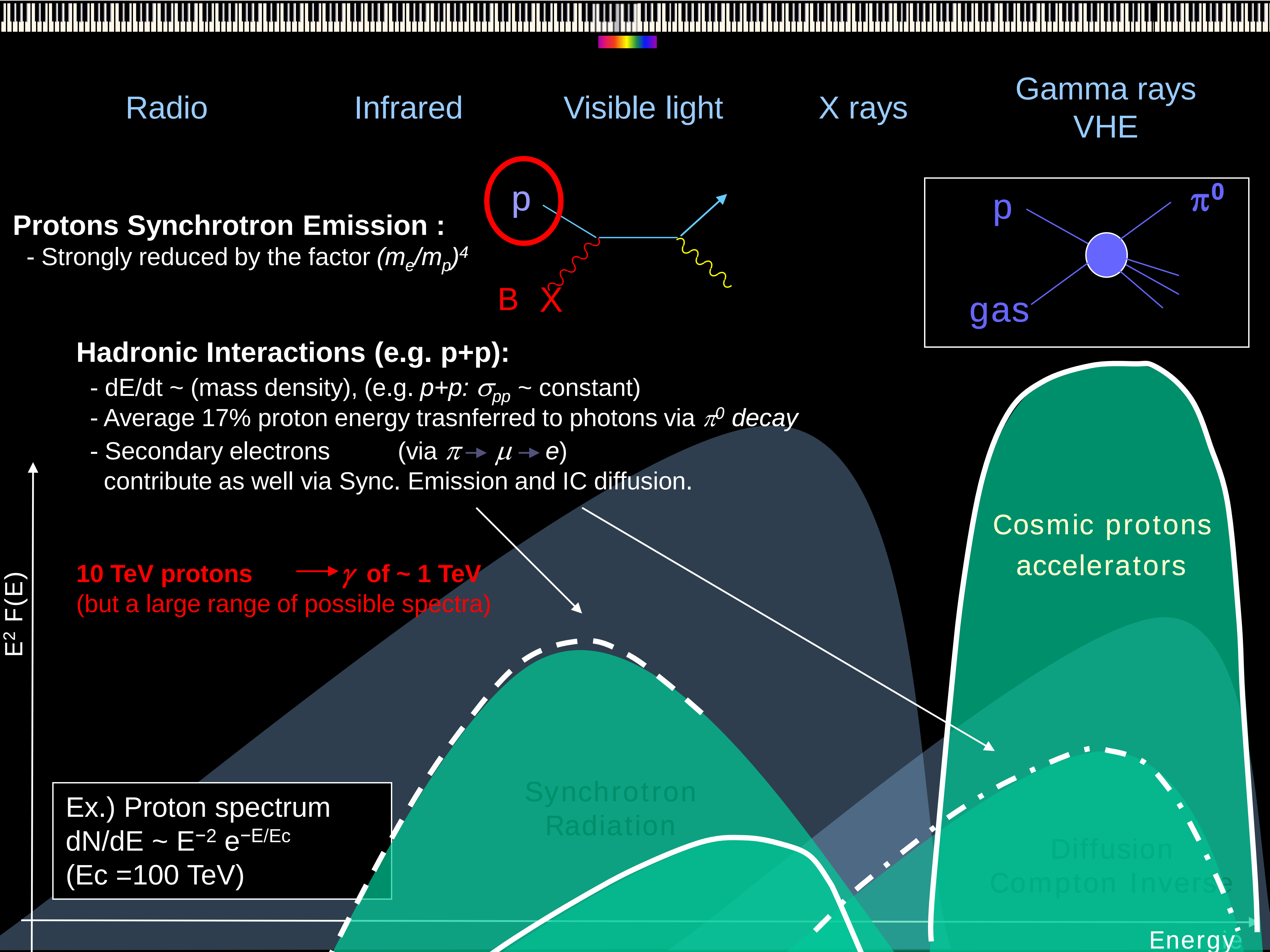


- Cosmology
  - Indirect measurement of the Extragalactic Background light
    - Probing the star formation history of the universe
  - Non-thermal content of galaxy clusters





Radio
Infrared
Visible light
X-rays
Gamma ray VHE
Non-thermal radiation tracing relativistic electrons and hadrons.
Parts of the e.m. spectrum to be explored:
- Radio (low energy electrons)
- Hard X-rays
- HE and VHE gamma-rays
Synchrotron Emission:
- dE/dt ~ (magnetic energy density) E²
- Spectrum E^-(α+1)/2
- E peak: ~ 0.087 (B/μG x E_e,TeV²) eV
(10 TeV e- = 0.1 keV (1 keV for large B) γ)
e
B
X
Satellites
e
CMB
IS
Inverse Compton
- dE/dt ~ (radiation energy density.) E²
- Spectrum E^-(α+1)/2
- E peak ~ 33 (kT_eV x E_e,TeV²) TeV
(10 TeV e- : 1 TeV γ)
Bremsstrahlung:
- dE/dt ~ (mass density) E
- More important than IC at TeV in dense environnement (>240 cm⁻³ for the CMB)
(10 TeV e -> 5 TeV γ)
SED: Spectral energy distribution = E² F(E) erg/s/cm²
dN/dE ~ E^-1.5
E² F(E)
Accelerators of cosmic electrons
Synchrotron radiation
Inverse Compton Diffusion
Ex.) Electrons spectrum
dN/dE ~ E^-2 e^-E/Ec
(Ec =100 TeV)
Energy



Radio
Infrared
Visible light
X rays
Gamma rays VHE
p
B
X
p
π^0
gas
Protons Synchrotron Emission :
- Strongly reduced by the factor $(m_e/m_p)^4$
Hadronic Interactions (e.g. p+p):
- dE/dt ~ (mass density), (e.g. p+p: σ_{pp} ~ constant)
- Average 17% proton energy trasnferred to photons via π^0 decay
- Secondary electrons (via $\pi \rightarrow \mu \rightarrow e$)
contribute as well via Sync. Emission and IC diffusion.
10 TeV protons $\longrightarrow \gamma$ of ~ 1 TeV
(but a large range of possible spectra)
E^2 F(E)
Cosmic protons accelerators
Synchrotron Radiation
Diffusion Compton Inverse
Ex.) Proton spectrum
$dN/dE \sim E^{-2} e^{-E/Ec}$
(Ec =100 TeV)
Energy

What we can learn using VHE Gamma rays?

In general it is expected :

To see the sites of high energy particle production!

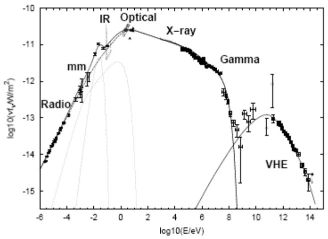
- Either bottom up (acceleration) or top down (decay)

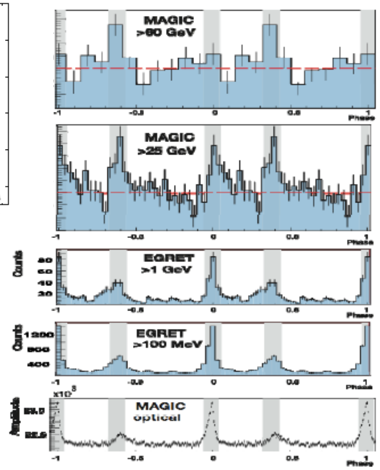
- **Proton** accelerators to produce TeV **π^0-decay gamma-rays –** correlated with the distribution of target material (gas) and not much radiation at lower energies
  - Must be many in our galaxy to explain local cosmic ray flux up to the “knee” at 1 PeV

- **Electron** accelerators to produce TeV IC and keV X-ray synchrotron emission
  - Must be some to explain local CR electrons
  - Would expect co-acceleration with protons
    - But much more rapid (factor ~100) energy losses

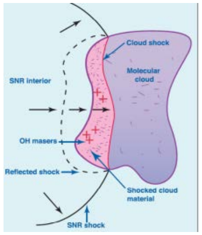
So what do we actually see???

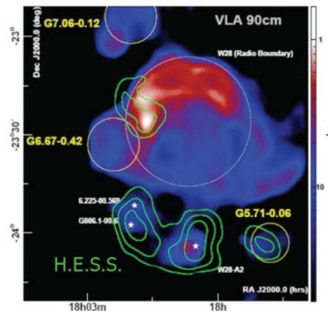
A lot of outstanding results…

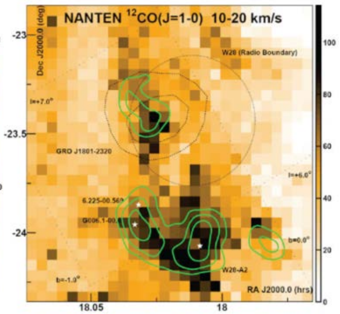




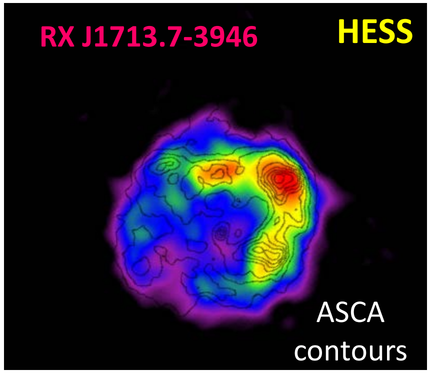
CRAB SED
and
pulsed emission





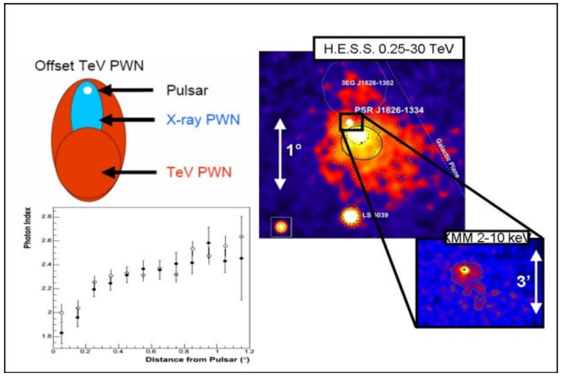


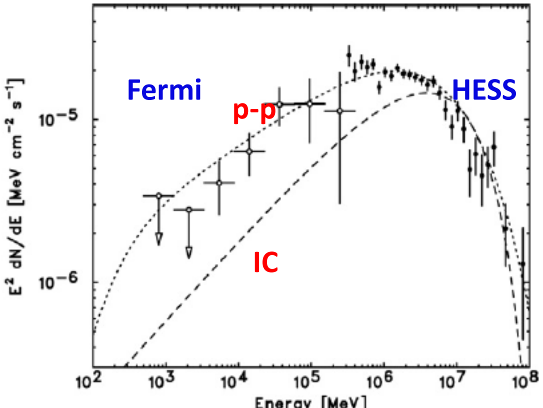
Molecular Clouds
Passive SNR p-target

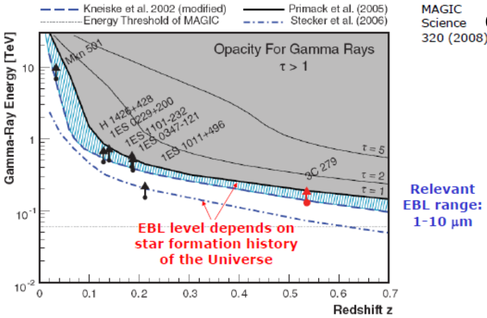


SNR, leptonic/hadronic;
morphology vs spectrum

Pulsar Wind Nebulae:
evolutionary path and
electron cooling

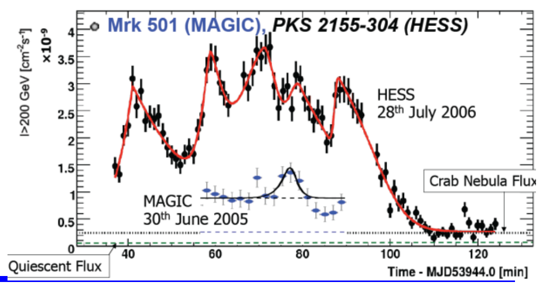






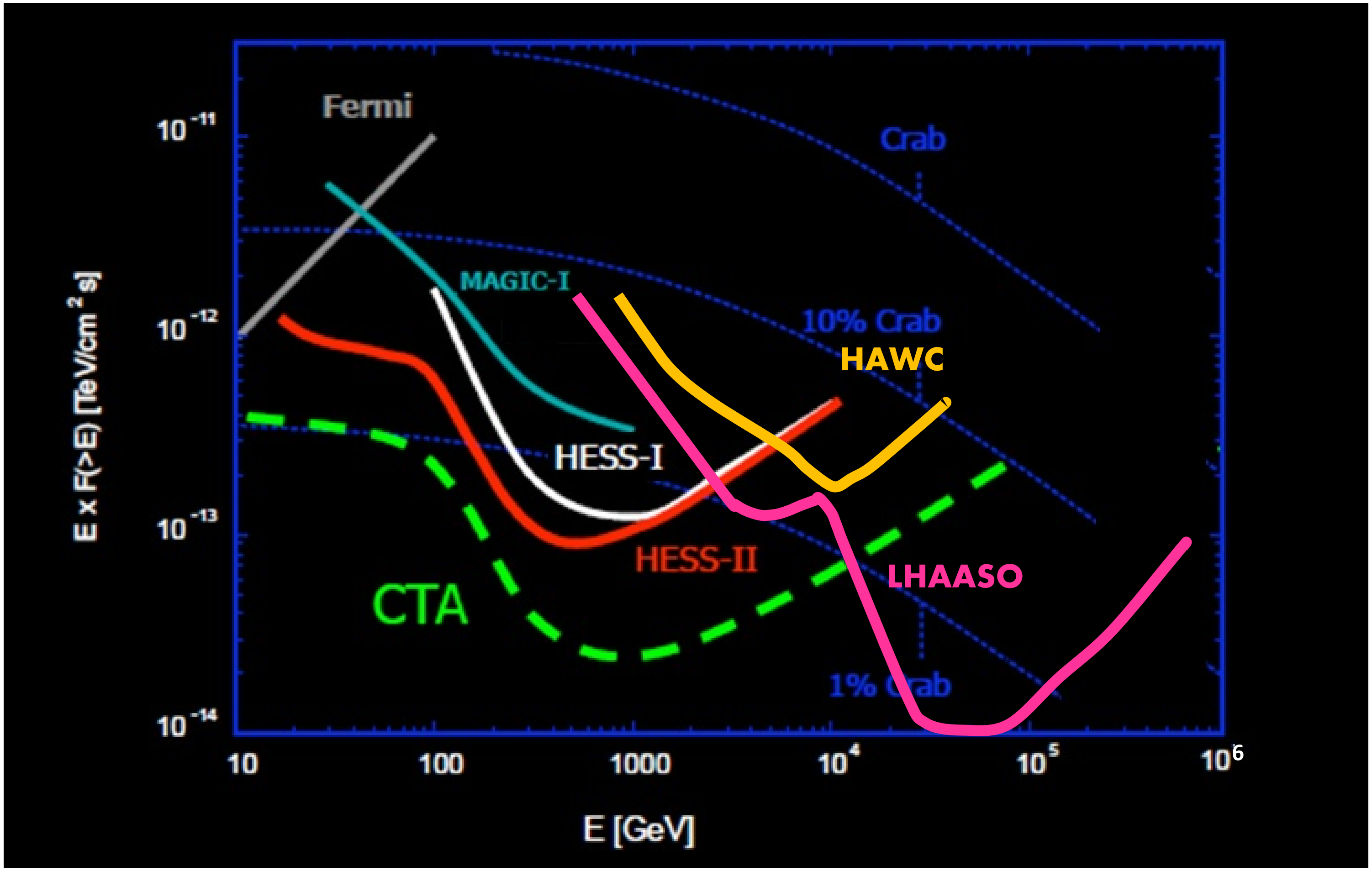
MAGIC
Science
320 (2008)

Active Galactic Nuclei:
constraining EBL density; flare as lab.



G.Lamanna

The future? PART 2....



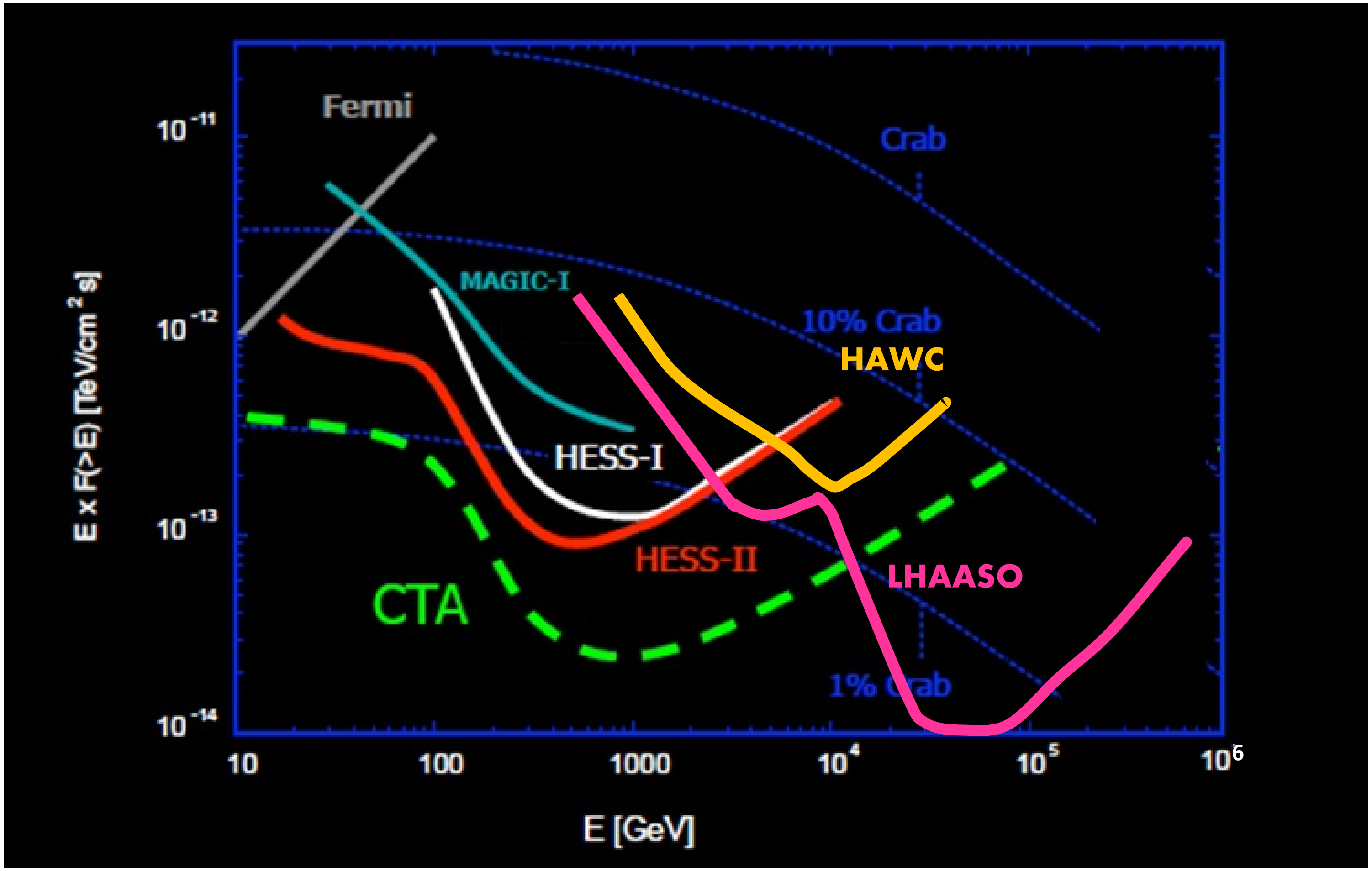
La Gamma Astronomie de très haute énergie au sol

Part II

Giovanni Lamanna

18 September 2013

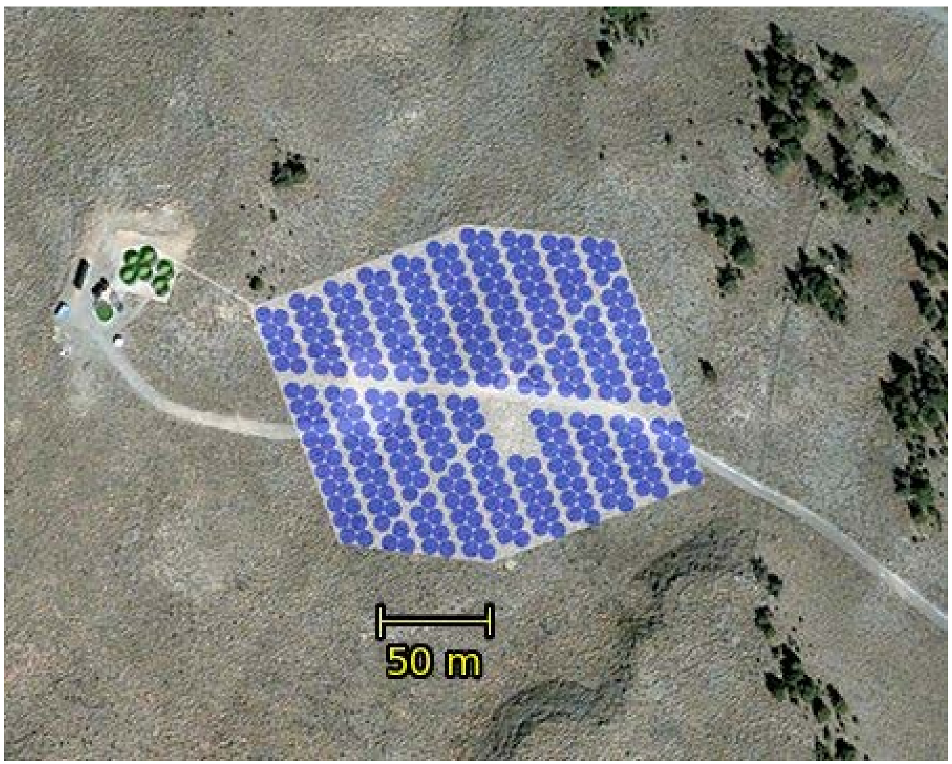
The future



Improved and larger sensitivity

Towards the advent of VHE gamma-ray astronomy

Next (after MILAGRO) generation of water Cherenkov detectors:
HAWC - High Altitude Water Cherenkov



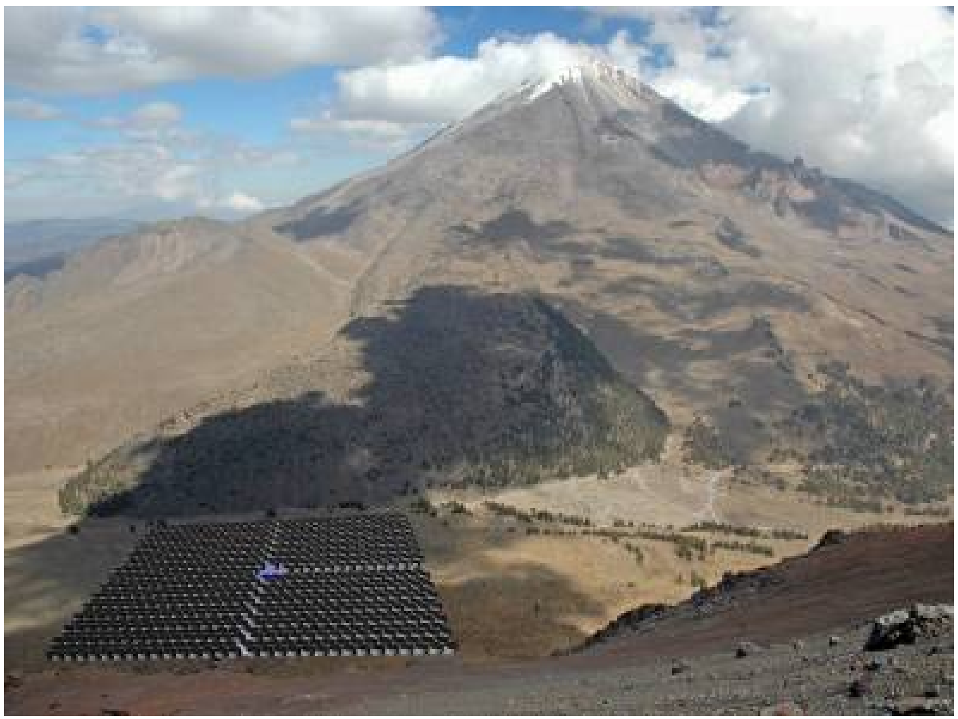
HAWC is under construction at a site 4100 meters above sea level on the northern slope of the volcano Sierra Negra (in central Mexico at 19◦N latitude).
Over 20 000 m^2

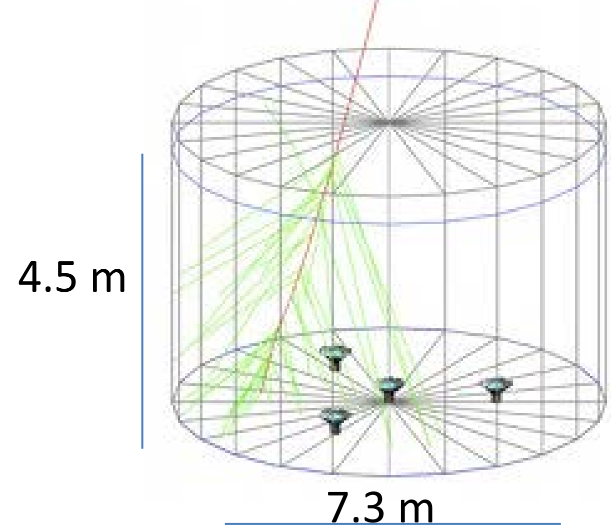
At E>10 TeV the energy resolution is < 50%

At E>10 TeV the angular resolution is < 0.1^o

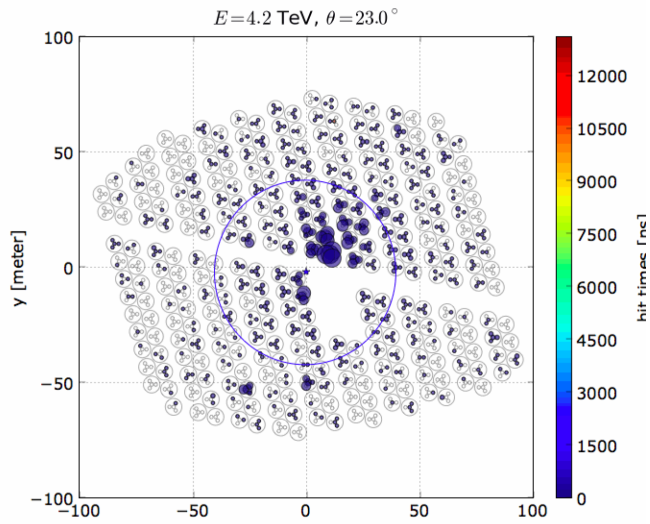
HAWC, in one year, is sensitive to integral spectra as low as $5 \times 10^{-13}\ cm^{-2}\ s^{-1}$ above 2 TeV (approximately 50 mCrab) over 5 sr.

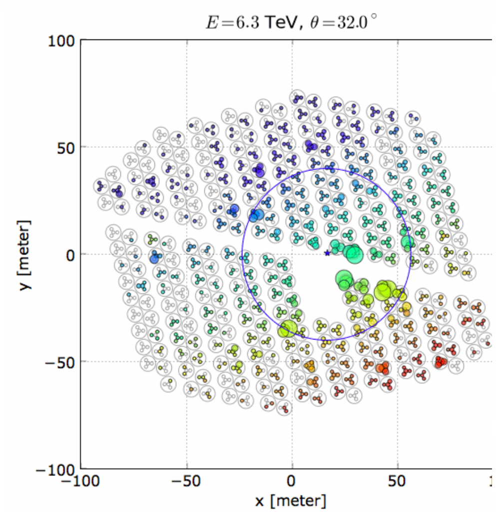
- 300 tanks
- Each tank: 3 peripheral and 1 central photomultiplier tube.
- 1200 PMTs in total.





C << (protons)

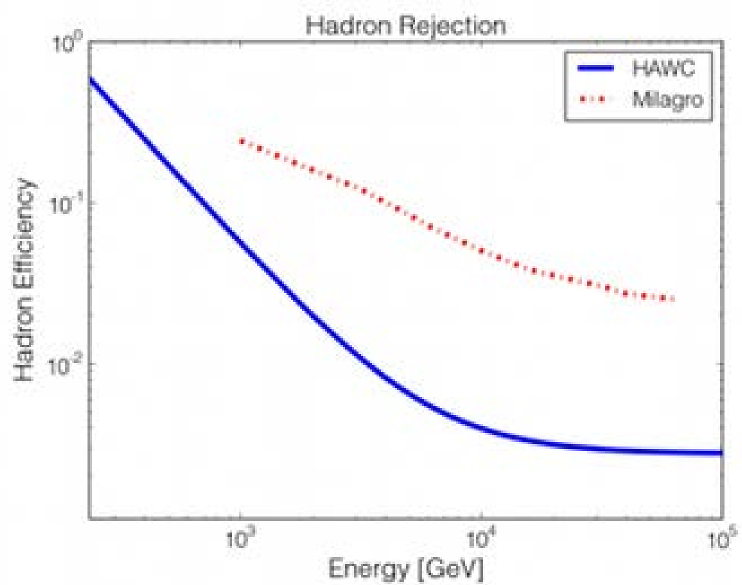




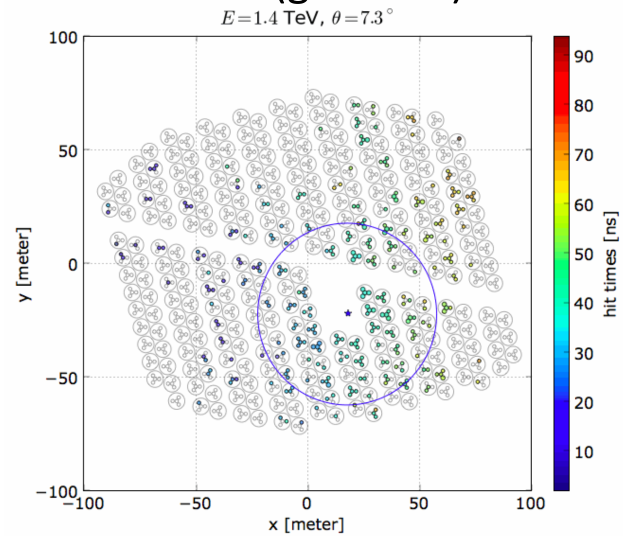
The compactness Nchan/CxPE40

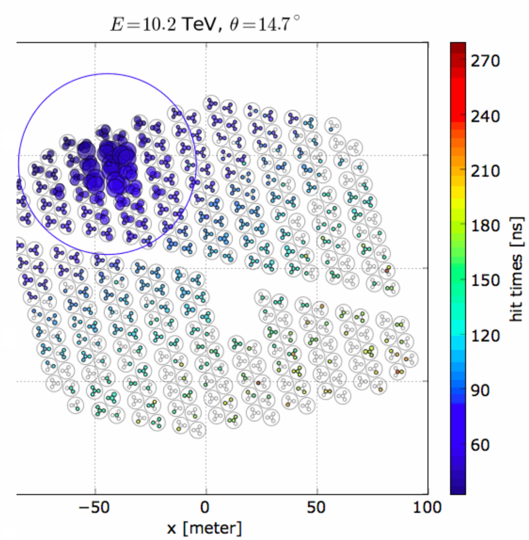
Nchan: number of PMTs in an event

CxPE40: total number of photo-electrons (PEs) in the PMT with the largest signal 40 meters away from the reconstructed air shower core.



C >> (gammas)





A Large High Altitude Air Shower Observatory :

Detection at ground of gamma-ray showers optimizing the rejection power with large collection surface and multiparameter measures

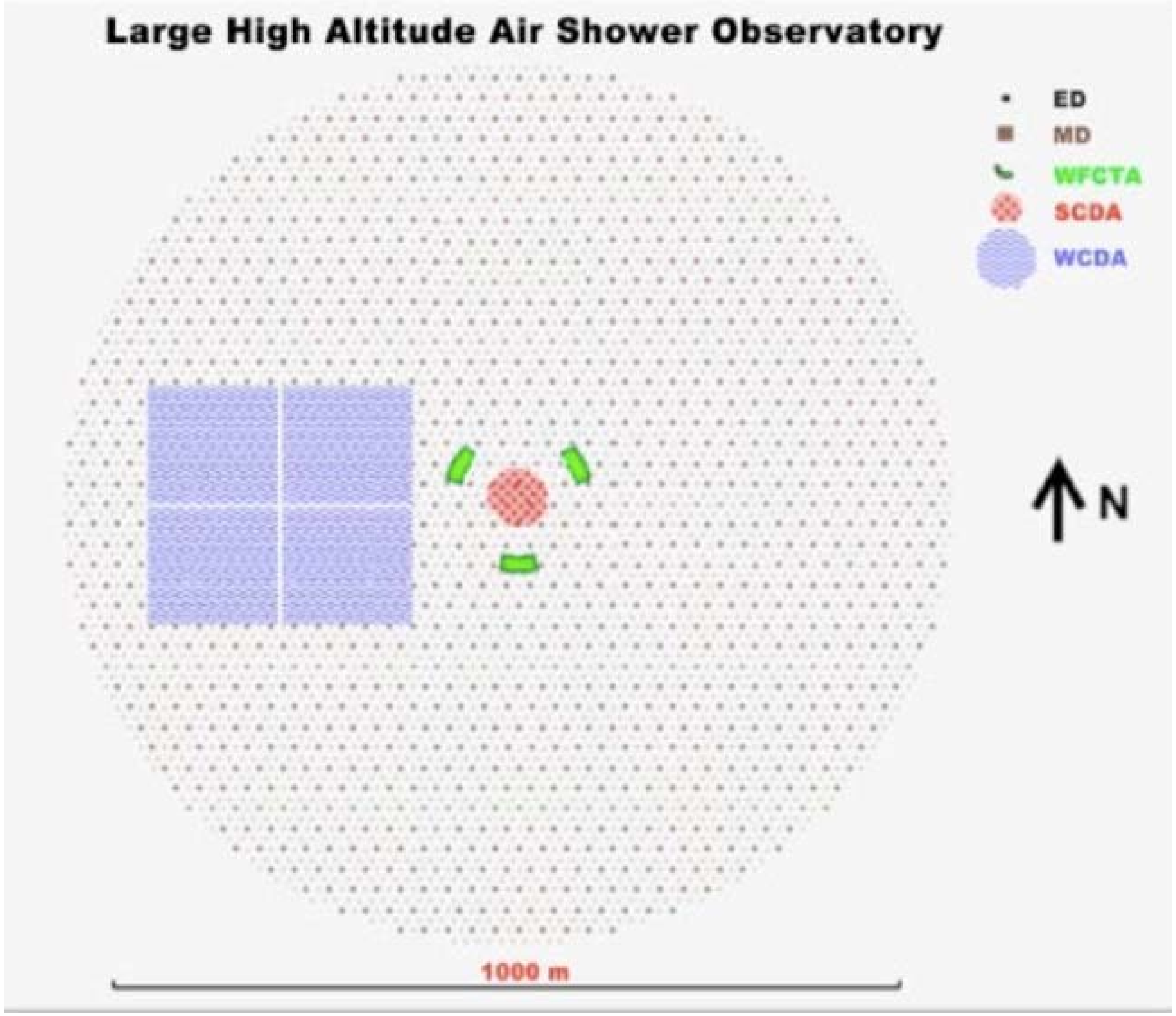
Objectives
- All sky survey γ-ray astronomy in the ~100 GeV-~1 PeV range
- high sensitivity and energy resolution → sources and energy spectrum
- full duty cycle, wide FOV and sensitivity → transient
- as good as possible γ-hadron discrimination power,
- high angular resolution (~ 1 deg for 10 TeV and ~0.1 deg. > 100 TeV)
- Cosmic ray detection between 10 TeV and 100 PeV

4300 m a.s.l.
Yunnan province (China)

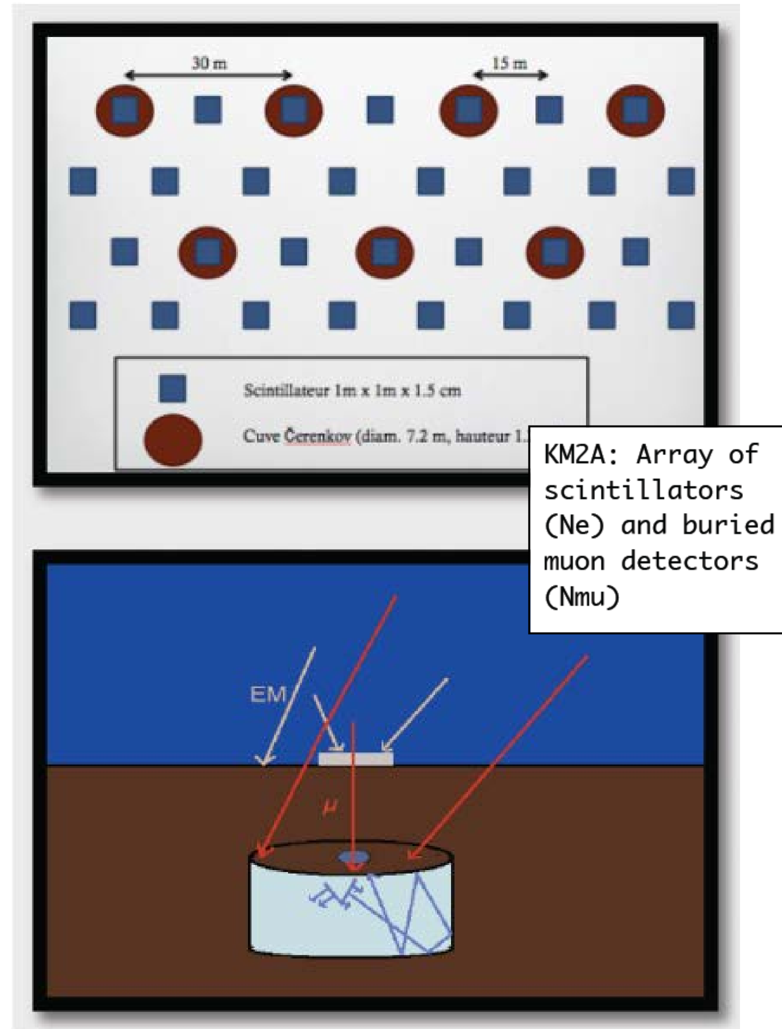
WCDA 90000 m2
Cherenkov detector for γ>100GeV
4 ponds of Water Cherenkov + μ detectors under water Cherenkov detectors

WCD: MILAGRO-like pools
~4 times HAWC in surface

WFCTA - Array of 24 WFV Cherenkov-telescopes for CRs

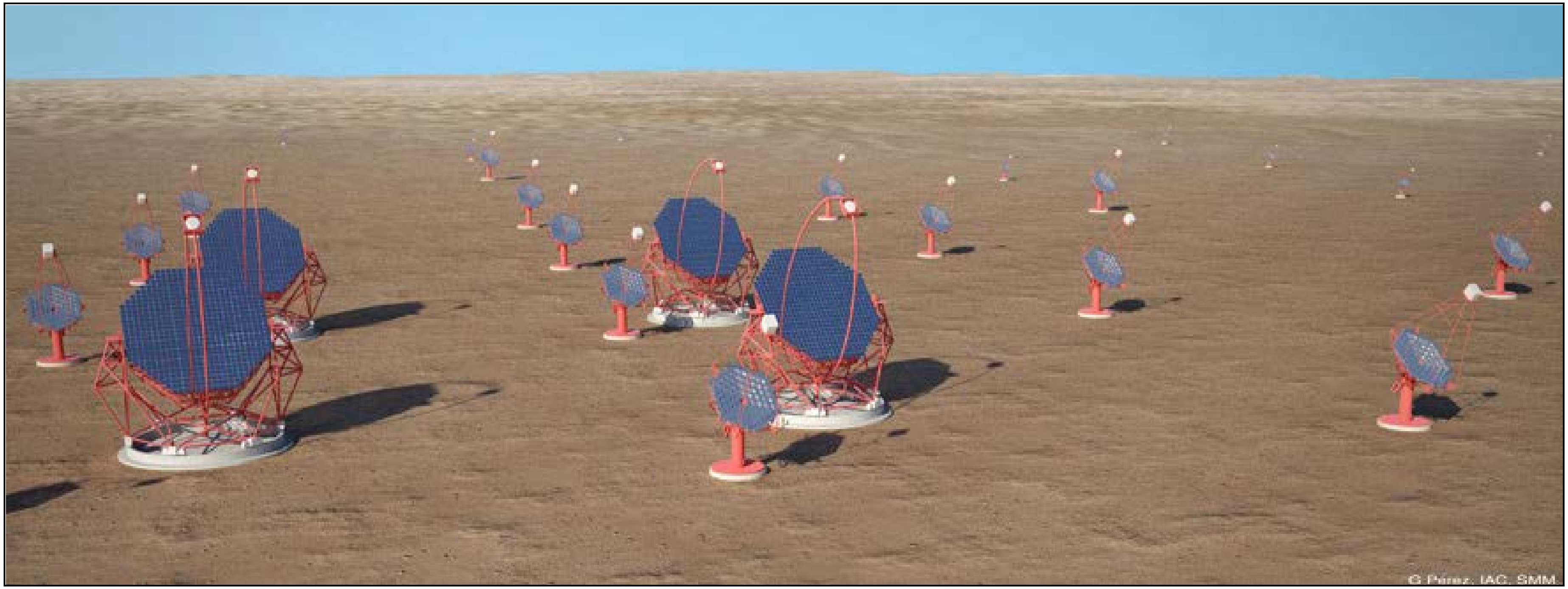


KM2A 1km2 complex array for γ >30TeV
and CRs Array of 5000 scintillation detectors (ED) to measure the secondary charged particles in an air shower and
array of 1200 detectors buried water Cerenkov detectors(MDs) to measure the muons



SCDA: the core of 80m diameter, covers a total area of 5000m^2 with 400 scintillation detectors, 0.5m × 0.5m × 1cm each covered with 7 r.l. lead plates.

Cherenkov Telescope Array

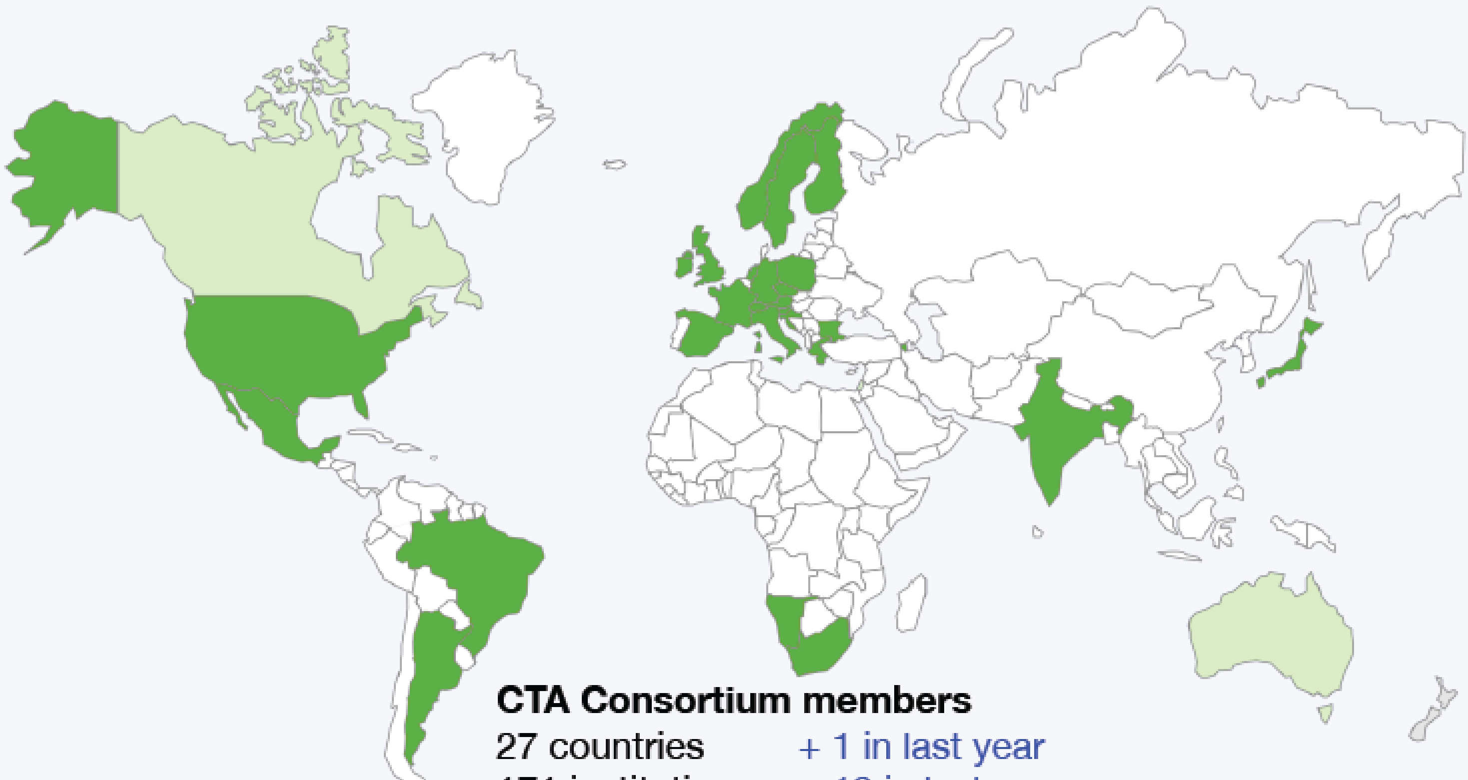


CTA: a worldwide challenge

COMMUNITY

- Members (27 countries)
- interested to join

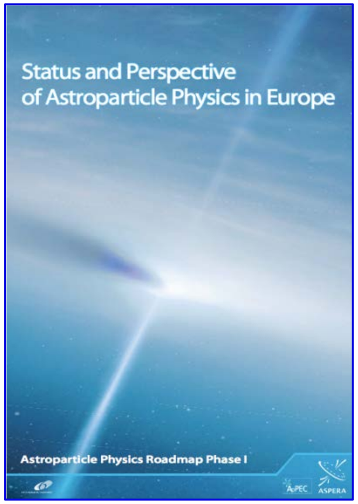
Canada, Australia, Israel

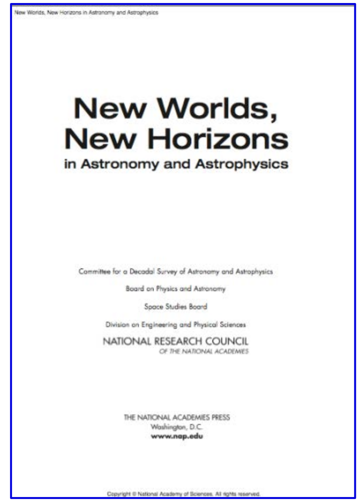


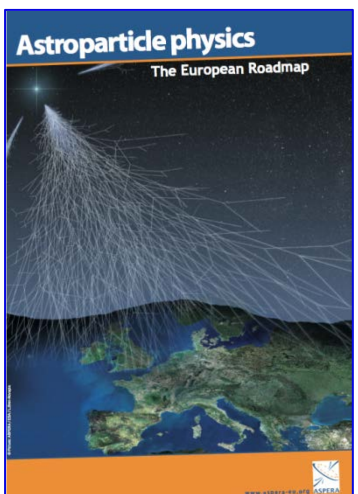
CTA Consortium members

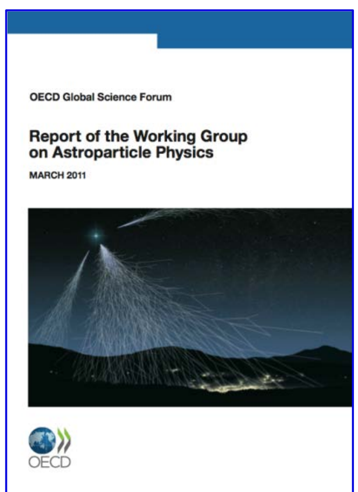
27 countries	+ 1 in last year
171 institutions	+ 19 in last year
1058 persons	+ 198 in last year

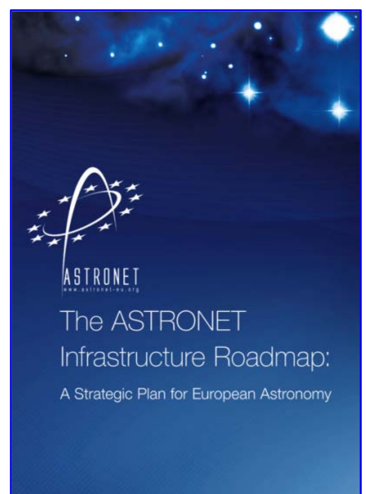
CTA concept in EU/USA roadmaps





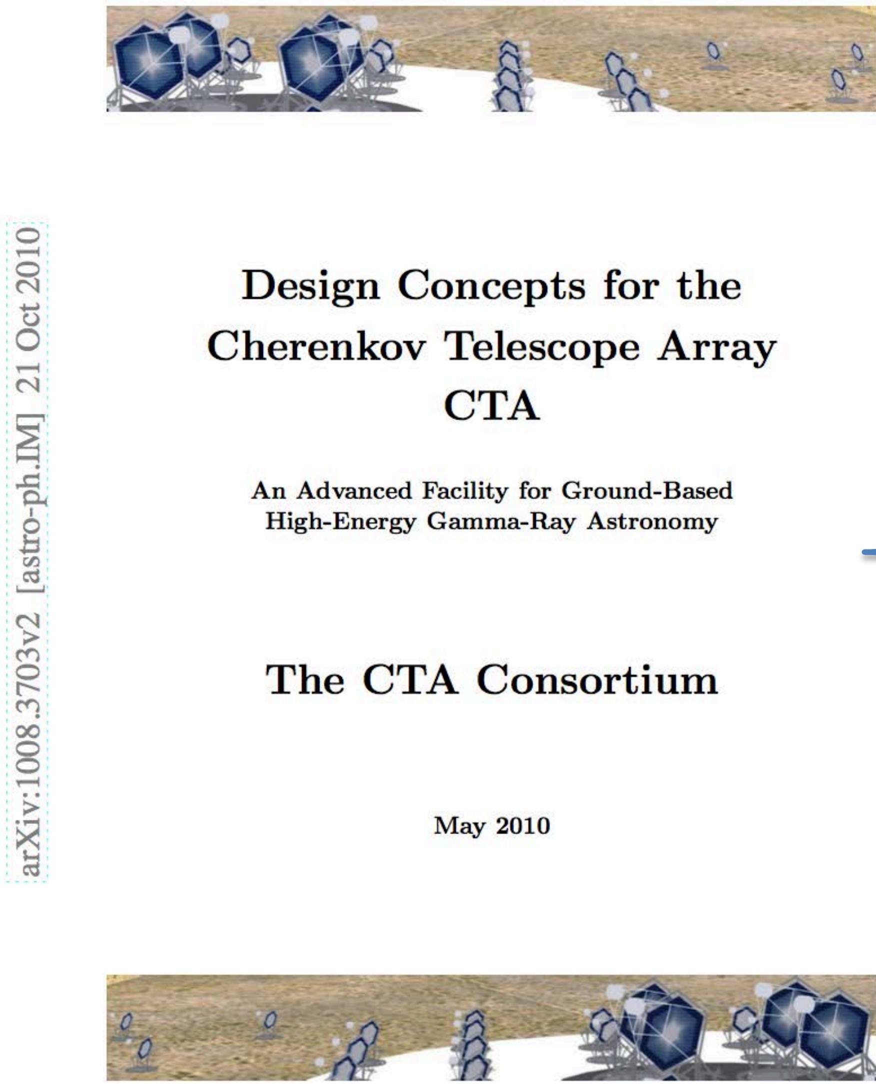






1. **Aspera 2008**
2. **ESFRI 2008**
3. **Decadal Survey 2010**
4. **Aspera Update 2011**
5. **OCDE 2011**
6. **Astronet 2010**

Significant boosts of capabilities + breakthroughs


arXiv:1008.3703v2 [astro-ph.IM] 21 Oct 2010

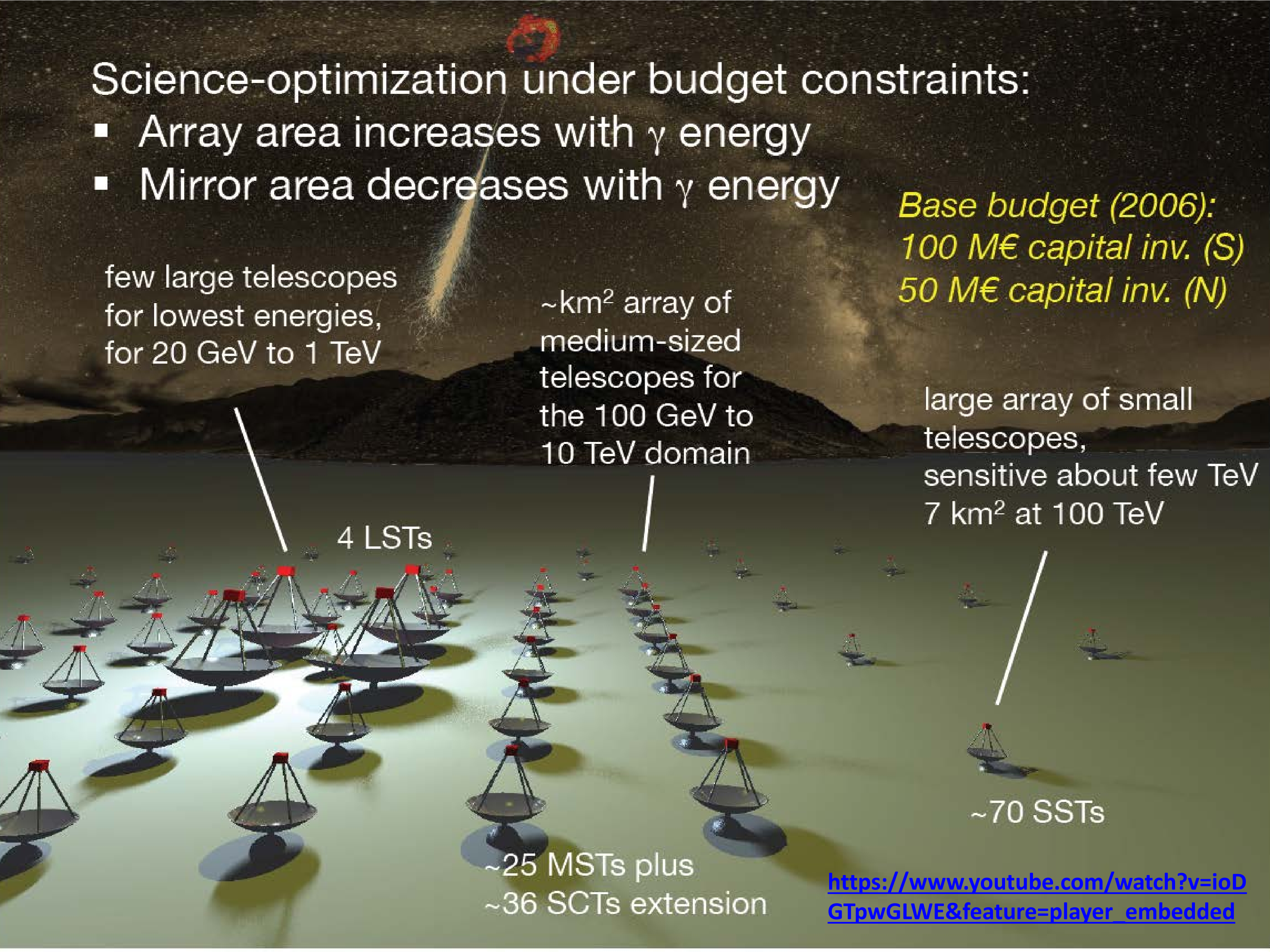
Design Concepts for the
Cherenkov Telescope Array
CTA

An Advanced Facility for Ground-Based
High-Energy Gamma-Ray Astronomy

The CTA Consortium

May 2010

- **Boost** — Increase sensitivity by up to a factor 10 at 1 TeV,
- **Boost** — Boost the detection area for transient phenomena and at the highest energies,
- **Boost** — Increase the angular resolution while maintaining a large field of view
- **New** — Provide energy coverage from some tens of GeV to beyond 100 TeV, and have
- **New** — 2-sites, flexibility of operation, allowing for sub-array and simultaneous multi-mode runs.
- **New** — Operate as an Observatory.



Science-optimization under budget constraints:
▪ Array area increases with γ energy
▪ Mirror area decreases with γ energy
Base budget (2006):
100 M€ capital inv. (S)
50 M€ capital inv. (N)
few large telescopes for lowest energies, for 20 GeV to 1 TeV
~km² array of medium-sized telescopes for the 100 GeV to 10 TeV domain
large array of small telescopes, sensitive about few TeV 7 km² at 100 TeV
4 LSTs
~70 SSTs
~25 MSTs plus ~36 SCTs extension
https://www.youtube.com/watch?v=ioDGTpwGLWE&feature=player_embedded

Current IACT experiments

CTA telescopes: 4 types, 3 classes, a great challenge

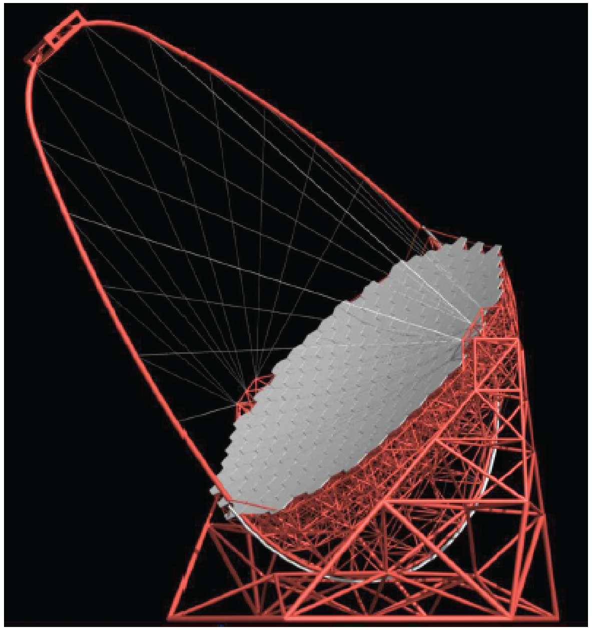
400 m² dish area
27.8 m focal length
1.5 m mirror facets

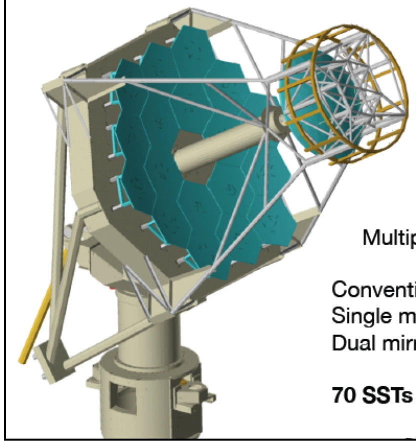
4.5° field of view
0.1° pixels
Camera ∅ over 2 m

Carbon-fibre structure

Active damping
of oscillations,
active mirror control

4 LSTs on each site





ASTRI Design
4.3 m mirror
9.6° foV
0.25° pixels

Multiple options under study:

Conventional single mirror, PMT camera
Single mirror, silicon sensor camera
Dual mirror optics, silicon & MAPMT camera

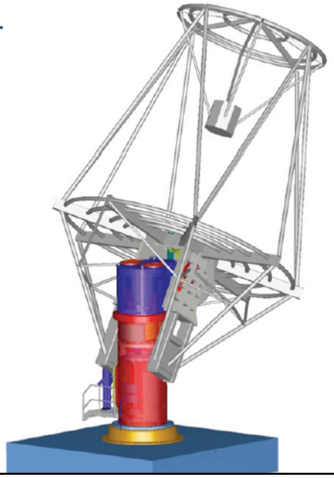
70 SSTs on Southern site

MEDIUM-SIZED DUAL MIRROR TEL.
EXTENDING THE MST ARRAY

9.7 m diameter
50 m² dish area
5.6 m focal length

8-9° field of view
11000 x 0.07° pixels

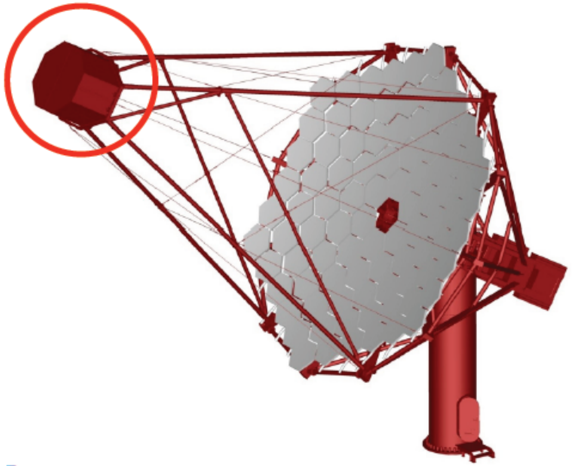
Extend South array
by adding 36 SCTs
contributed mostly by US



100 m² dish area
16 m focal length
1.2 m mirror facets

7-8° field of view
~2000 x 0.18° pixels

25 MSTs on South site
15 MSTs on North site

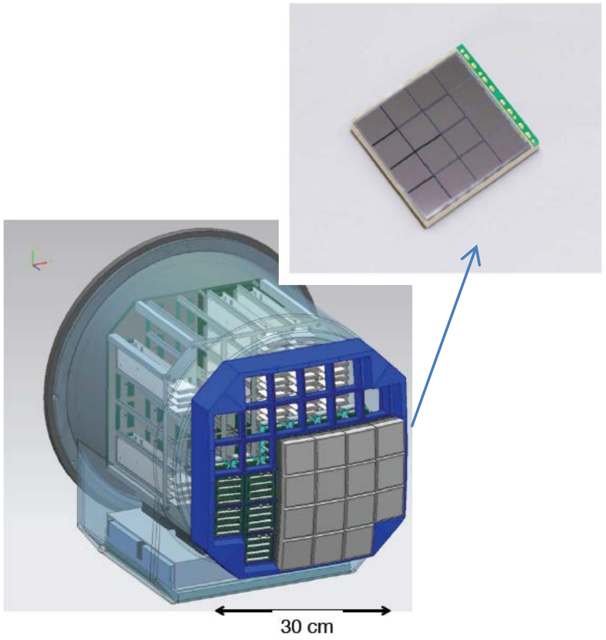


New generation photodetectors Camera: SiPM

Silicon Photomultipliers garantee small sensitive surfaces and pixels with large photo detection efficiency.

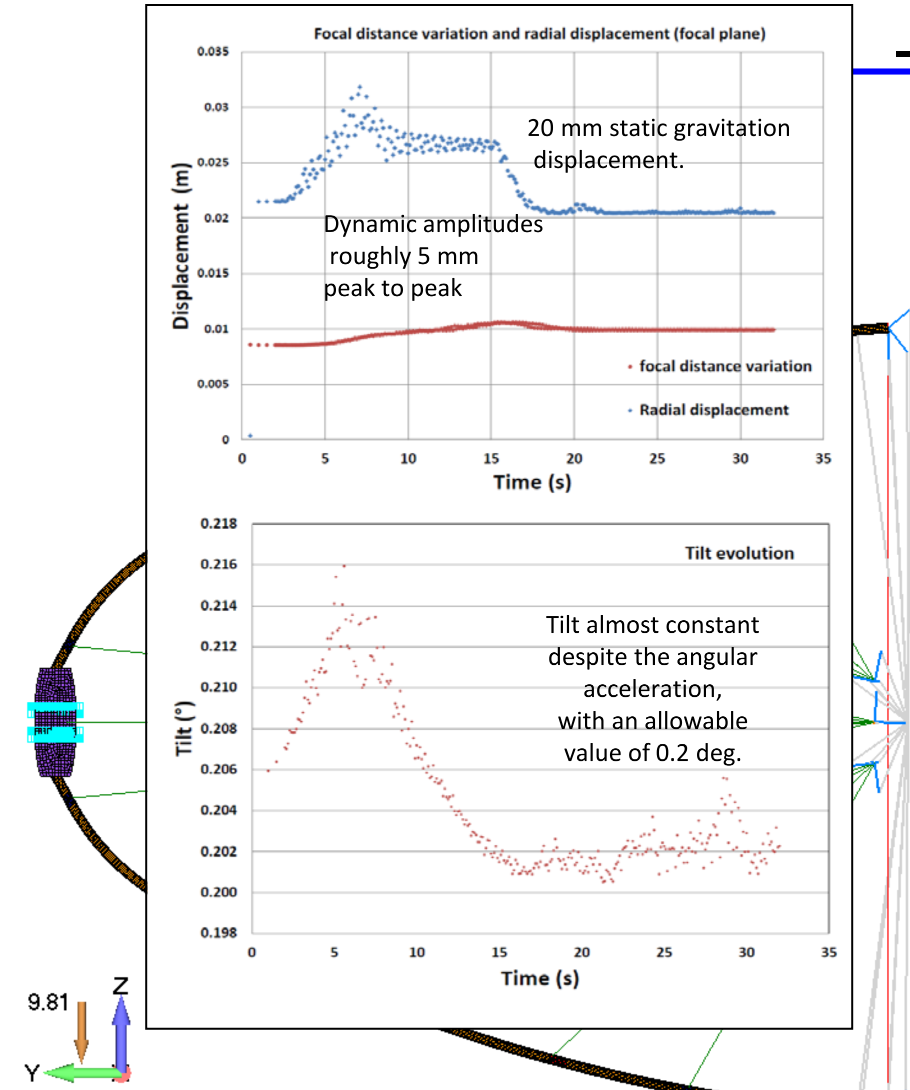
MST and SST -> applied in the dual mirror S.C. telescope designs for a large FoV (8-9 degrees) compact camera.

LST -> lighter camera and lowering down the trigger energy threshold towards 20 GeV.



Si single photon sensitive devices built from an avalanche photodiode (APD) array. Up to 1000 APD per square millimeter operating in Geiger-mode.
Generate signals within a dynamic range from a single photon to 1000 photons for just a single square millimeter area device.
The supply voltage varies between 25 V and 70 V, thus being from 30 to 50 times lower than PMs.

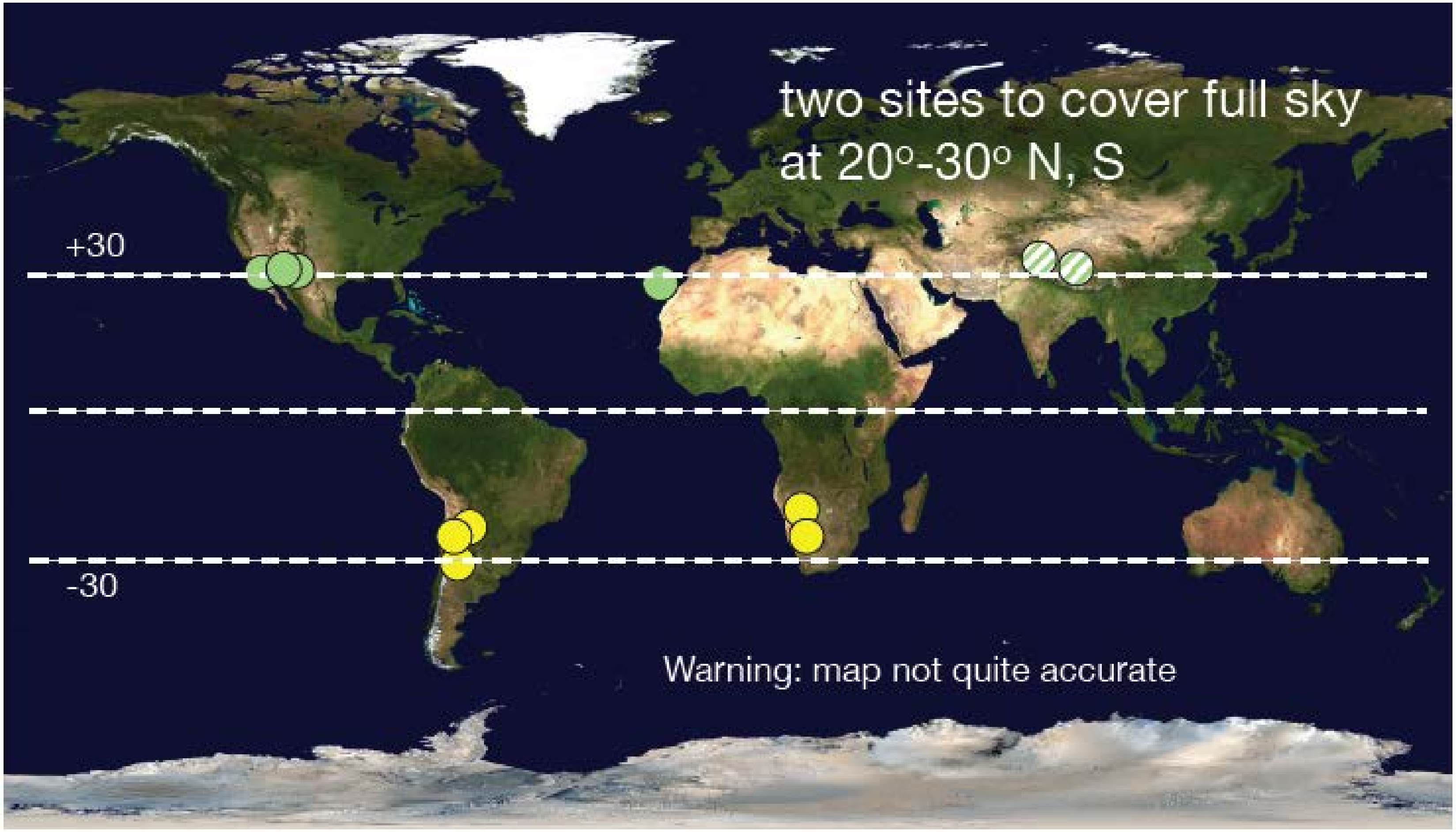
LST: simulation of GRB alert



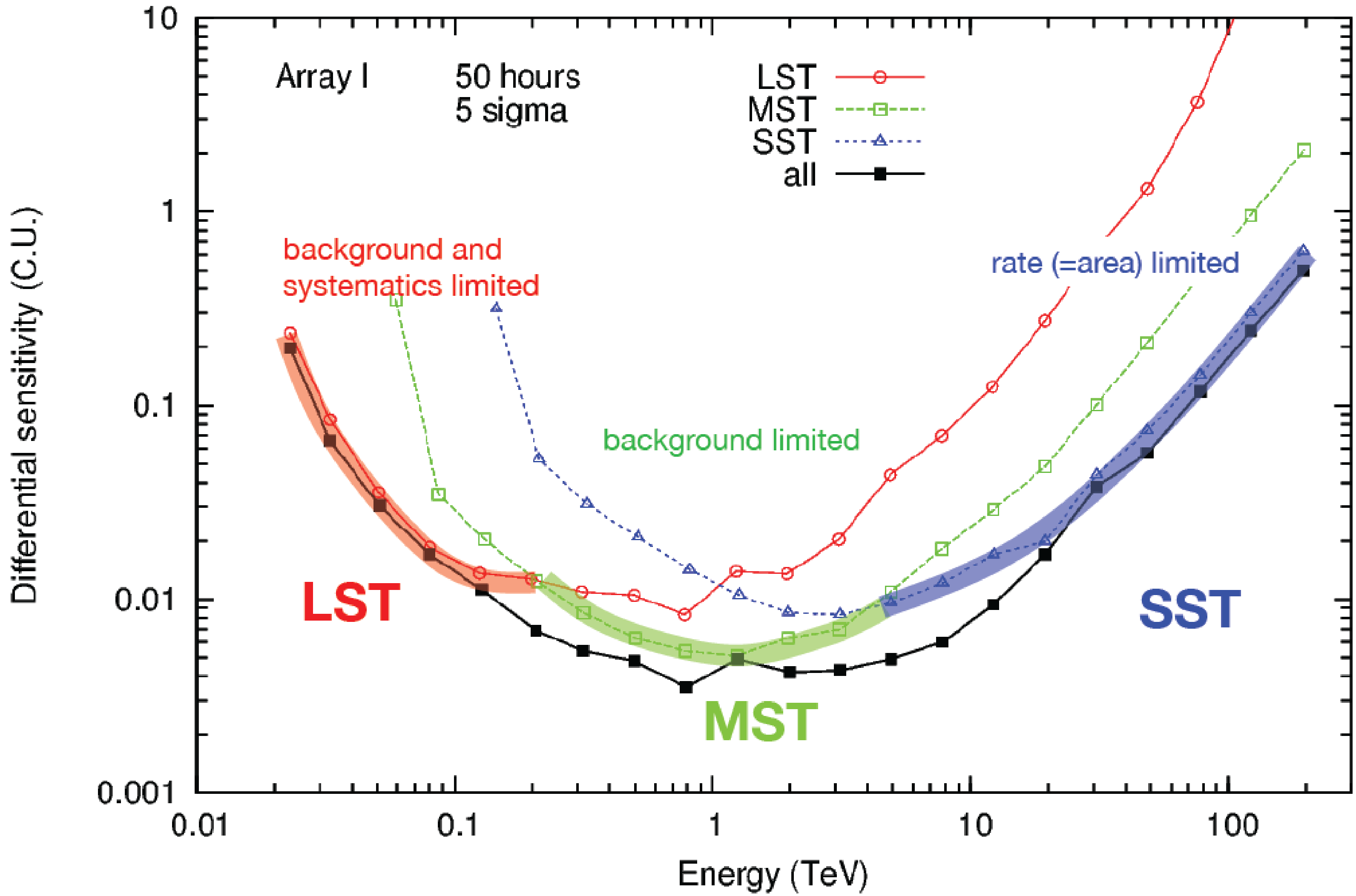
Carbon Fiber structures
(stronger and lighter)
Minimizing mass of the camera-masts to increase the first eigen-frequency

able to perform observations and take data immediately after the repositioning procedure. During the entire process and also during the subsequent 10 s the residual displacements of the camera are well below the maximum specifications.

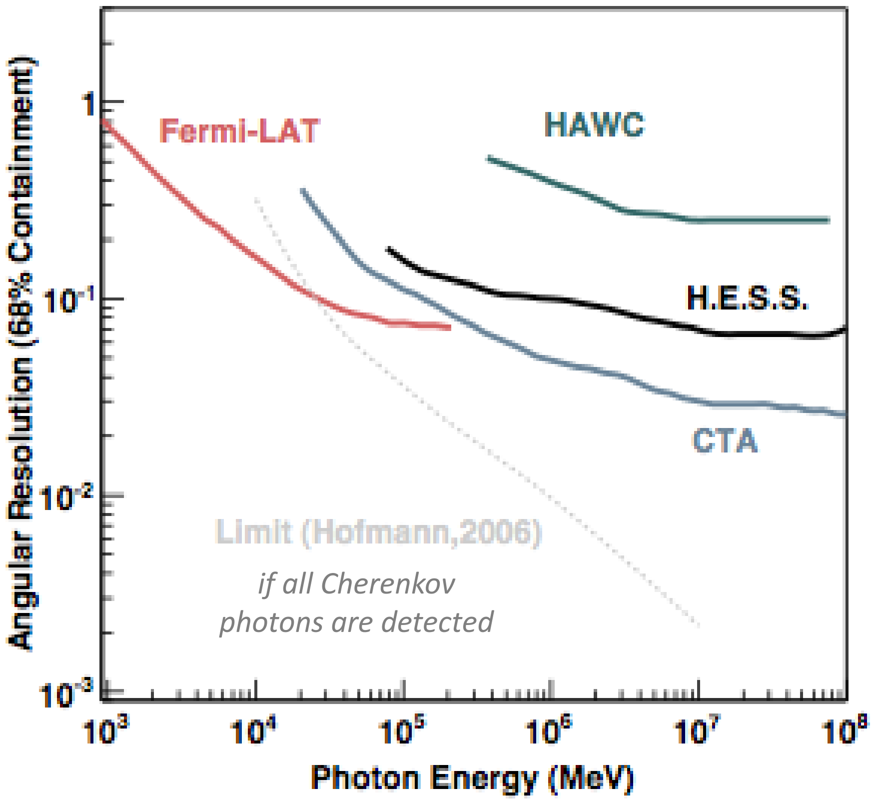
CTA sites candidates

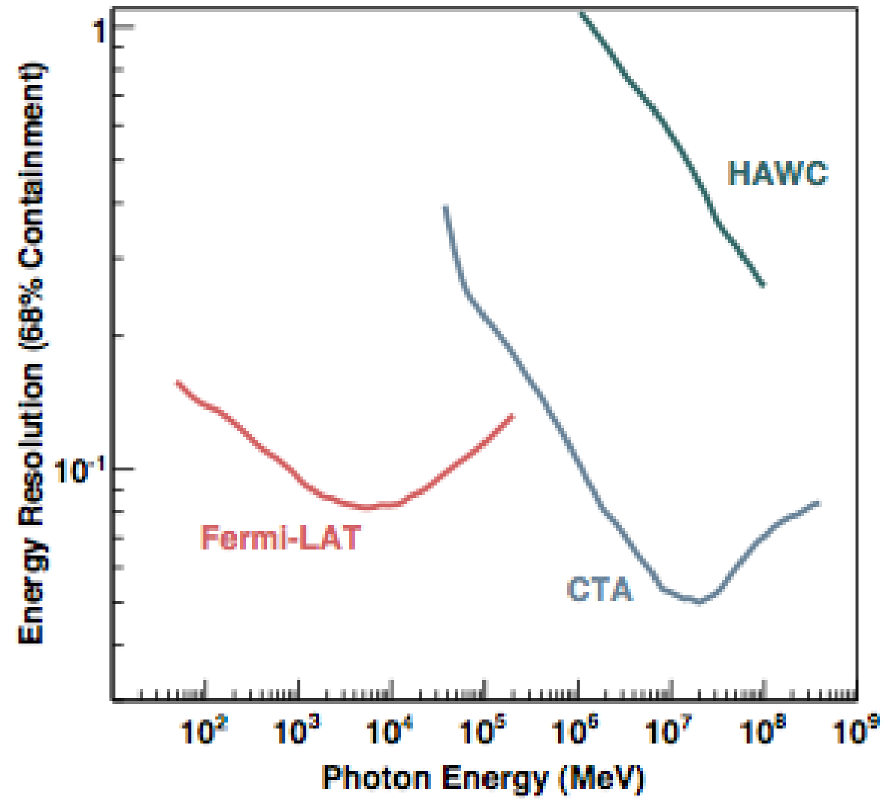


Sensitivity in units of Crab flux



Resolutions

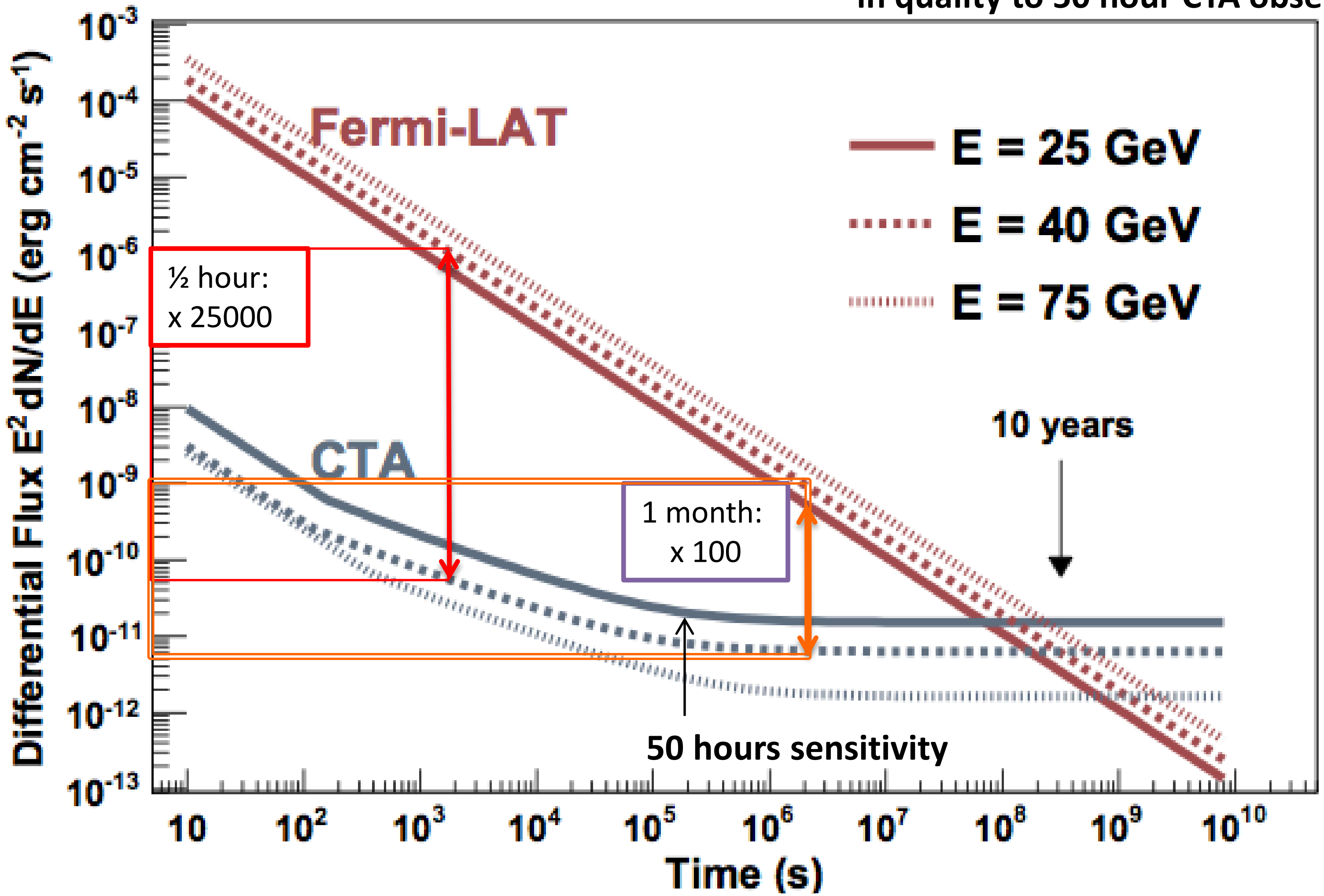




As a function of event duration / integration time

At close to the threshold energy bins CTA is more senitive than Fermi

at ~ 40 GeV the Fermi-LAT measurements (within the 10-year mission) are comparable in quality to 50 hour CTA observation.



CTA advantages for short time-scale phenomenology

The deepest surveys of the sky

Which surveys is CTA required to provide and why?

- Galactic plane survey (GPS)
  - More than half of known VHE sources in the plane (|b|<1.5°)
  - Most extended and non-variable (SNRs, PWNe)
  - Limited area to cover, homogeneous dataset

Objective: |l|<60° & |b|<2° in 240h at uniform sensitivity of ~3mCrab

(HESS survey: 1500h over l ∈ [-90°;60°] sensitivity ranging in 20-85mCrab)

population studies, dark accelerators, target identification, CR-ISM diffuse, serendipity

- Allsky survey
  - CTA can improve on surveys by water Cherenkov arrays (except variability)
  - Such blind survey never done before by ACTs

Objective: 1/4th sky in ~300h at uniform sensitivity ≥100GeV of ~20mCrab

(Milagro: 300-600mCrab >1TeV in 3yrs. HAWC: 50mCrab >1TeV in 1yr with 1° ang. res.)

AGN census, Galactic wind/halo/cloudlets, dark matter subhalos, new objects

THE CORE SCIENCE TOPICS: EXAMPLES OF GOALS (*vs* REQUIREMENTS)

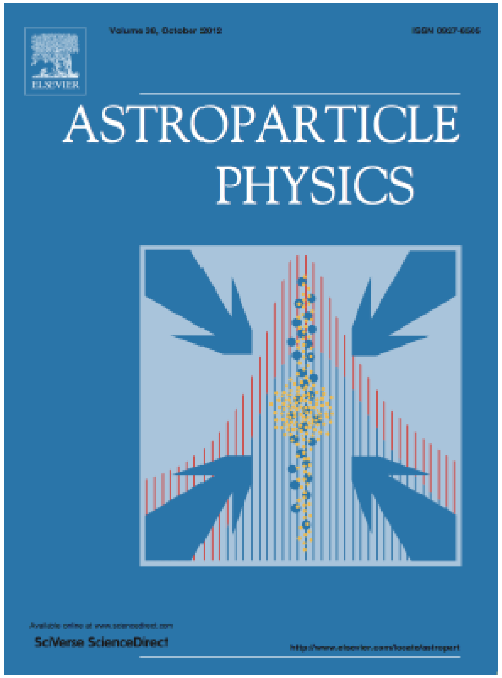
Seeing the High-Energy Universe with the Cherenkov Telescope Array
- The Science Explored with the CTA

Special issue of "Astroparticle Physics" in press

Overview articles & case studies

350+ pages

Vol. 43 March 2103



The origin and propagation of cosmic-rays

- **Goal:**
  - **Test SNR-origin of comic-rays; and lepto-hadronic production & propagation**

- **Requirements**
  - Build SNR population (leading to an essentially complete Galactic sample)

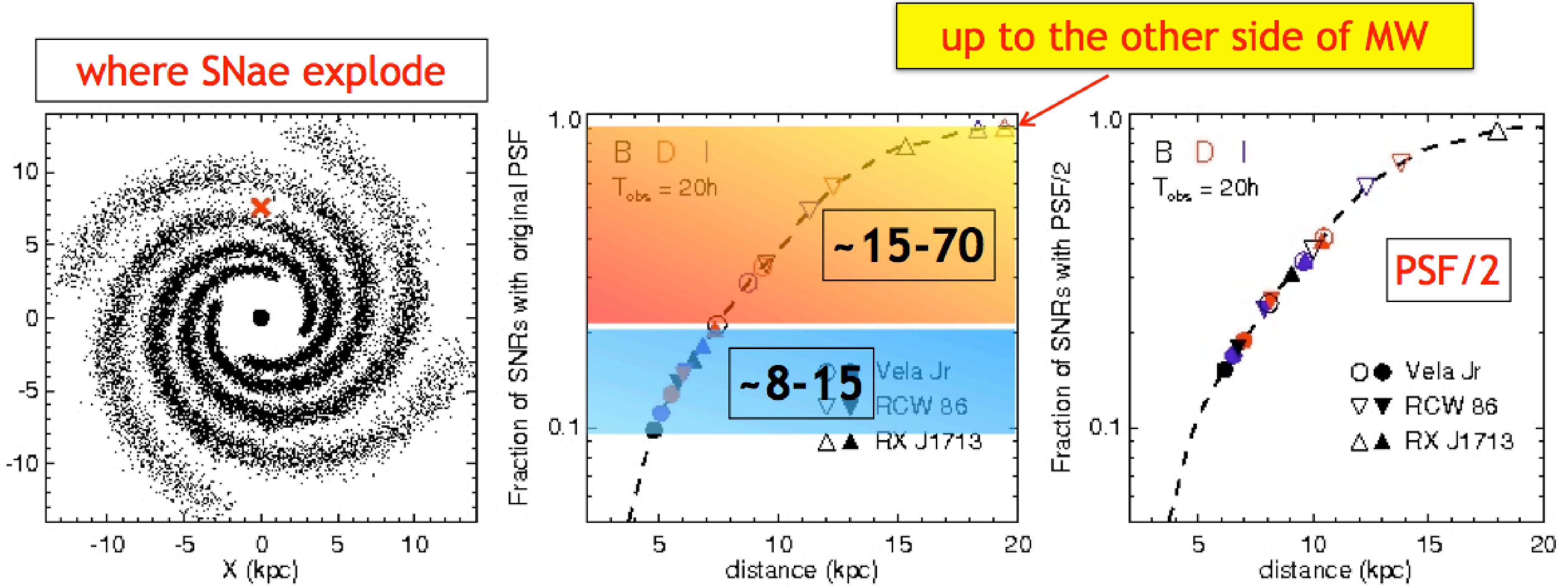
  - Resolve bright SNR filaments and shells with up to 1-3 arcmin at 10 TeV (measuring width of filaments can help resolve the issue of leptonic or hadronic acceleration there, comparison with X-ray observations)

  - Sensitivity at 50 TeV should be enough to detect plausible pevatron candidates in short times (>3σ excess in 8-10 hours), to be followed by depeer observation

Building up the SNR population

1) Assume that RXJ1713, Vela Jr or RCW86 have "typical" luminosity

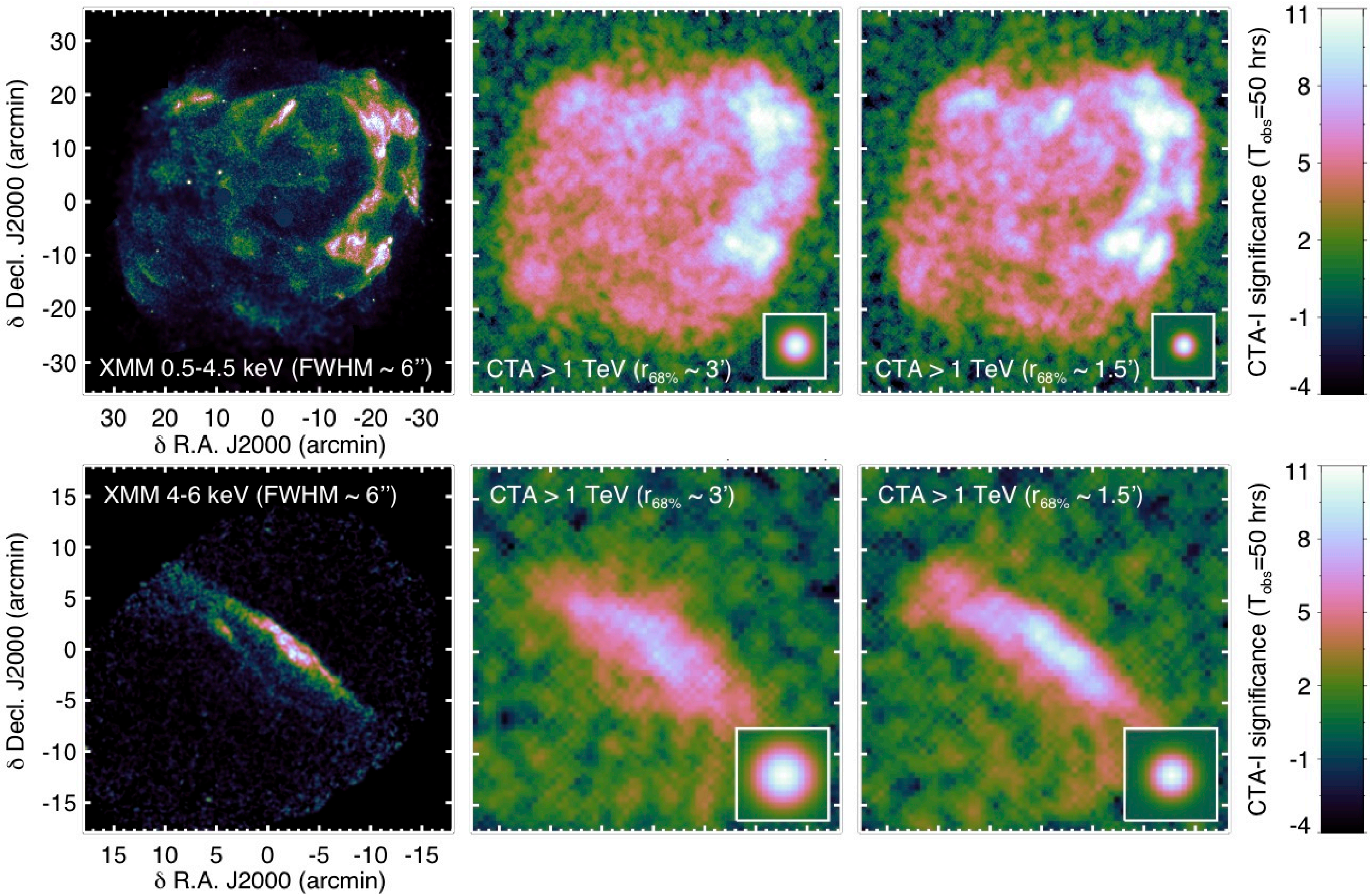
2) Compute the HD and HR and count SNRs (20h obs.)



TeV-bright phase **~3000 yrs** + **2.6 SN/century** = **80 SNRs** emitting TeV

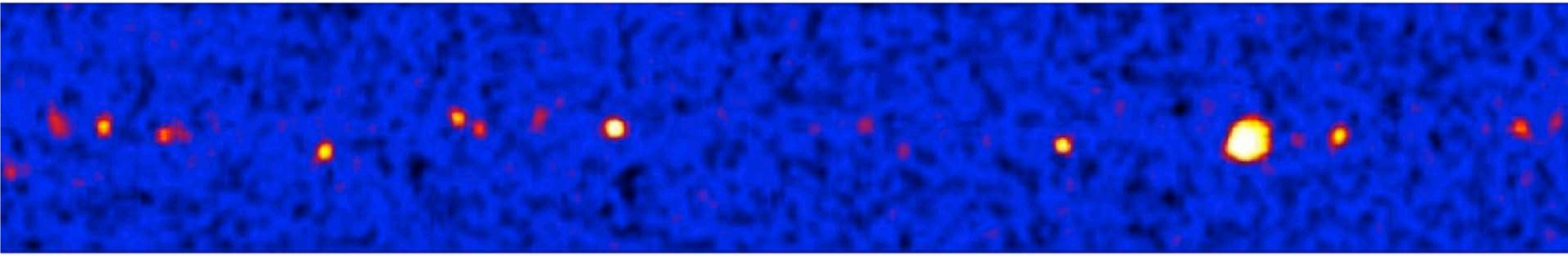
Old SNRs (e.g. W28, IC443 ecc...) are not included in this estimate!

Resolving structures (e.g., RXJ 1713-3946 & Vela Jr.)

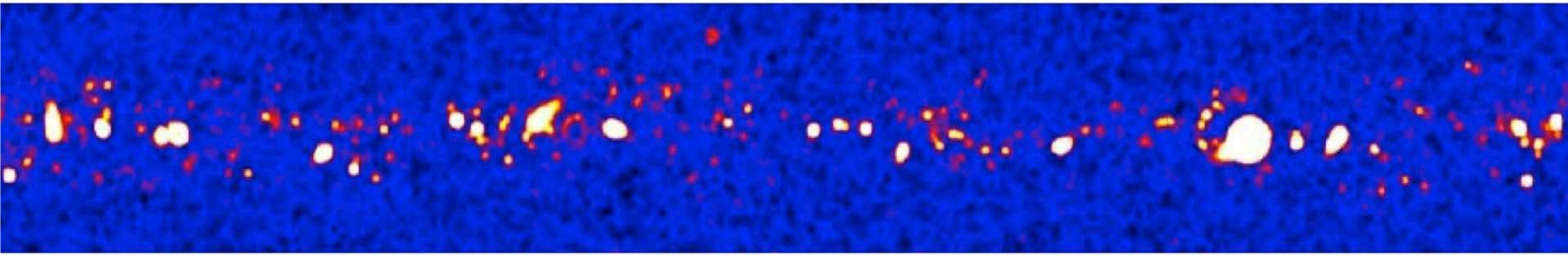


A visual comparison with the H.E.S.S. survey

H.E.S.S.



CTA, for same exposure



expect ~1000 detected sources

Black holes and their use as probes of the SFH

- **Goal:**
  - **Build up a classified population of high and very-high energy emitting AGN (both in flaring and quiescent states), covering various types and redshifts, for studies on classification, unification scheme(s), evolution, gamma-ray origin...**

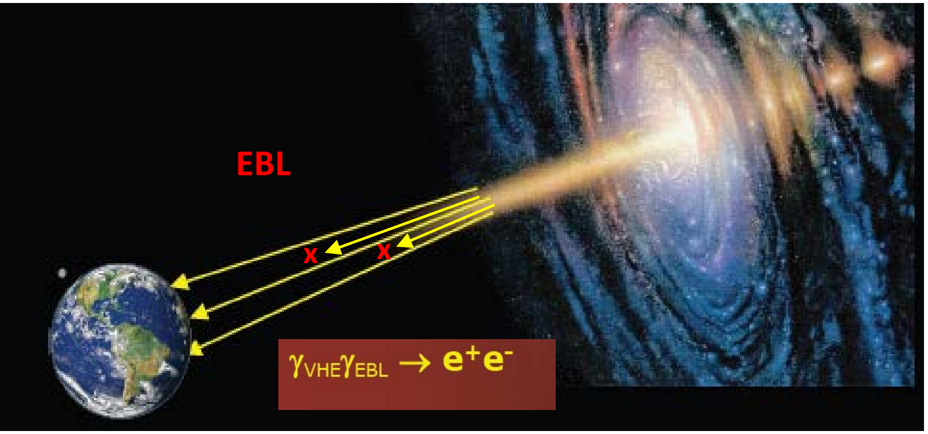
- **Requirements:**
  - Sensitivity to measure of a large sample of AGN (both in flaring and quiescent state), preferentially by means of an unbiased survey

Black holes and their use as probes of the SFH

- **Goal:**
  - **Provide a detailed measurement of EBL strength and distinction between intrinsic and propagation effects**

- **Requirements:**
  - Have a low threshold: e.g., to measure an unattenuated part of the spectrum (with a minimum lever arm of half a decade in energy) for sources at a redshift of 1 (about 50% of the universe), an energy threshold of 30-50 GeV is required

The gamma ray propagation : AGN and Cosmology



Spectra of AGN (VHE) : power law but curved as a function of energy and distance (Γ >> with z >>):

- The most distant ones must be brighter to be observed

- H.E. γ absorbed by IR (via pair production e^+e^-) of the « extragalactic background light » (EBL)

EBL: link between the history of the galaxies and the H.E. astrophysics.

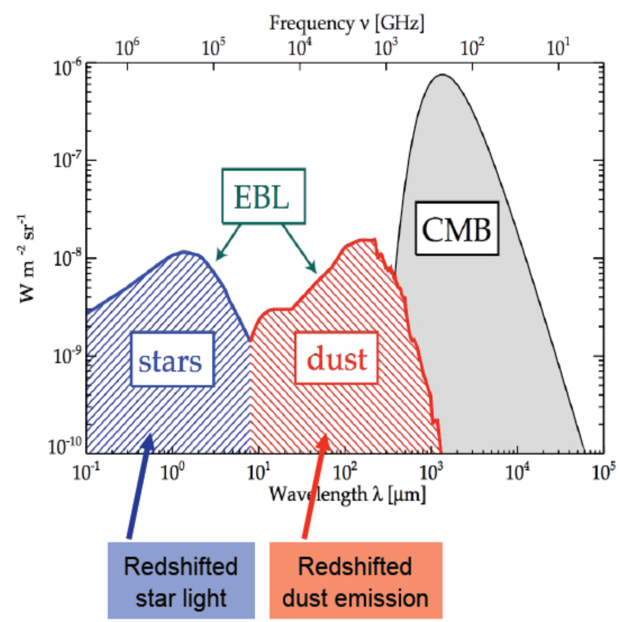
EBL Theoretical definition:

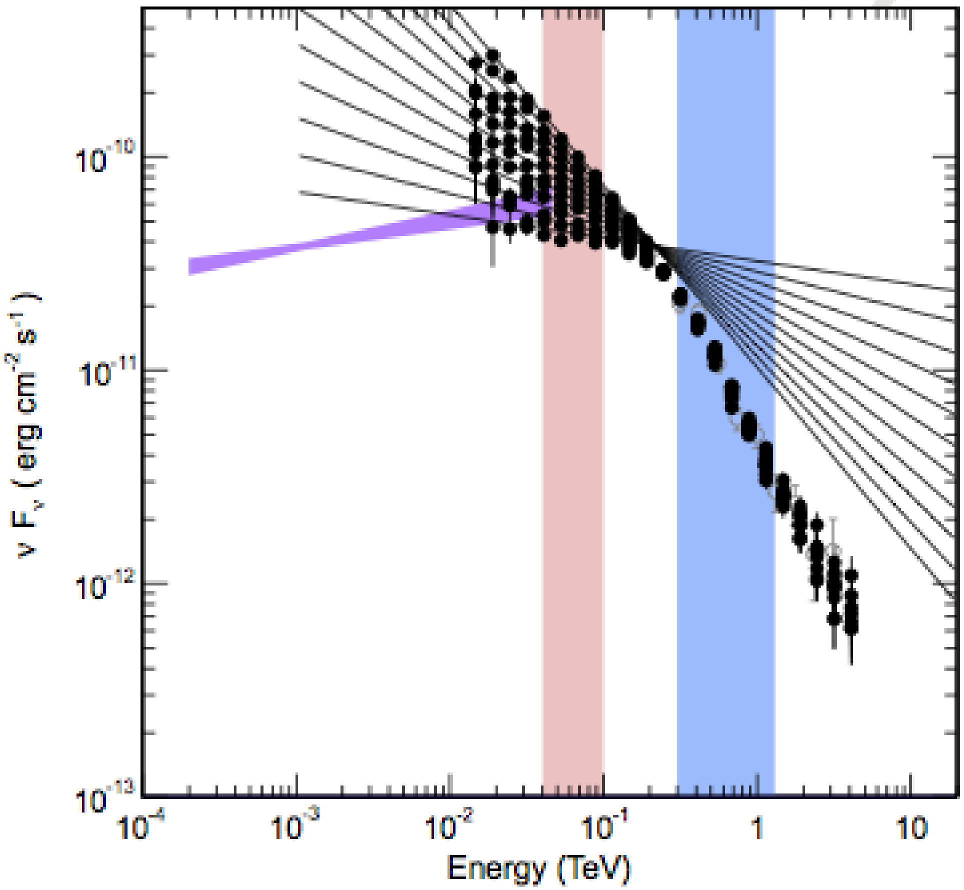
- « extragalactic background diffused light»: light emitted by all objects in the Universe along its history (stars, galaxies, quasars...) filling up the extragalactic space as an ocean of photons.

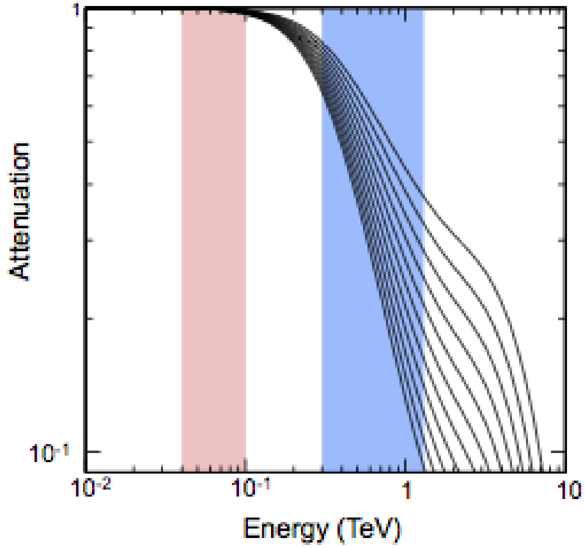
(~ 1/20 of the CMB energy inn UV, visible and IR.)

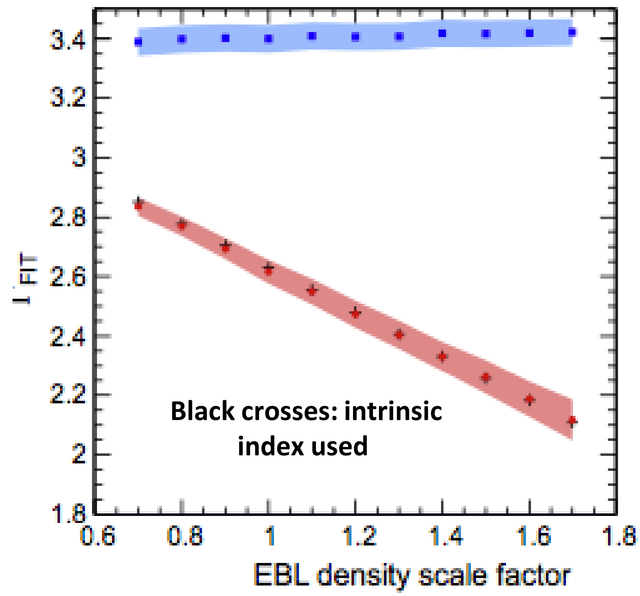
EBL observational definition :

- All the light beyond our galaxy (z=0 background)



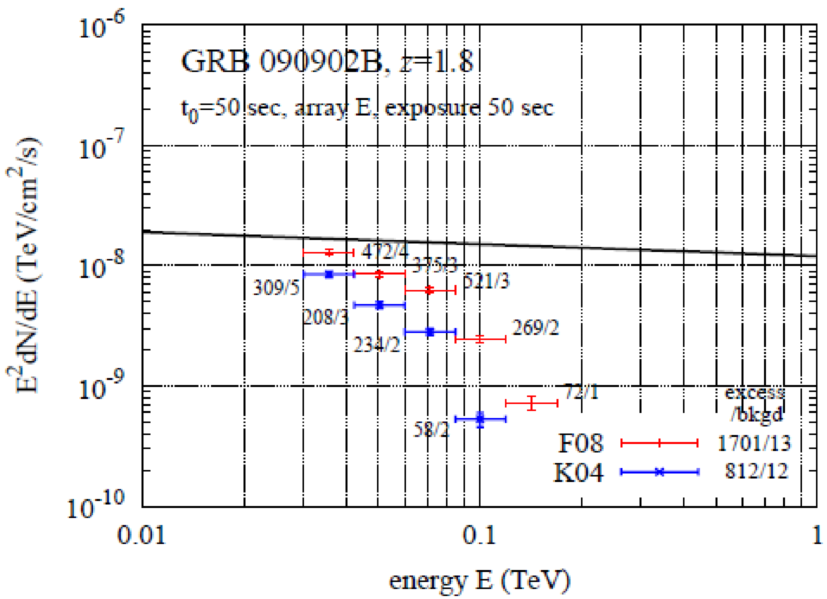


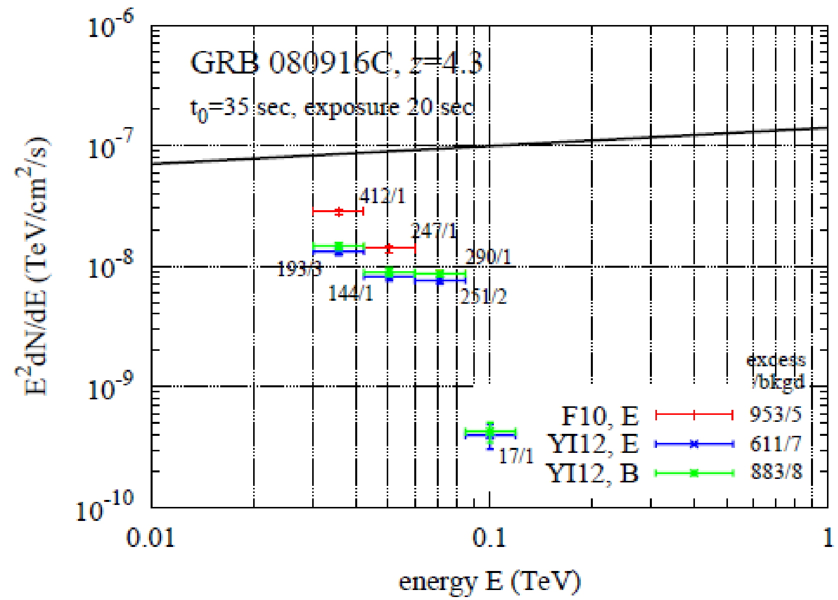




Simulation of **quiescent** spectrum of PKS 2155-304 (z=0.116): distinguishing different models for EBL (20 h of observation). Results using **bright flares but shorter timescales** (6 minutes) are entirely comparable.

Gamma Ray Bursts





- ~50 s observation of a bright burst at z=1.8 (GRB 090902B-like):
  Fermi (1 photon, E>30 GeV, t=80 s) -> CTA (> 1000 photons)
  Spectrum determination possible between 50 and 100 GeV
  (intrinsic spectrum extrapolated from Fermi-LAT + EBL attenuation)

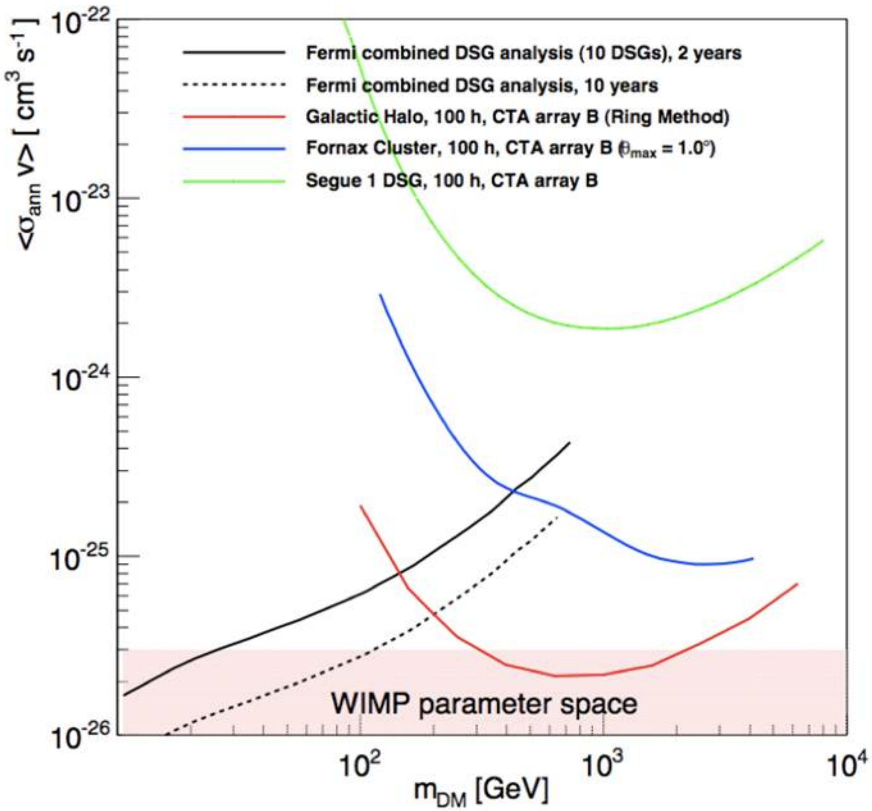
- 20 s interval at z=4.3 (GRB 0809016C-like) (harder spectrum, higher flux, from Fermi-LAT) allows to distinguish different EBL models (but none information about intrinsic). Lower energy thresold (20-30 GeV) is needed.

Dark matter

-Observing the region around the Galactic Center
-Dedicated observational strategies
 -> CTA will reach the canonical velocity-averaged annihilation cross-section of **$\sim 3 \times 10^{-26}$ cm^3 s^{-1}** in only 100 h observation DM mass above 300 GeV.

<ins>If signatures of DM</ins>:
 a) appear in direct-detection experiments or at the LHC,
 -> gamma-ray observations will provide a complementary approach.

 b)do not appear as may be the case for sufficiently heavy DM candidates,
 -> CTA may be the only way to look for such particles.



- Some quantum gravity models predict deviations from Einstein's postulate that the speed of light is constant, i.e.:

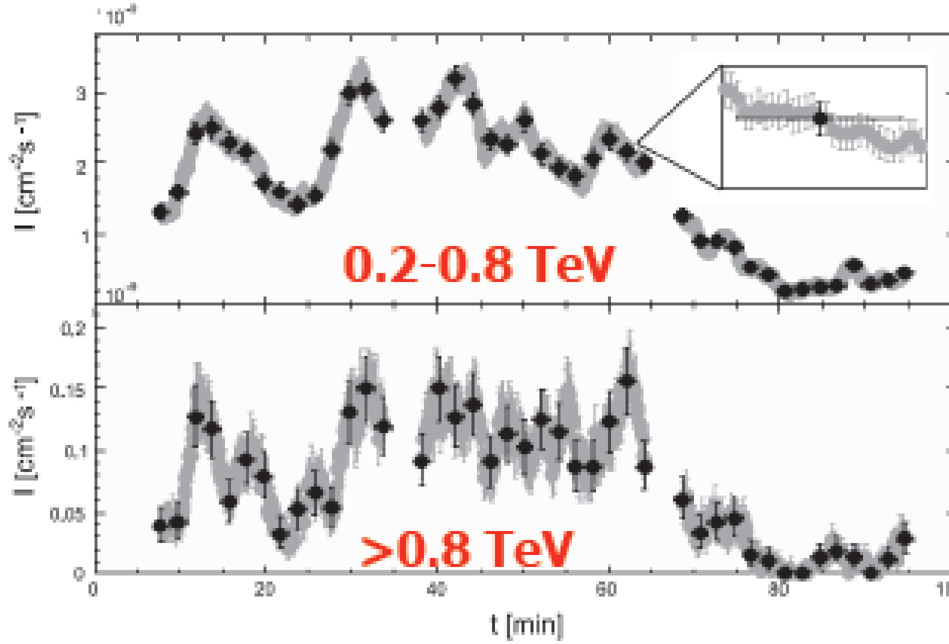
$$c' = c\left(1 \pm \frac{E}{k \cdot M_p} + ..\right) \quad , M_p \approx 1.2 \times 10^{19}\, GeV \,, k \approx 1$$

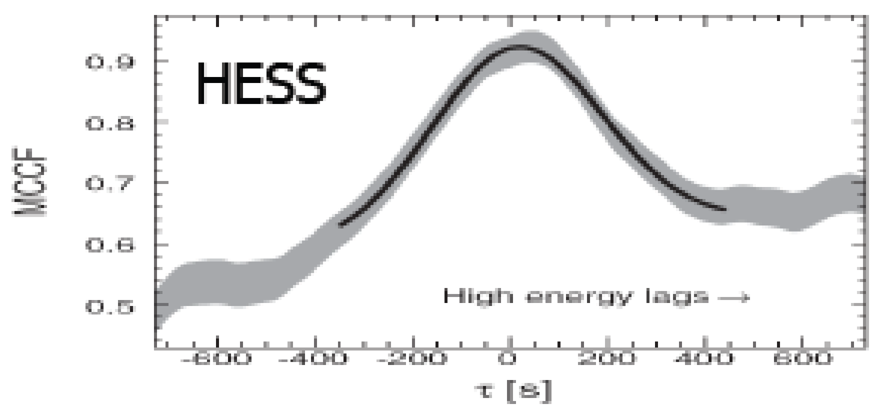
- Which would lead to a time delay between photons of different energies:

$$\Delta t_{QG} = L\left(\frac{1}{c_2} - \frac{1}{c_1}\right) \approx \frac{\Delta E}{k \cdot M_p} \frac{L}{c}$$

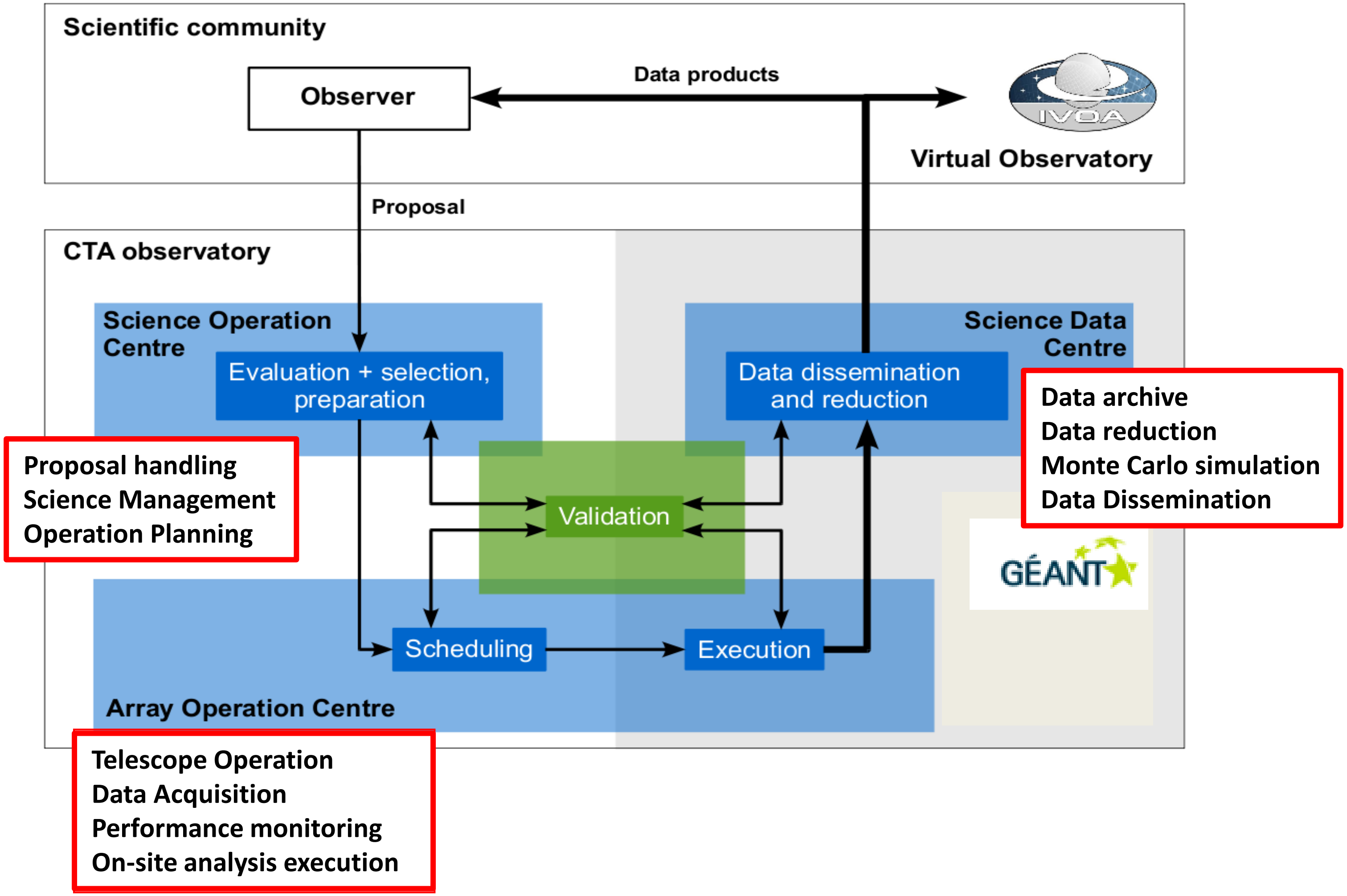
- To detect this effect we need high energy photons, huge distances and short timescales…

- A 2.5σ time lag seen by MAGIC for Mrk 501 butween high and low energy photons
  - *k* ~ 3%
  - Albert et al 2008 PRD
  - Quantum gravity effect?
- But not seen for 3x more distant PKS 2155-303 with more statistics
  - Time dispersion <100 seconds after 1 billion years of travel time!!!
  - *k* > 6%
  - Aharonian et al 2008 PRL
- For more sensitive instruments with wider energy ranges, the limits on *k* will approach 100% (the Planck scale!)





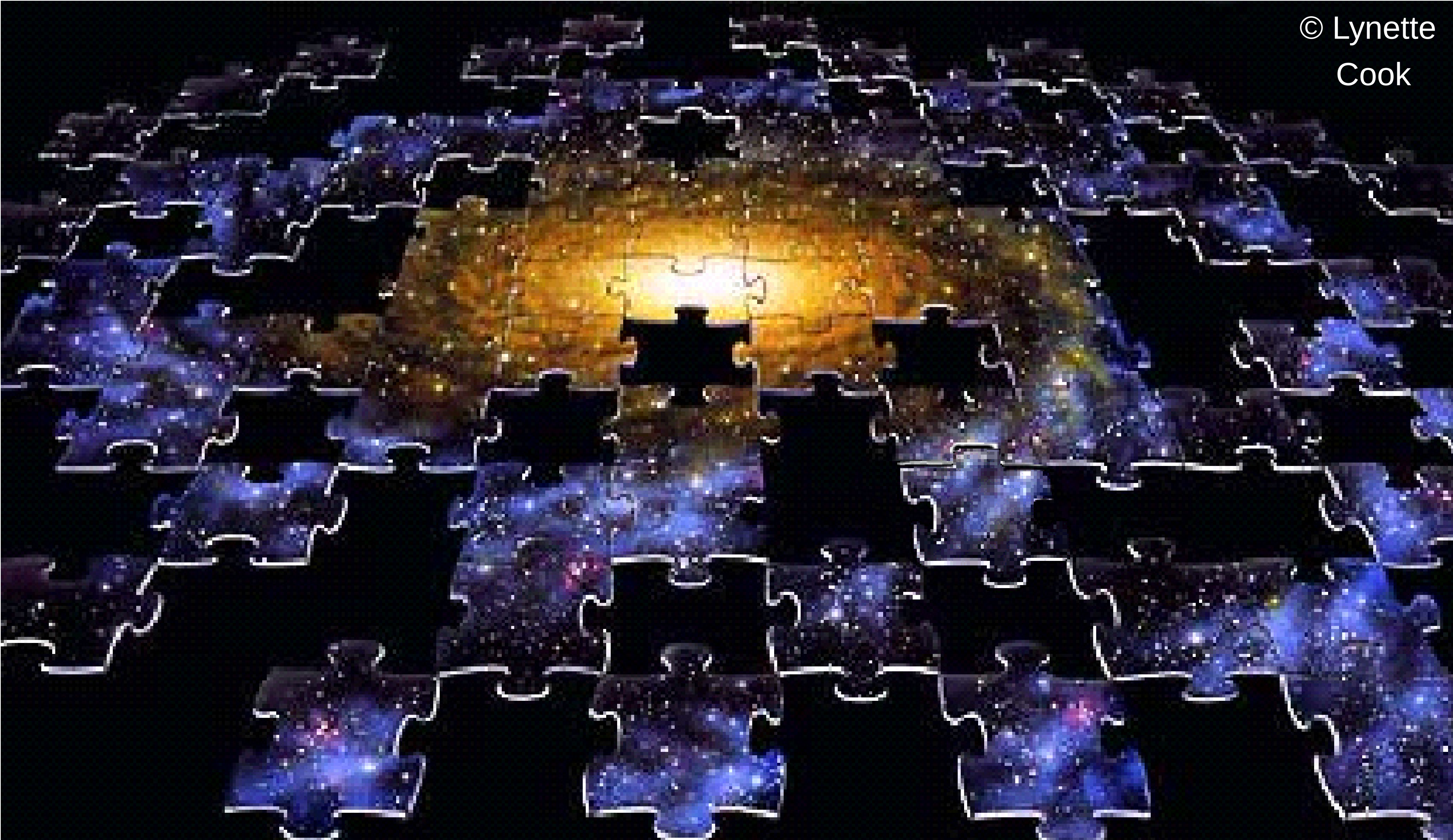
CTA is a PB big data scale project and operating as an Observatory




cta
cherenkov telescope array

CONCLUSIONS

- **Very interesting and varied physics can be done with an observatory-scale facility in the VHE regime**
- **Physics impact of the facility will affect all topics in modern astrophysics, and will produce legacy datasets.**
- **The operation of new facilities (HAWC, LHAASO, CTA) is opening a new window in astronomy**



The age of real VHE gamma ray astronomy has started