Introduction to experiments of astroparticle physics

J. Rico – IFAE
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Astroparticle physics

- What is astroparticle physics?
- Wikipedia says:
  - **Astroparticle physics**, the same as **particle astrophysics**, is a branch of particle physics that studies elementary particles of astronomical origin and their relation to astrophysics and cosmology.
  - It is a relatively new field of research emerging at the intersection of particle physics, astronomy, astrophysics, detector physics, relativity, solid state physics, and cosmology.
  - Partly motivated by the historic discovery of neutrino oscillations, the field has undergone remarkable development, both theoretically and experimentally, over the last decade.

Questions

1) What is the Universe made of?
   In particular: What is **dark matter**?
2) Do **protons** have a **finite life time**?
3) What are the **properties of neutrinos**?
   What is their role in cosmic evolution?
4) What do **neutrinos** tell us about the interior of the **Sun** and the **Earth**, and about **Supernova** explosions?
5) What is the **origin of cosmic rays**?
   What is the view of the sky at extreme energies?
6) Can we detect **gravitational waves**?
   What will they tell us about violent cosmic processes and about the nature of gravity?

Pillars of Astroparticles

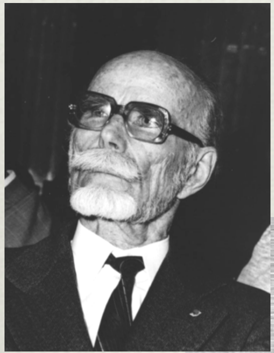
- High energy (cosmic) neutrinos
- Ultra-high energy cosmic rays
- Very high energy gamma-rays
- Dark matter
- Gravitational waves

I will concentrate on the first three items, with a focus on large infrastructures

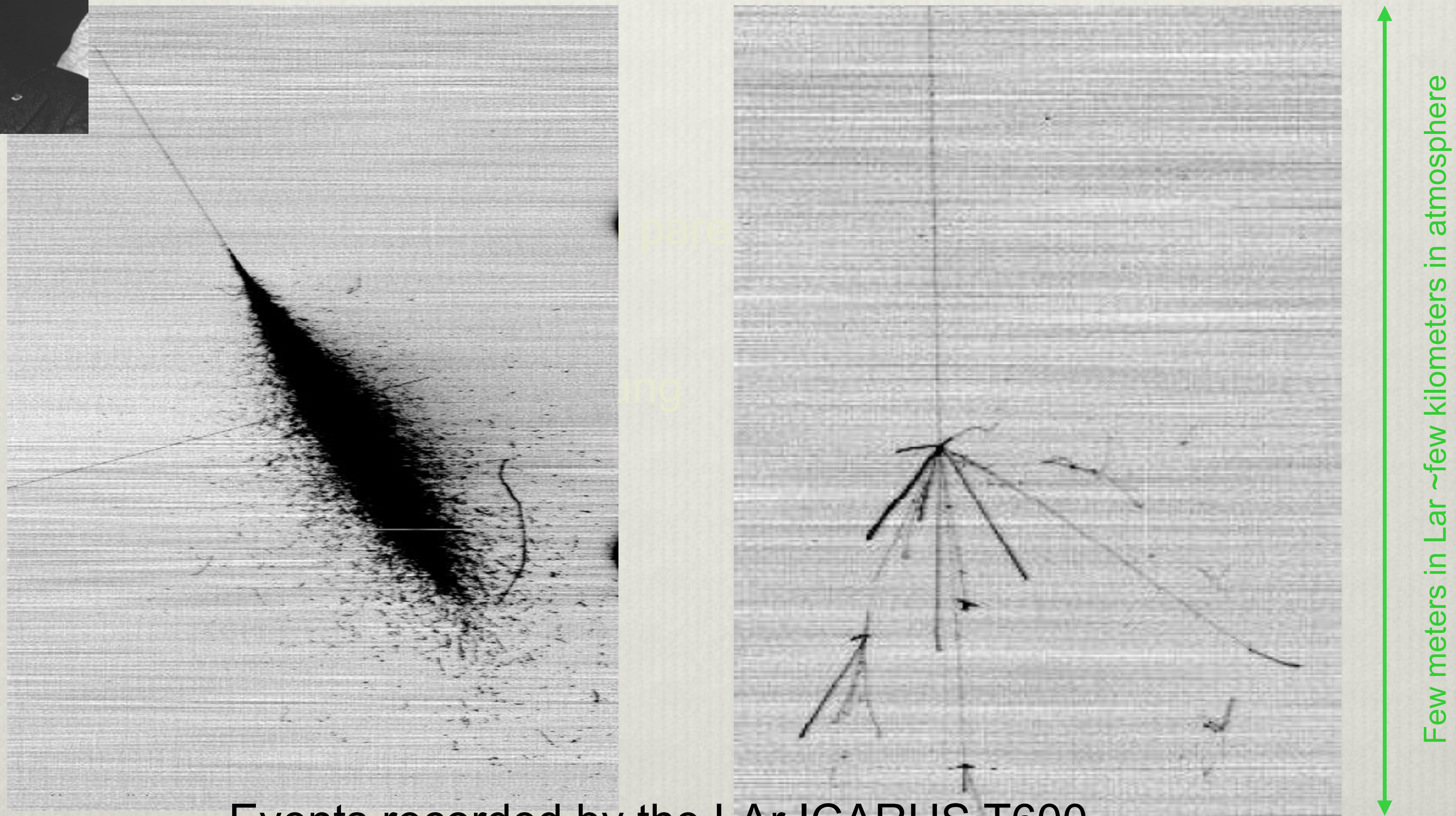
Presentation mostly stolen from Manel Martínez, who in turn stole it from more people…

Principle of detection

Extensive Air Showers



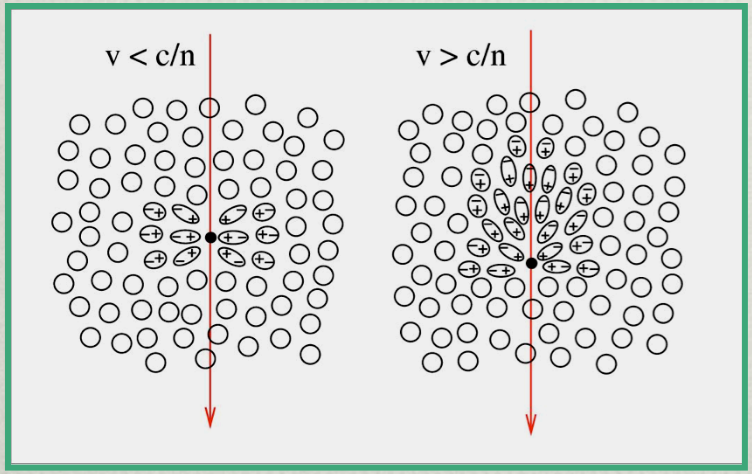
- Gammas and CR's interact in the upper parts of the atmosphere, producing particle cascades (discovered by Pierre Augher in 1938)

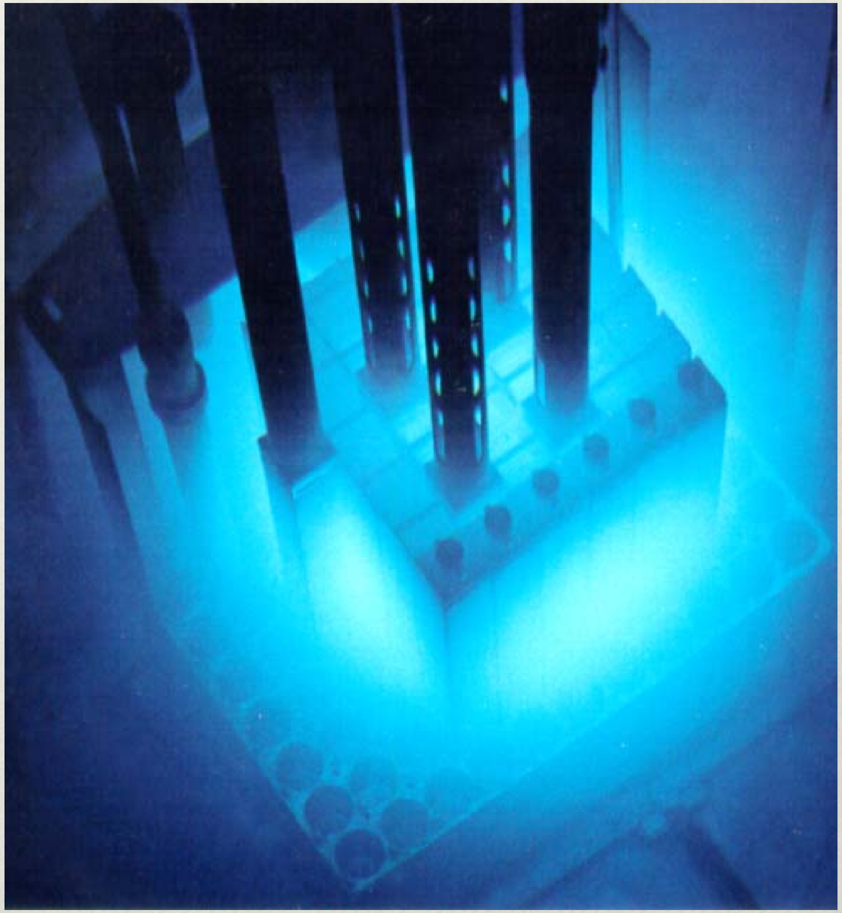


Events recorded by the LAr ICARUS T600

Cherenkov radiation

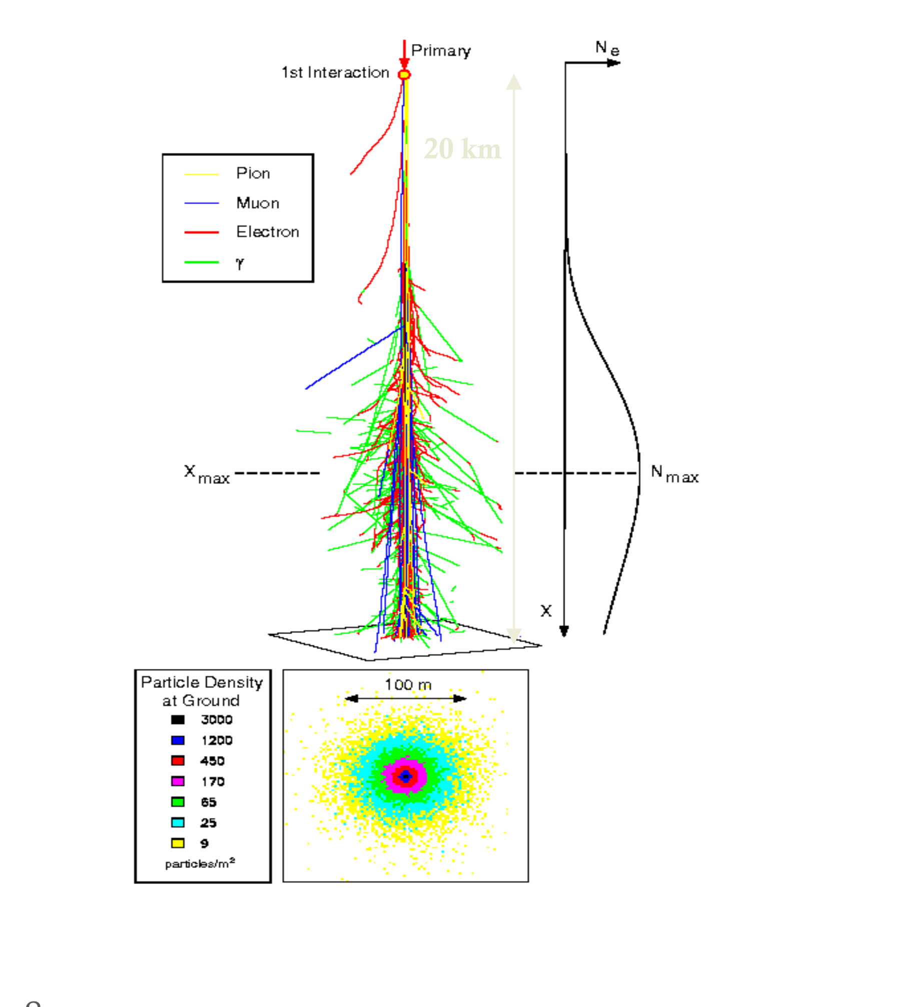
- If charged particles travel faster than light in the medium they produce Cherenkov radiation

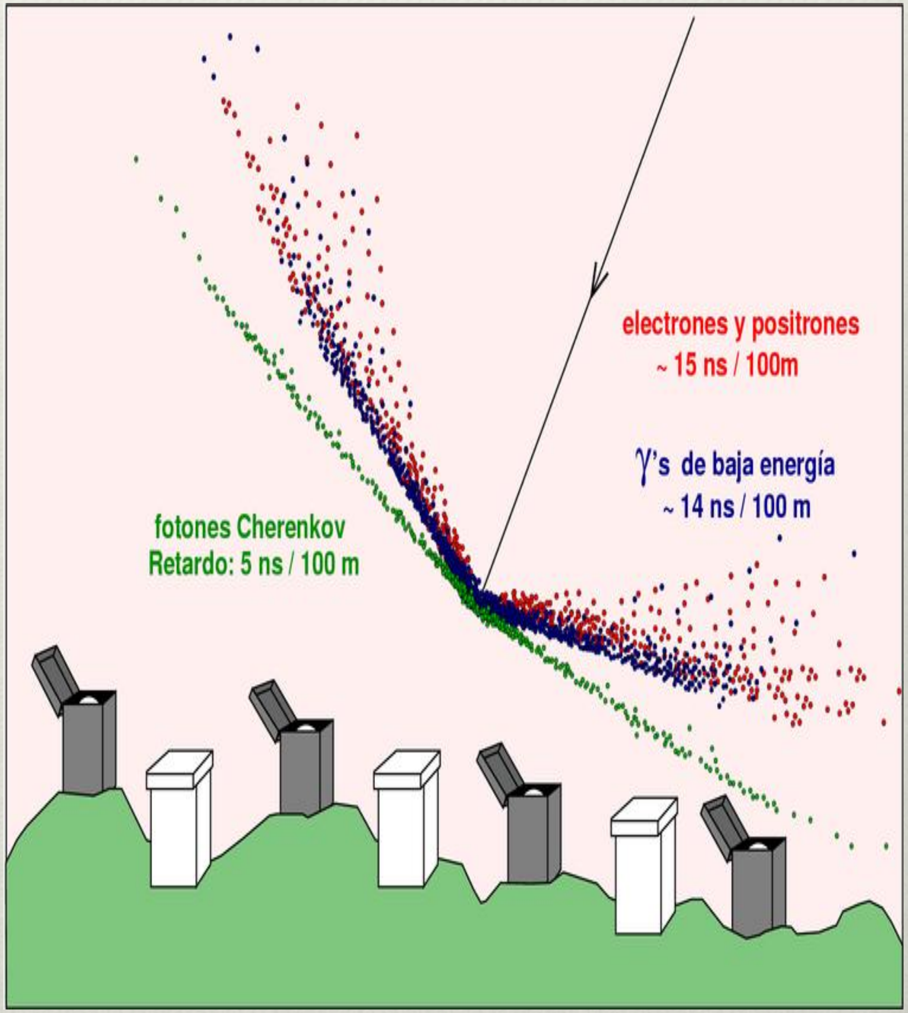




Ground detectors

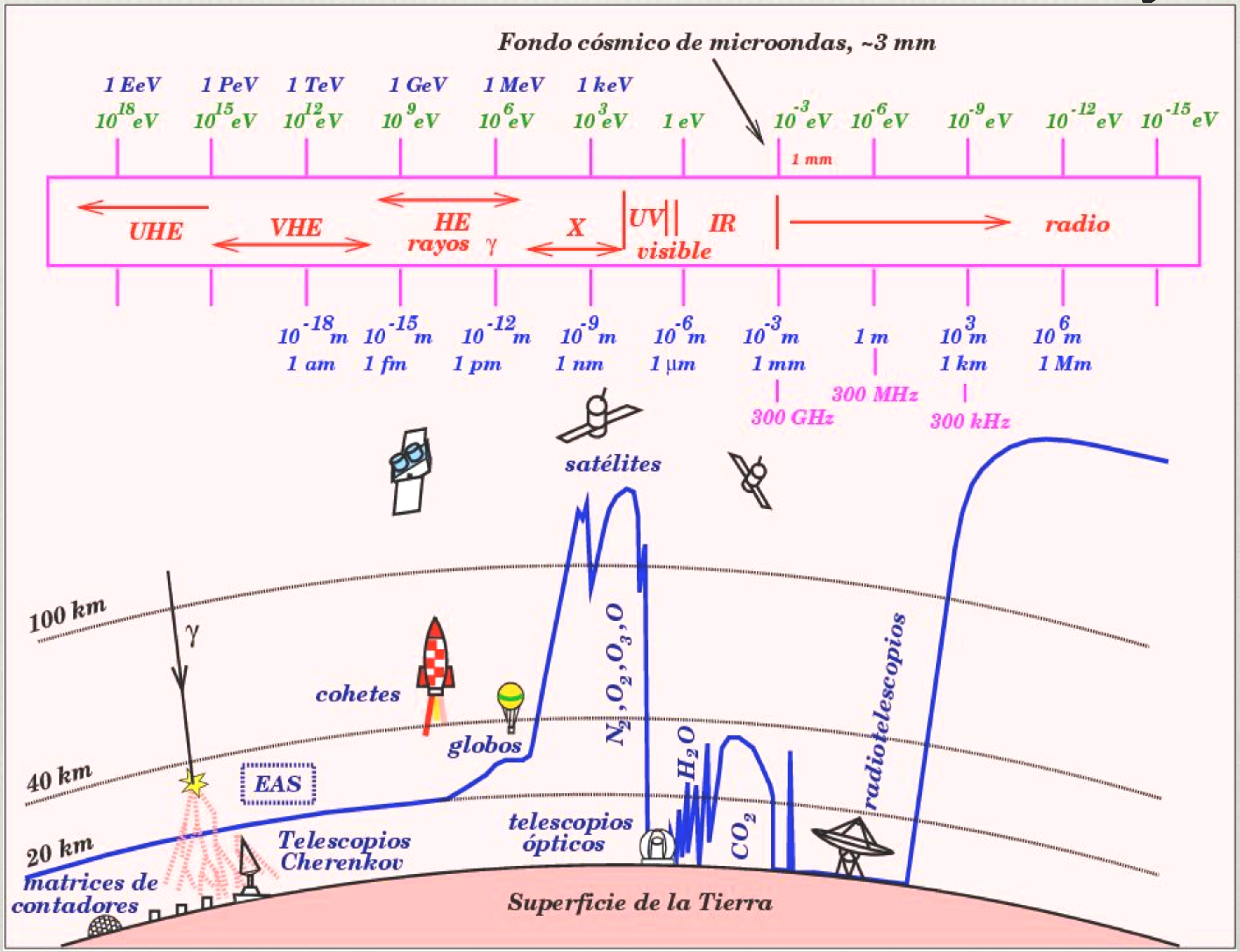
Atmospheric showers





High energy Gamma Rays

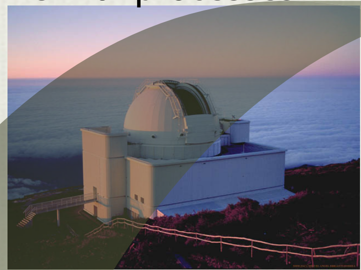
Windows of astronomy



The new astronomies

Infra-red(10^{-2} eV)
1856 C. Piazzi Smyth
Dust-hidden regions

Optical (~1 eV)
<3000AC, 1609 Galileo
Thermal processes



UV (5 eV-1 keV)
~1920 (balloons) 1946 (OSO)
Solar physics,
Young stars, …

X-rays (1 keV-500 keV)
1962 Giaconni (Scorpius X1)
Compact objects, SNRs,…

Towards Very High Energy (VHE)

Radio (10^{-6} eV)
~1930 K. Jansky
CMB, Pulsars,
Radiogalaxies, …
Regiones de

γ-rays (500 keV-1 GeV)
~1960, 1975 (COS-B)
Solar flares, GRBs, pulsars,
SNRs, jets, …

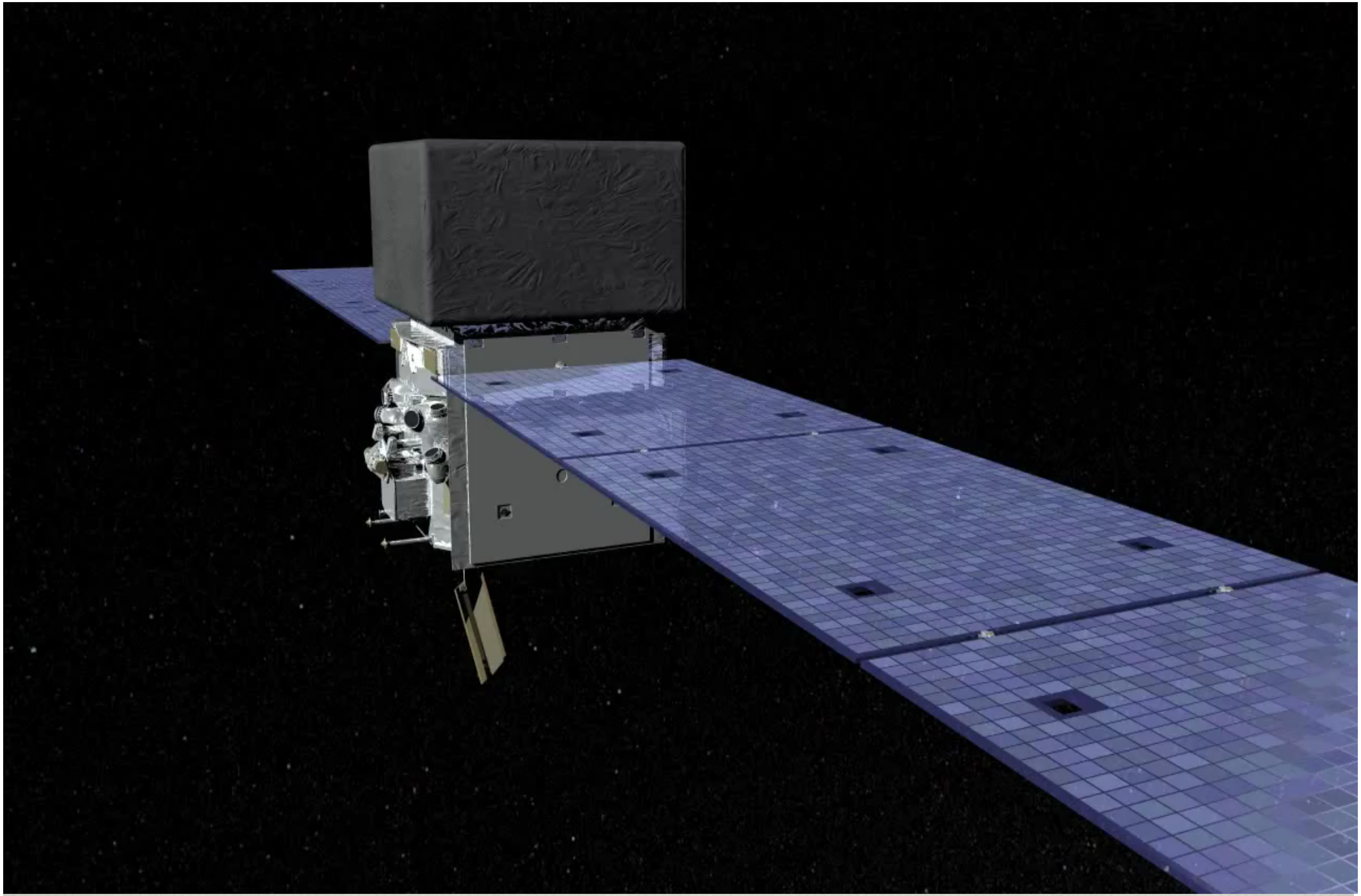
Gamma astronomy in space

- Feenberg y Primakoff 1948, Hayakawa & Hutchinson 1952, Morrison 1958: First theoretical predictions of γ-ray production in the Universe
  - Interaction CR with interstellar gas
  - Supernova explosions
  - Interaction of accelerated electrons with magnetic fields
- Explorer XI 1961: detection of 100 γ-rays (isotropic)
- Spy satellites (60-70's): GRB's
- OSO3-7 (70's): γ-rays from the Sun (2.2 MeV line from neutron capture)
- COS-B (1975-82): First map of γ-ray sky
- EGRET (1991-2000): 270 γ-ray sources
- Fermi/LAT (2008-2018): ~2500 sources so far

The Delta II rocket carrying the Fermi spacecraft
Image credit: NASA/Jerry Cannon, Robert Murray

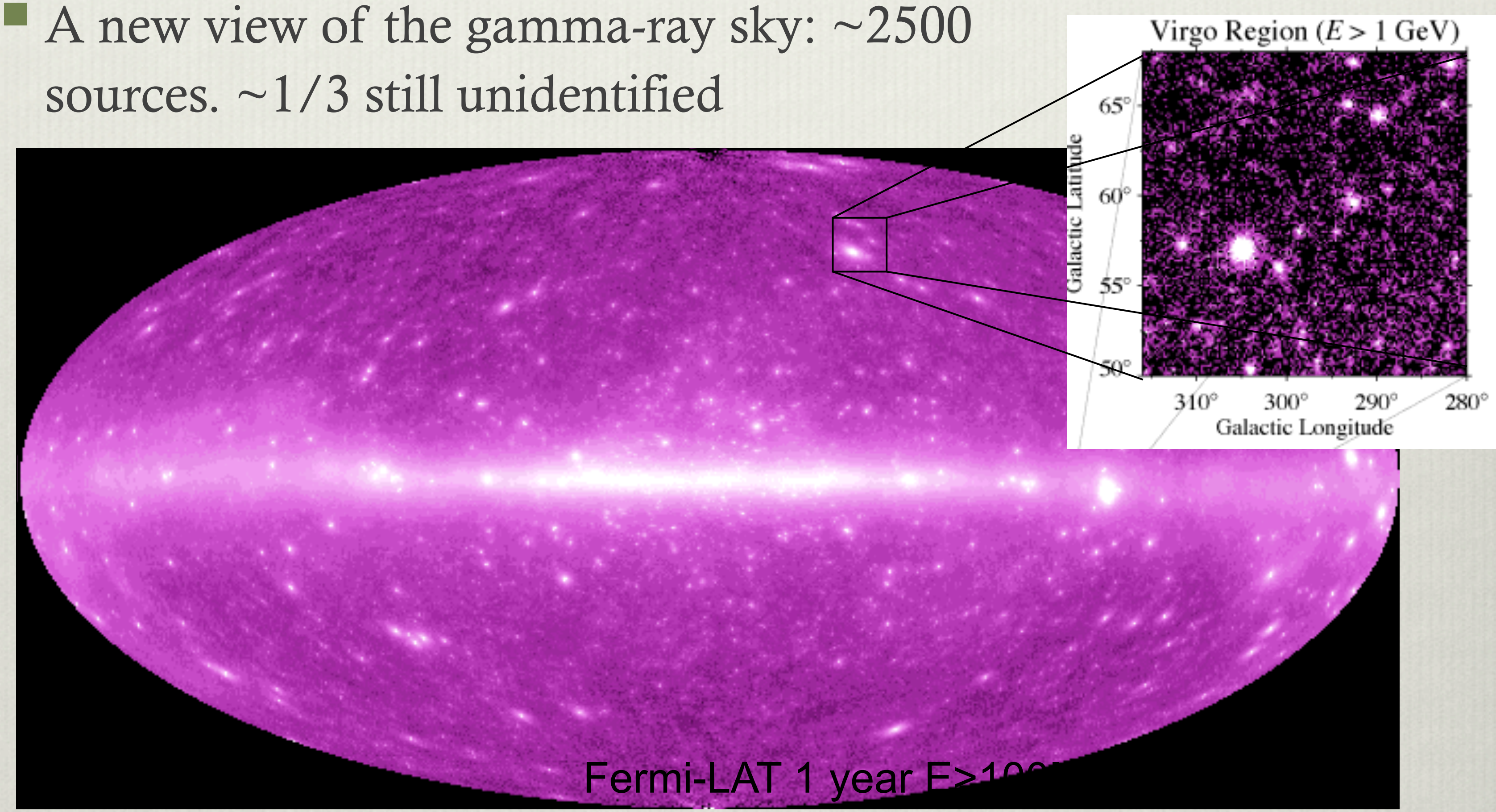
Fermi-LAT

- Space-borne detector. Anticoincidence shield + tracker + calorimeter (no magnet)
- Almost background free
- Energy range 30 MeV – 300 GeV
- Energy resolution 10-15%
- PSF ~1° (0.1°) at 1 (100) GeV
- Field of view 2.4 sr (1/5 of sky)
- Survey mode: full sky every 2 orbits (three hours). Slew to keep ToO in FOV
- Operates since August 2008



The gamma-ray sky

- A new view of the gamma-ray sky: ~2500 sources. ~1/3 still unidentified

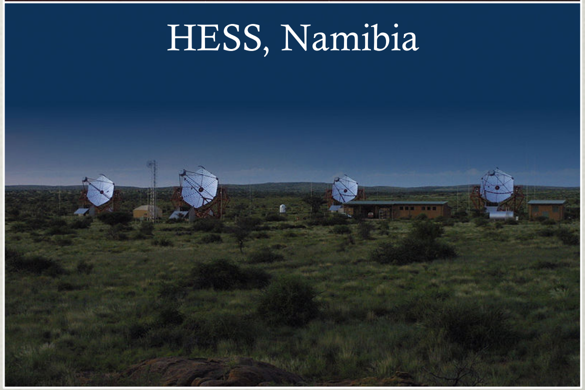


❖ But: at E>~10 GeV fluxes are low: < 1 ph/cm^2/yr

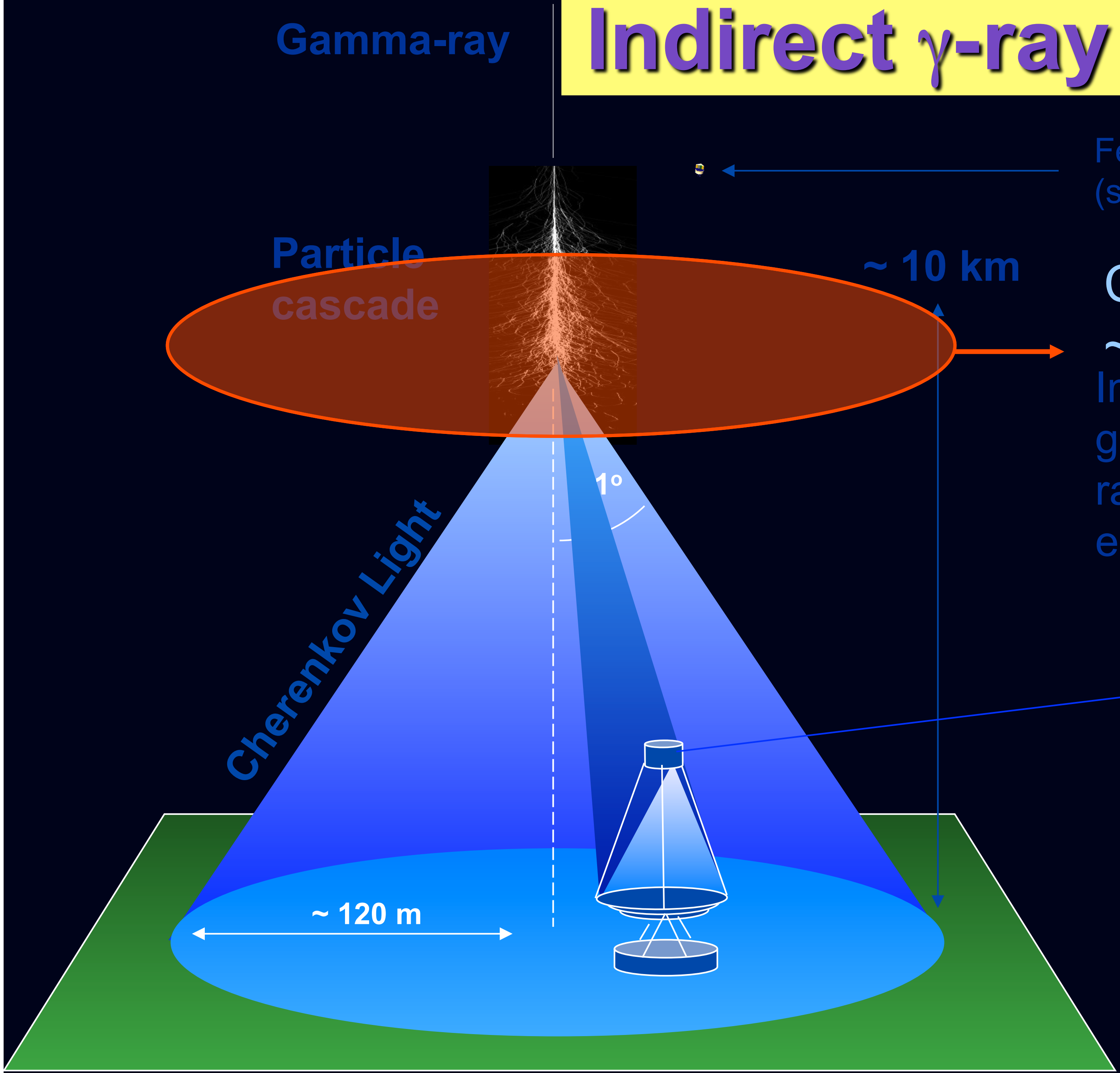
→ more collection area is needed

VHE instruments: Cherenkov telescopes

- Gamma-ray fluxes drop exponentially with energy ➔ for energies above ~100 GeV we need larger collection areas ➔ Cherenkov telescopes
- Huge CR background ➔ Imaging technique
- Energy range ~100 GeV – 100 TeV
- Energy resolution 10-15%
- PSF ~0.1° at 1 TeV
- Field of view 3-5 deg diameter (~0.005 sr)
- Pointed observations, systematic scans of limited regions
- Array of 4 (VERITAS, HESS) and 2 telescopes (MAGIC)
- Operating since 2003 (HESS), 2005 (MAGIC) and 2006 (VERITAS)



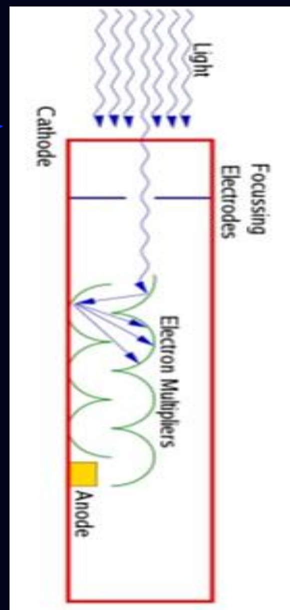
Indirect γ-ray detection



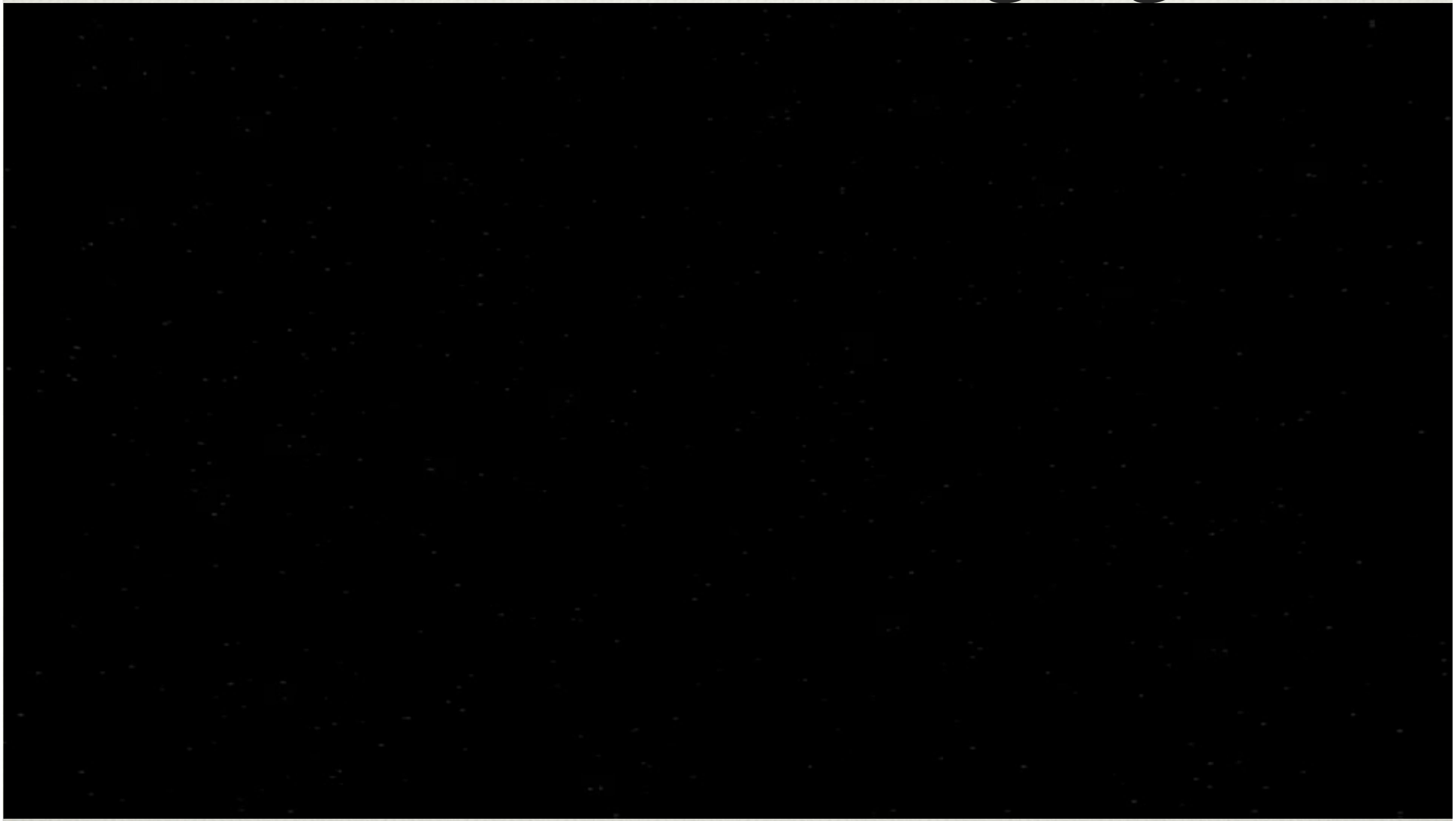
Fermi
(slightly magnified)

Collection area:
~ 10^5 m^2

Important since gamma-rays are rare at these energies (1/m^2 mnth)



Cherenkov imaging



Imaging technique

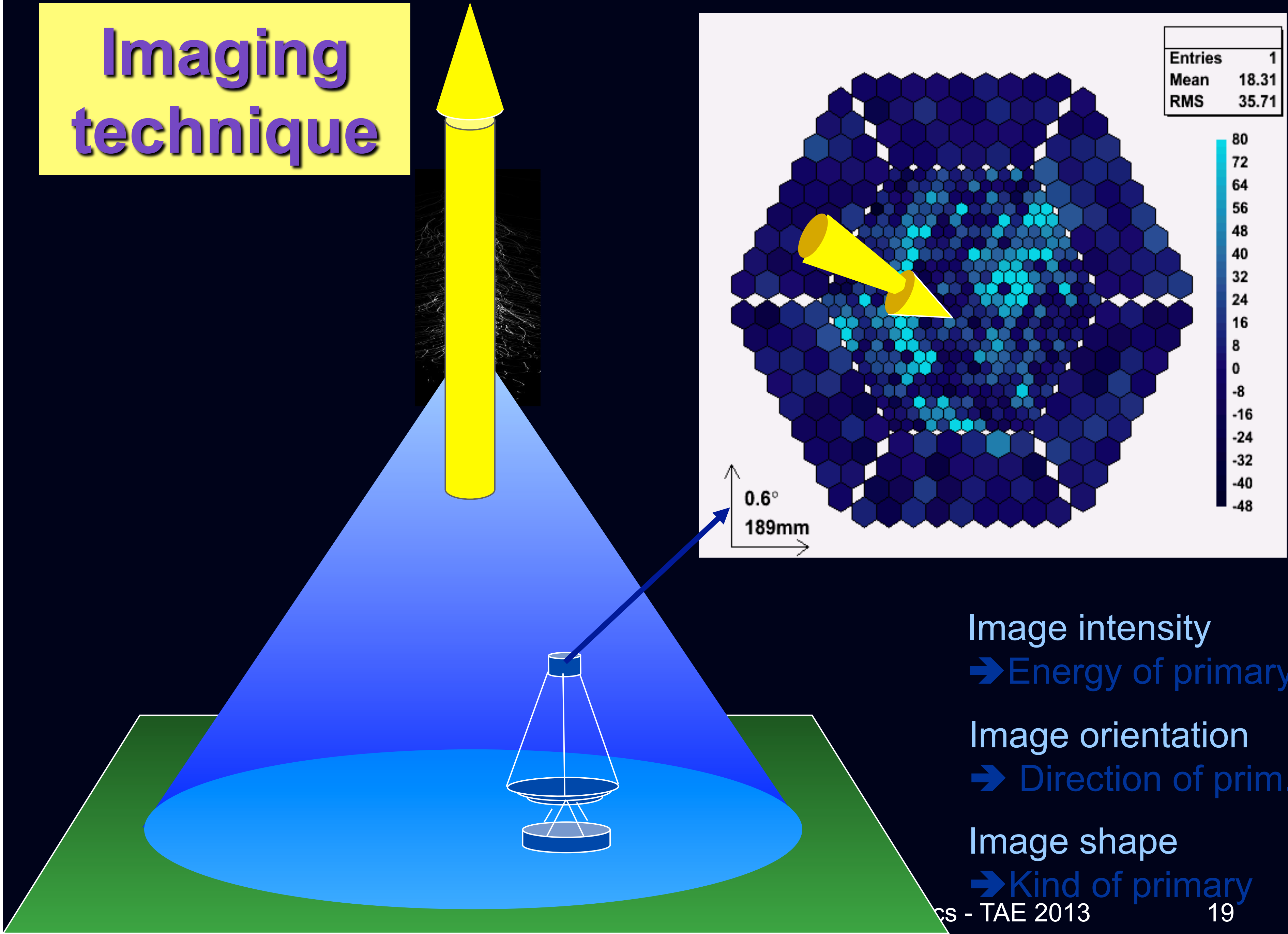
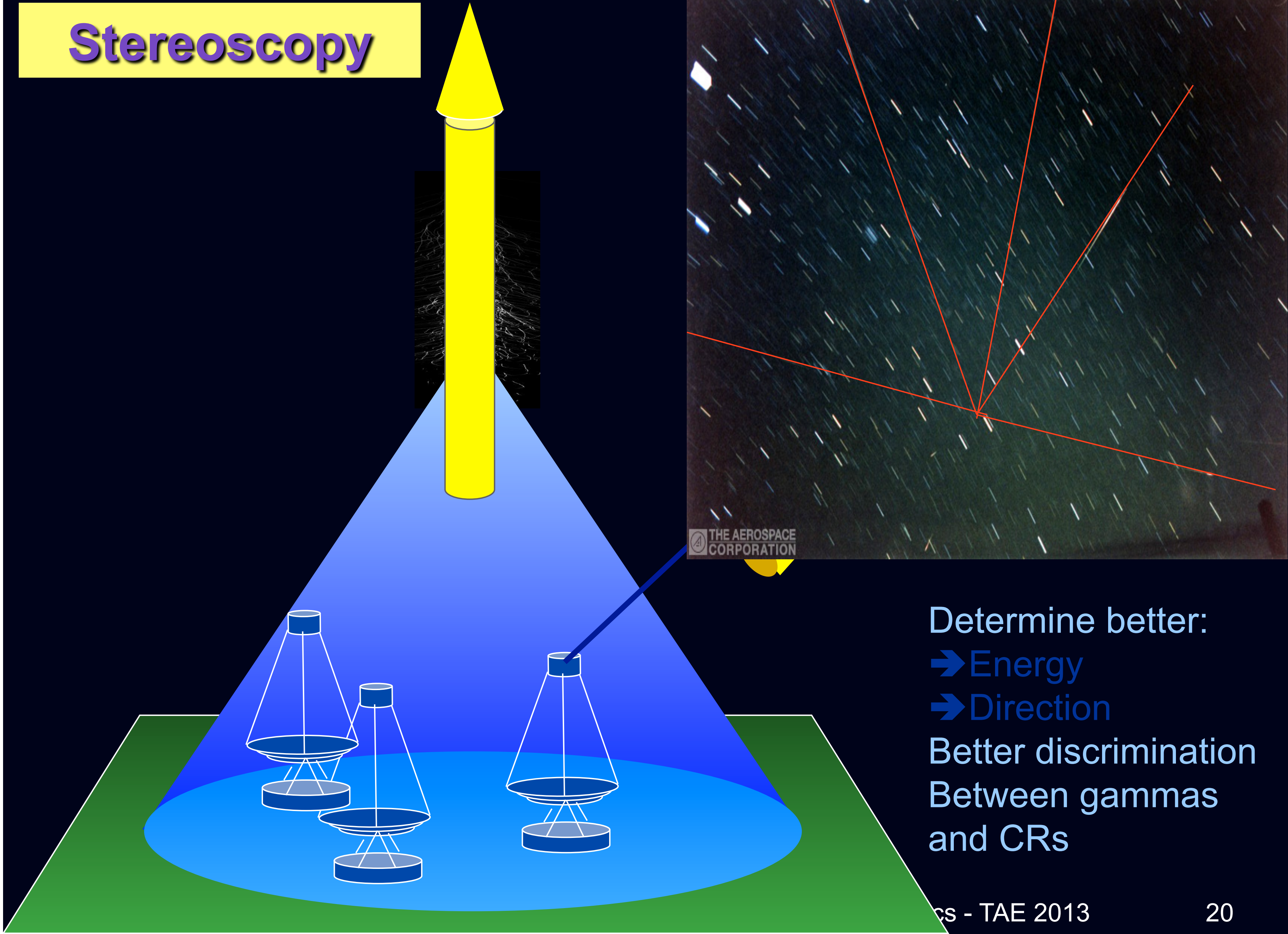


Image intensity
➔Energy of primary

Image orientation
➔ Direction of prim.

Image shape
➔Kind of primary

Stereoscopy



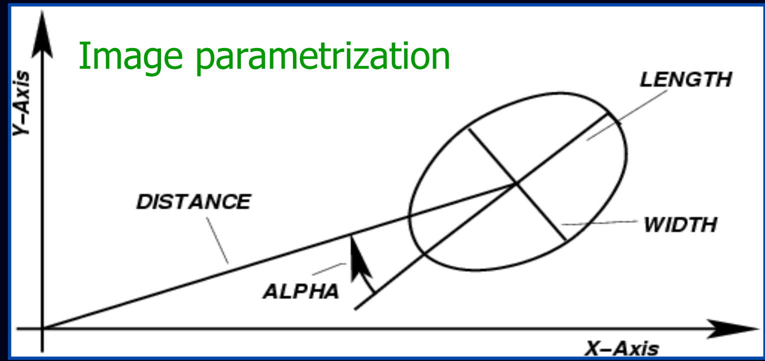
Determine better:

- ➔Energy
- ➔Direction

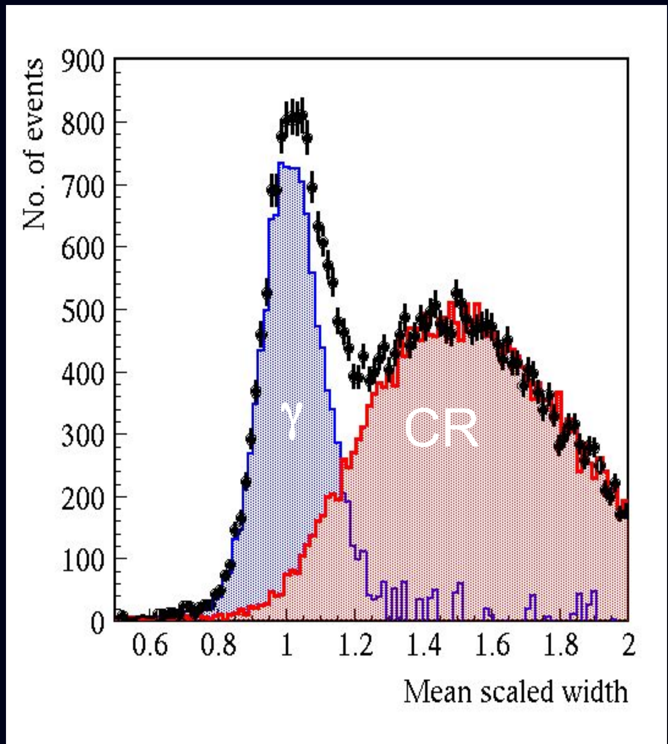
Better discrimination Between gammas and CRs

Removing the CR background

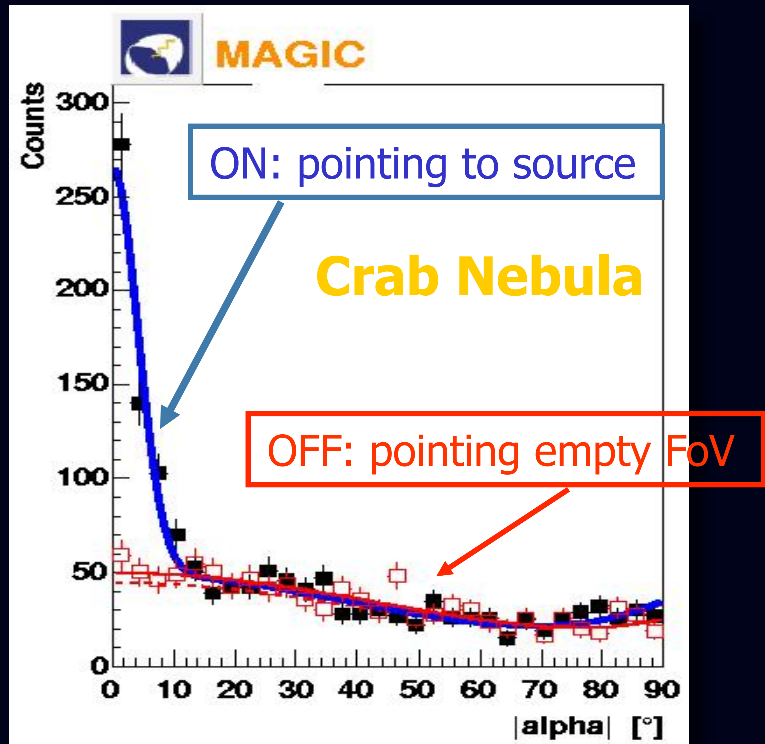
- Cherenkov images are parameterized by the light distribution (shape, position, orientation…)



(1) Shape: γ-rays are more **regular and narrower**

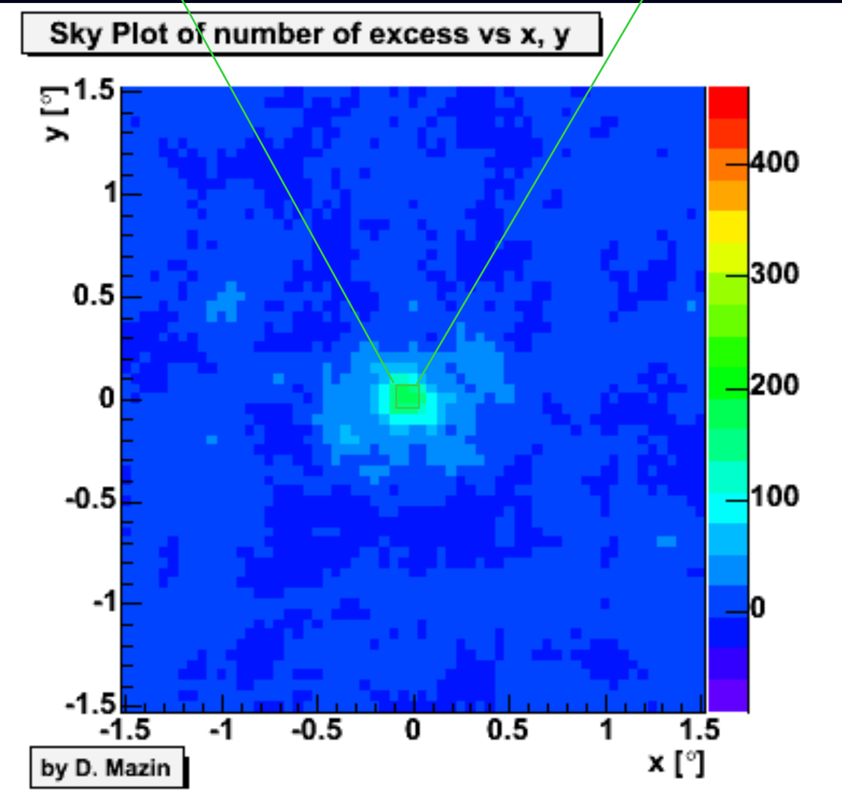


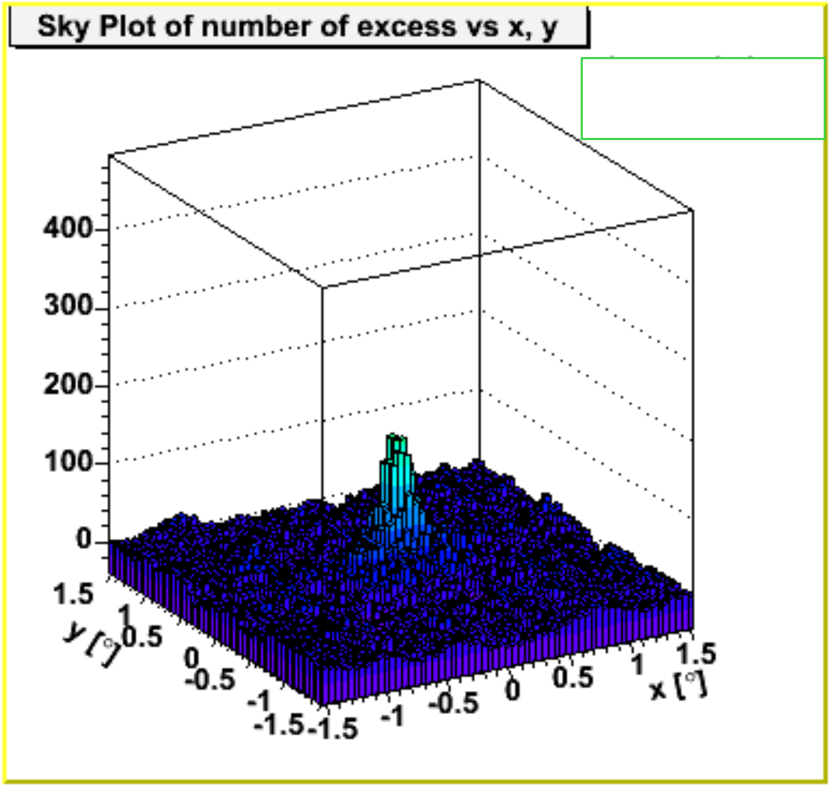
(2) **Direction**: γ-rays coming from pre-established direction



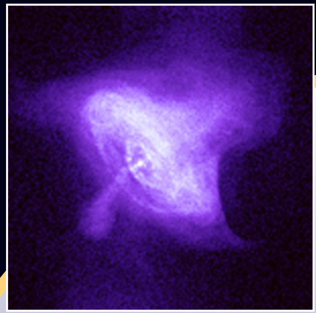
Detecting the Crab Nebula

- The Crab Nebula is one of the most intense γ-ray source and its flux is very stable
- Therefore it is used as a cablibration source by γ-ray telescopes
- Typical angular resolution is ~0.1° → The Crab Nebula is point-like

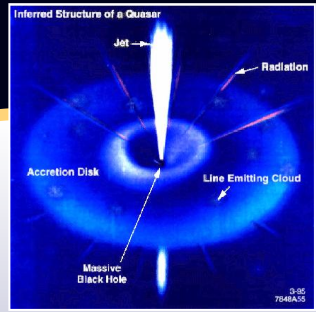




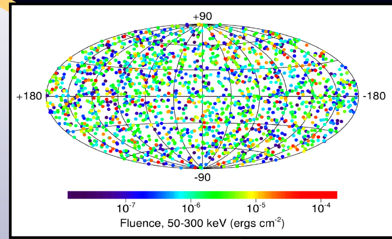
Physics program



Pulsars



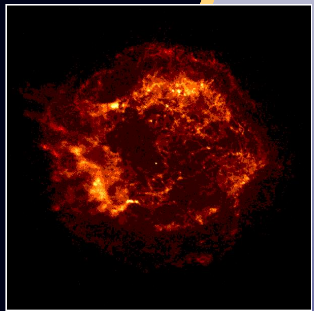
AGNs



GRBs

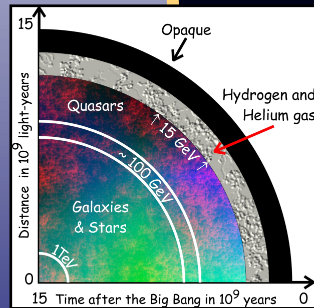
Astrophysics

Fundamental Physics

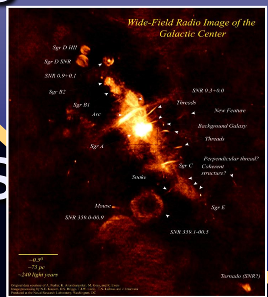


Supernovas

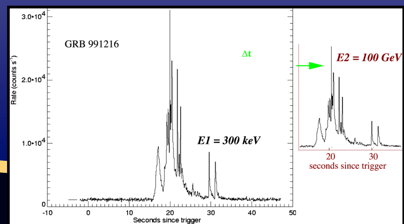
Origin of cosmic rays



Cosmological horizon

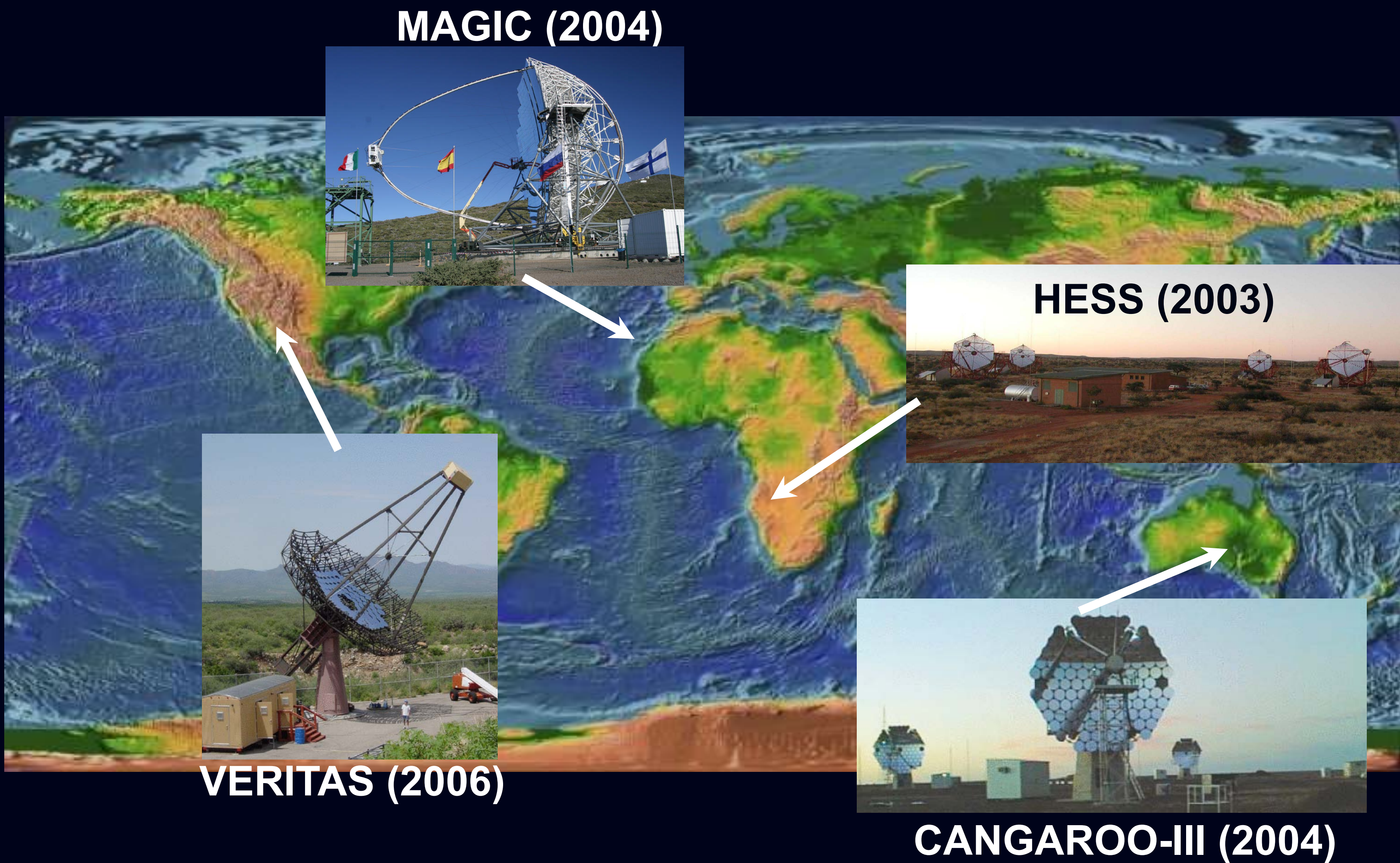


Dark Matter



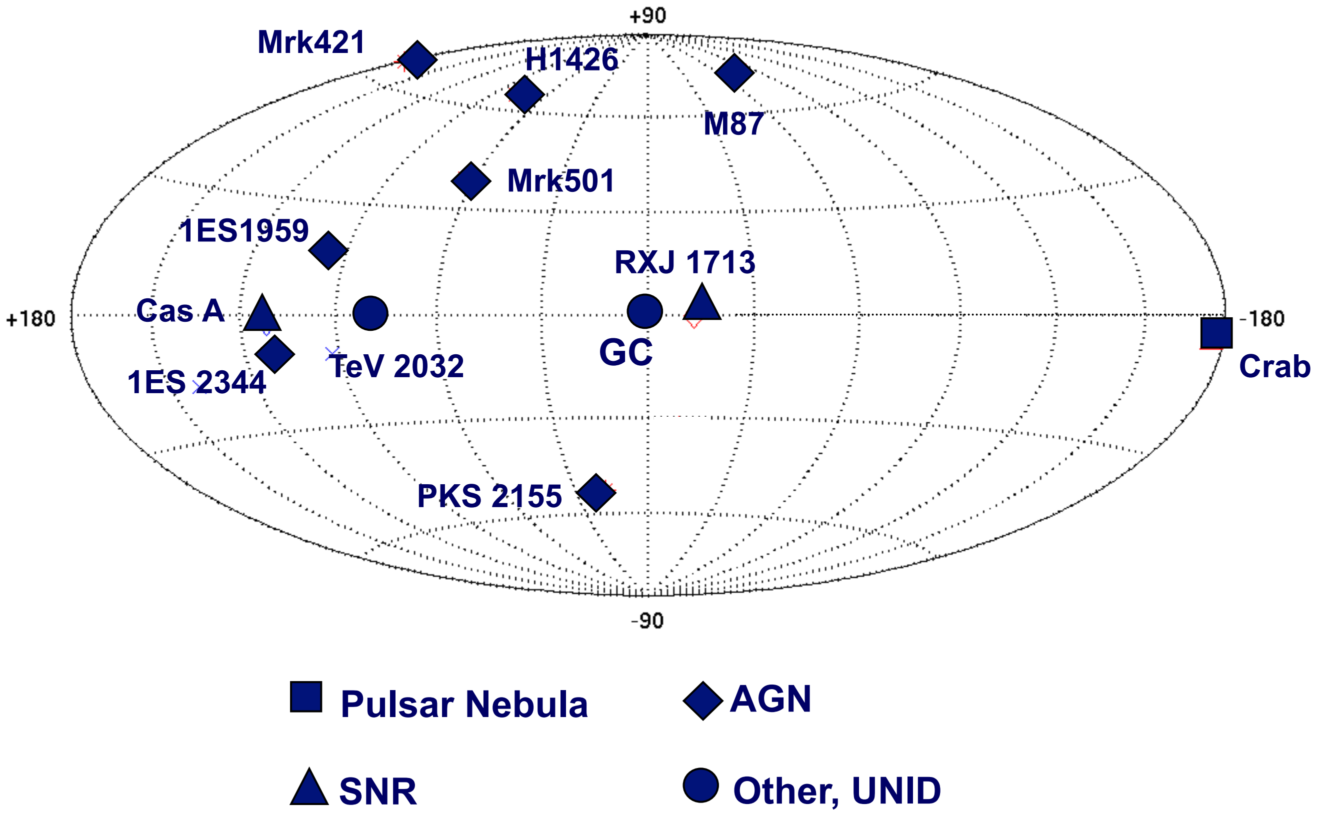
Quantum gravity

2nd generation of Cherenkov telescopes



The VHE (E>100GeV) sky

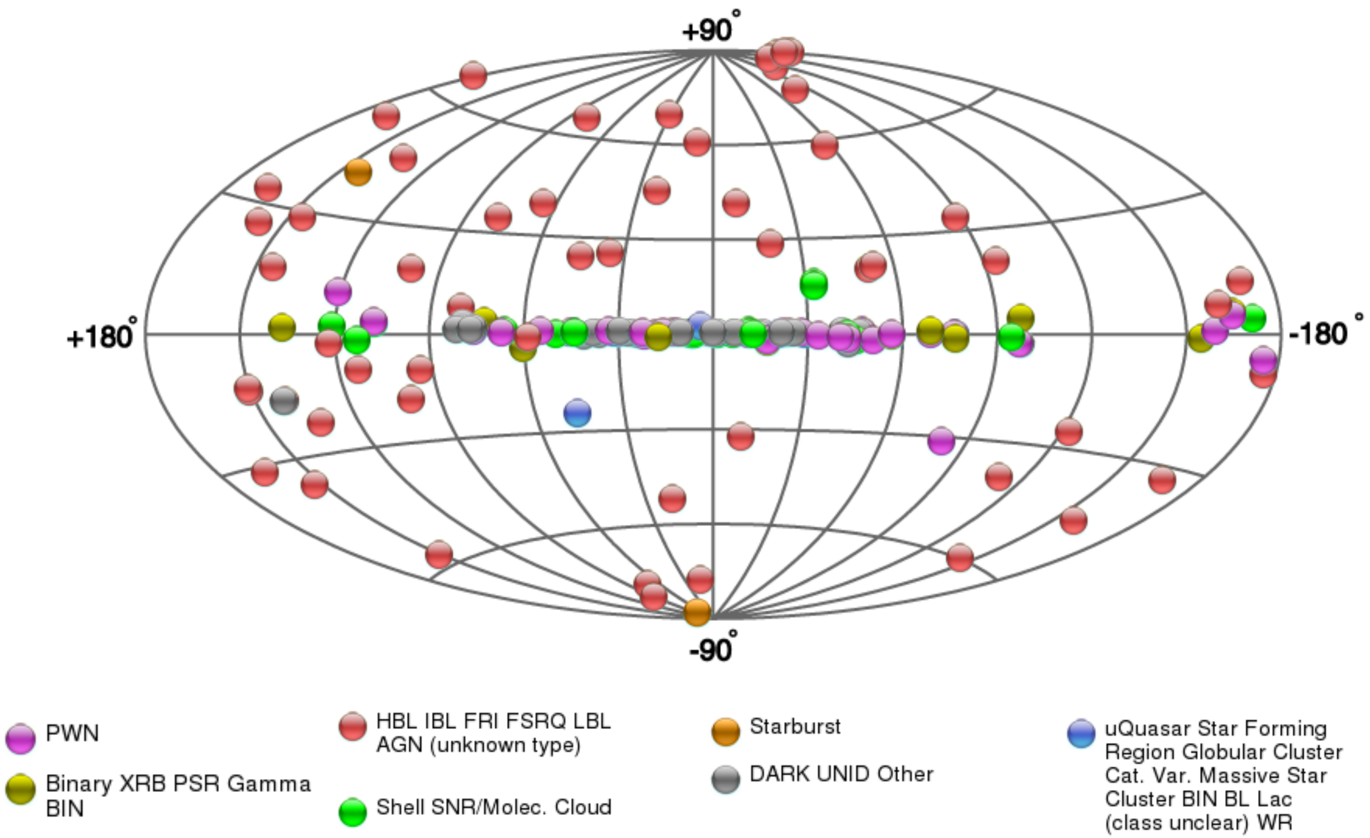
2003



Total: 12 sources

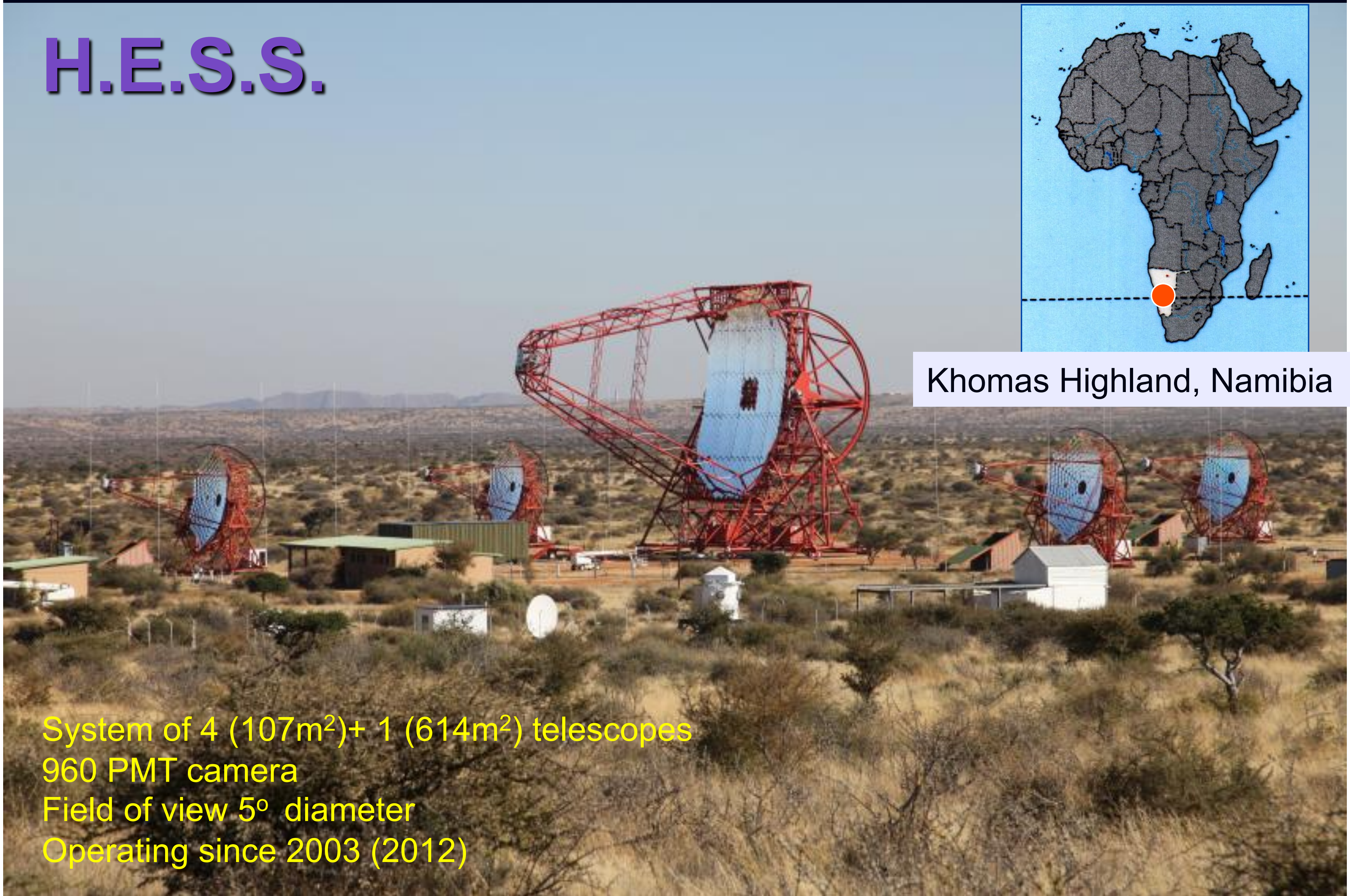
The VHE (E>100GeV) sky

2013



Total: 145 sources

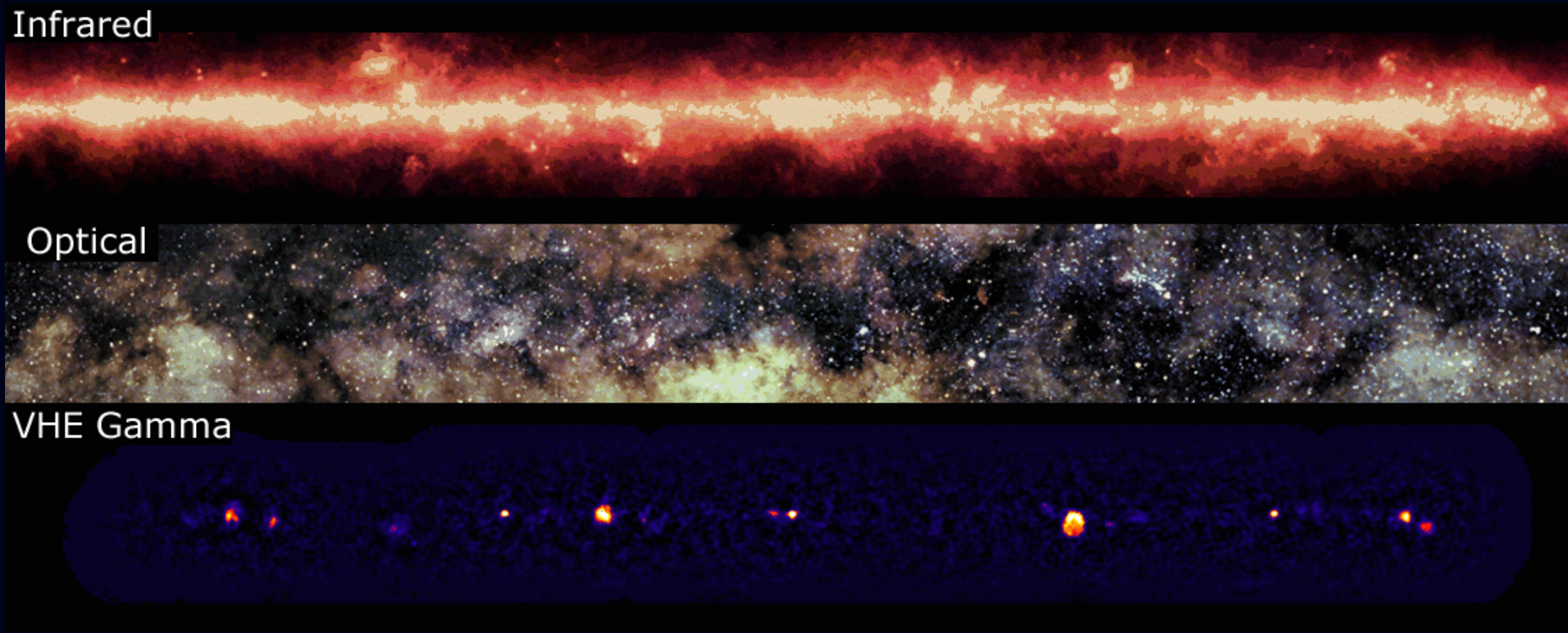
H.E.S.S.



Khomas Highland, Namibia

System of 4 (107m^2)+ 1 (614m^2) telescopes
960 PMT camera
Field of view 5^o diameter
Operating since 2003 (2012)

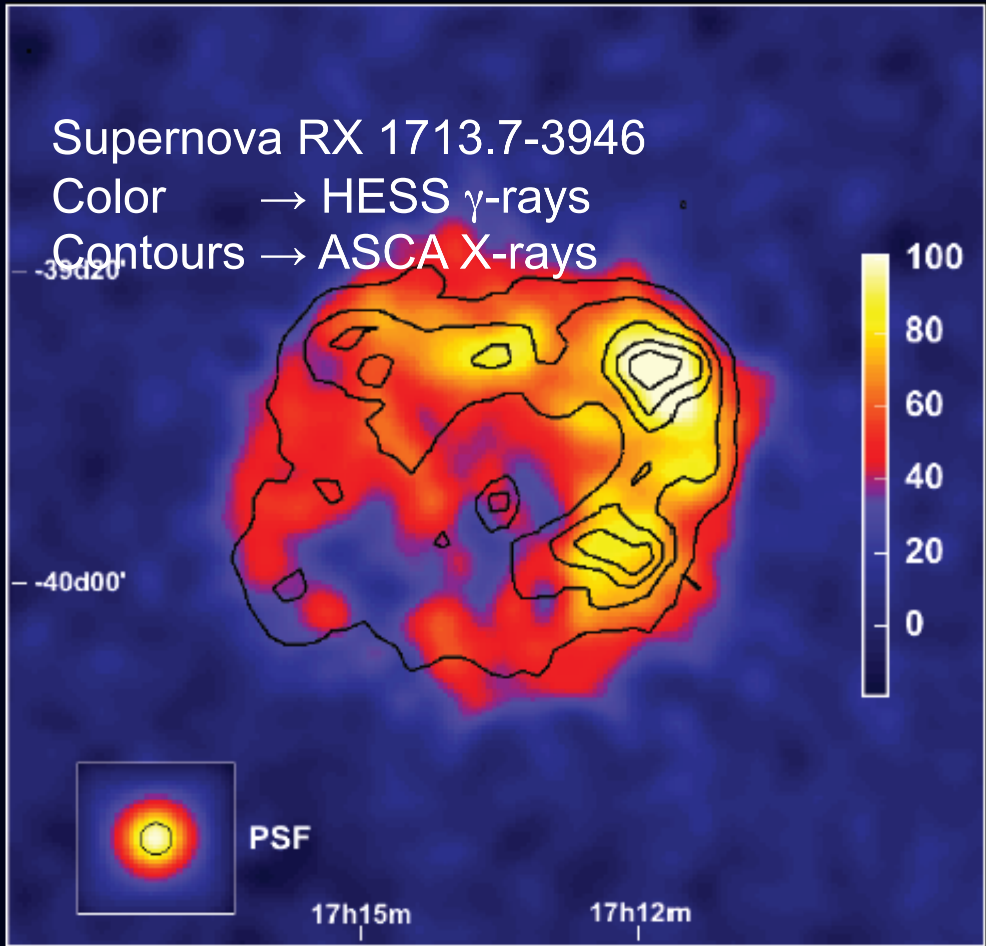
The inner part of the Galaxy



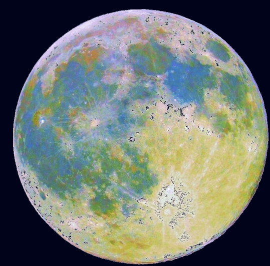
• HESS has performed a systematic scan of the inner part of our Galaxy detecting VHE emission (E>250 GeV) from many previously unknown sources, including supernova remnants, pulsar wind nebulae, compact binary systems and a number of unidentified sources

Supernova RX 1713.7-3946

- **HESS also got the first resolved image of an extended source in γ-rays**



- High correlation X- and γ-rays
- The aparent size of the moon at the same scale is like this:

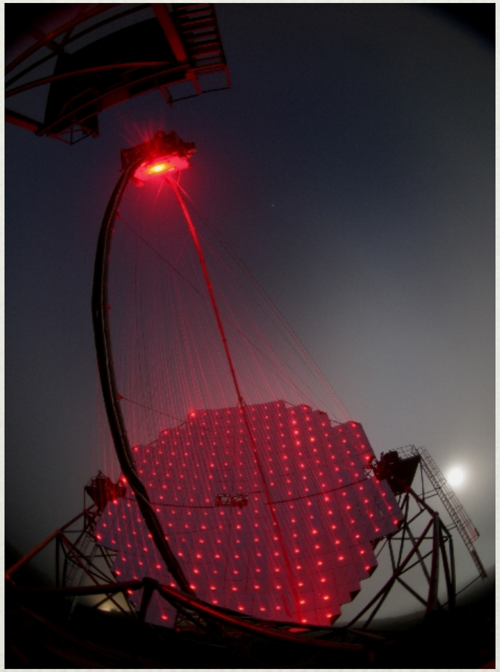


MAGIC

- System of 2 (236m^2 mirror) telescopes at the Observatorio del Roque de los Muchachos (Canary Islands)
- Lowest energy threshold so far → overlap with Fermi-LAT
- Operating since 2004 (2009)
- Operated by International Collaboration of ~180 scientist with a key participation of Spain

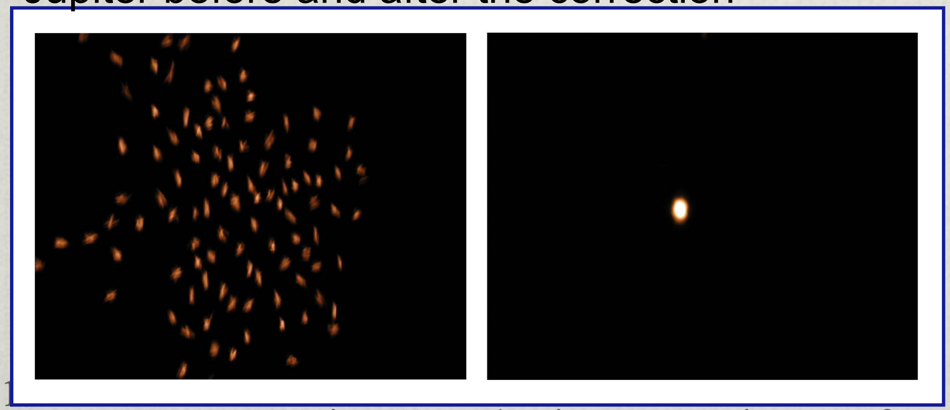
Big but light telescopes

- Structure is very light (65 t) so that telescope can be moved fast → catch GRBs
- Light structure deforms and mirros positions have to be corrected dynamically

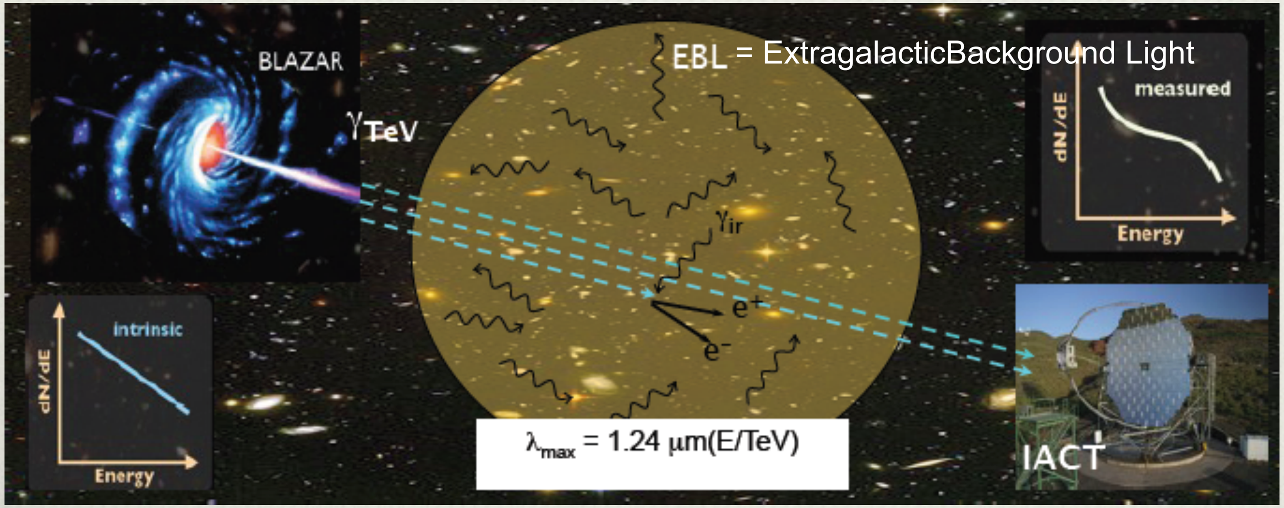


Telescopes are repositioned in less than ~40 s

Jupiter before and after the correction

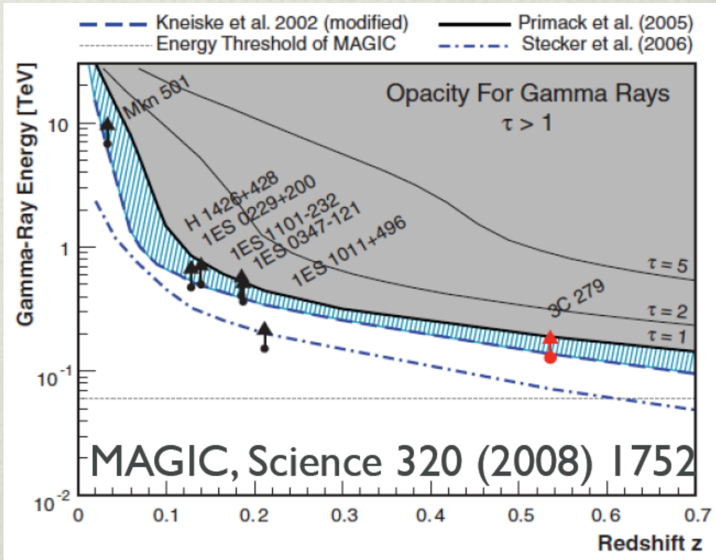


Low energy threshold pays off (1)



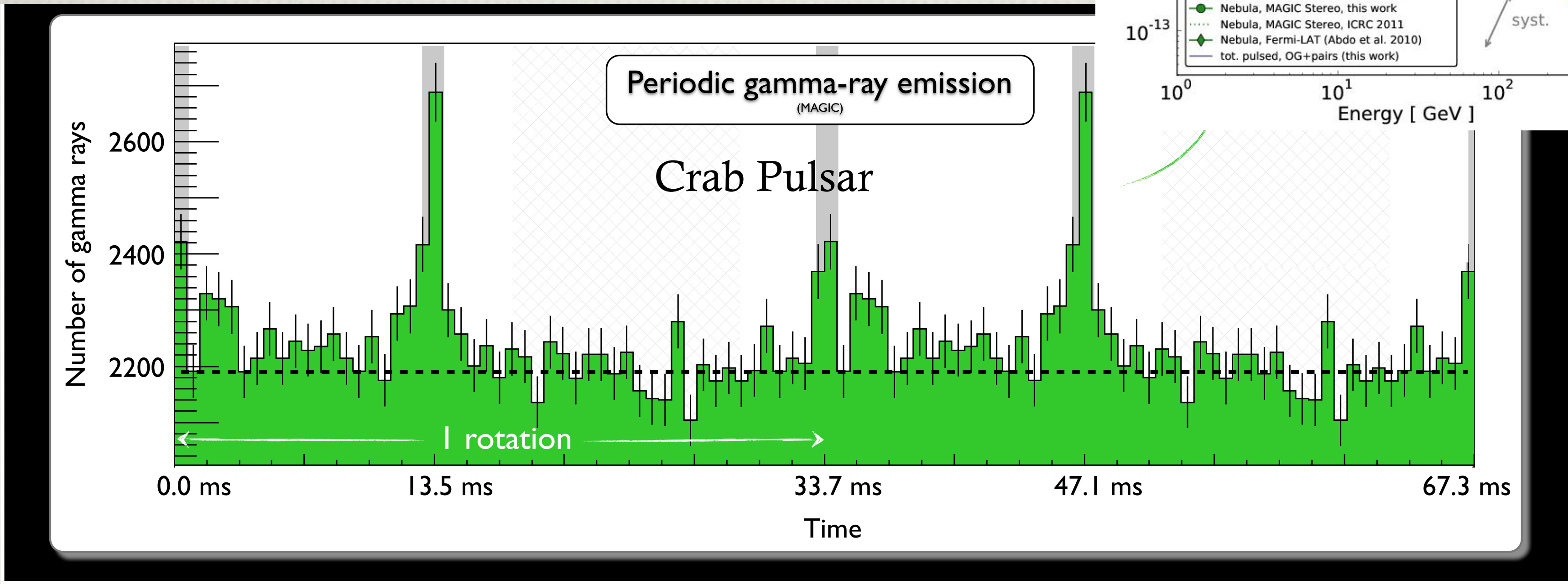
- Gamma rays from distant sources interact with EBL
- Measured spectrum modified by pair creation
- By measuring the distortion of the gamma-ray spectrum wrt intrinsic one we are measuring EBL

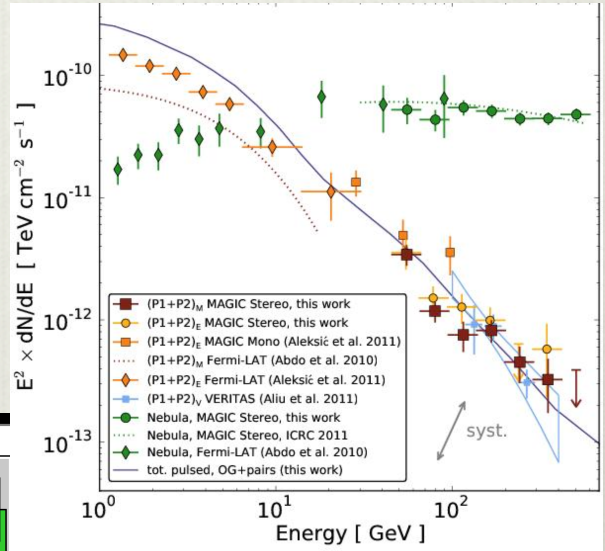
- The "gamma-ray" horizon depends on the energy
- MAGIC has observed the most distant sources thanks to lowest threshold
- Allows to study evolution of EBL



Low energy threshold pays off (2)

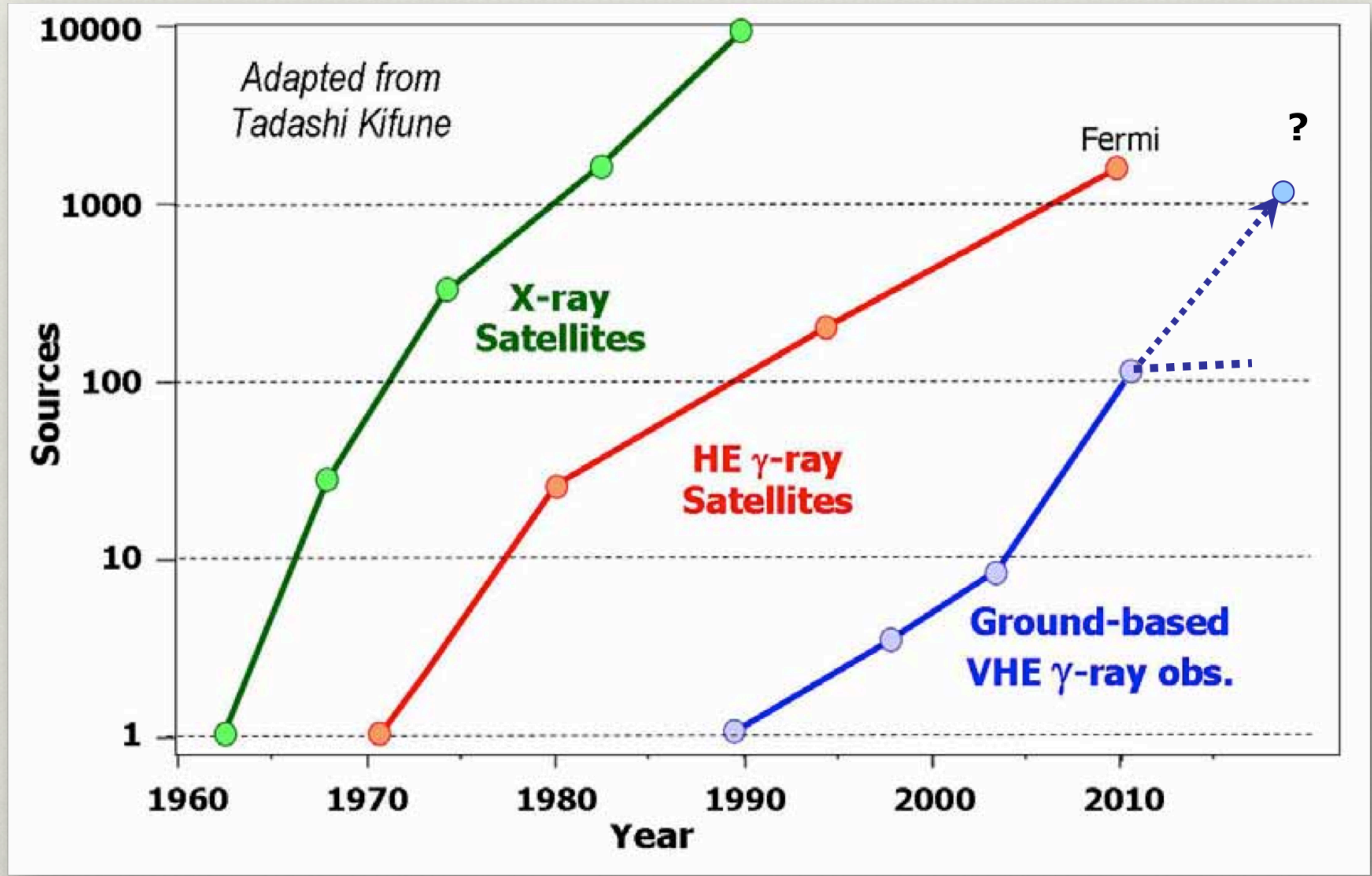
- Electromagnetic emission from pulsars was believed to have sharp cutoff below 10 GeV
- VERITAS+MAGIC has shown that it can reach at least 400 GeV





The future of γ-ray astronomy

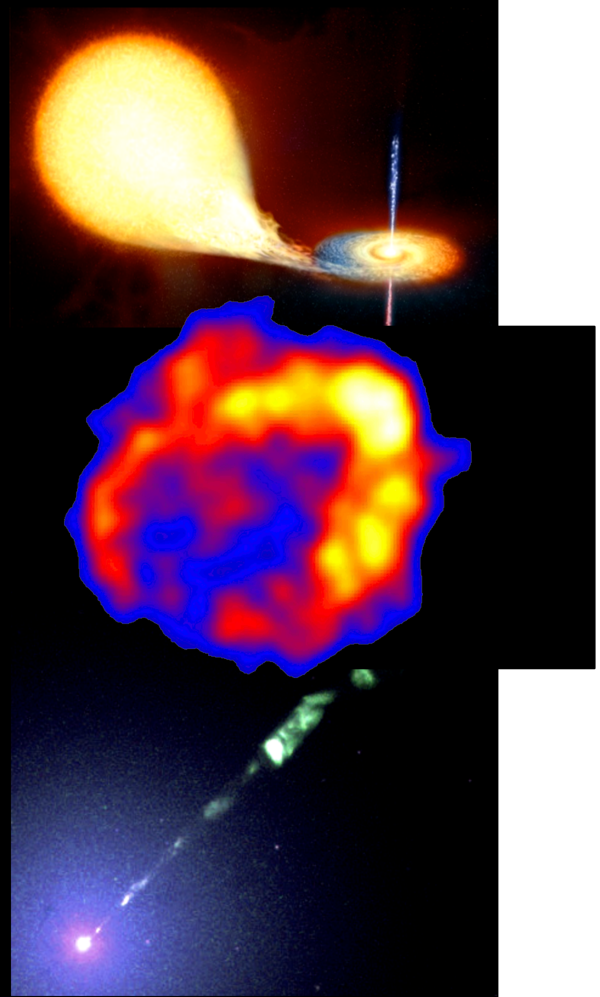
- Present generation has been already amortized



TeV Astronomy: Highlights

Over 400 publications in high-impact journals:

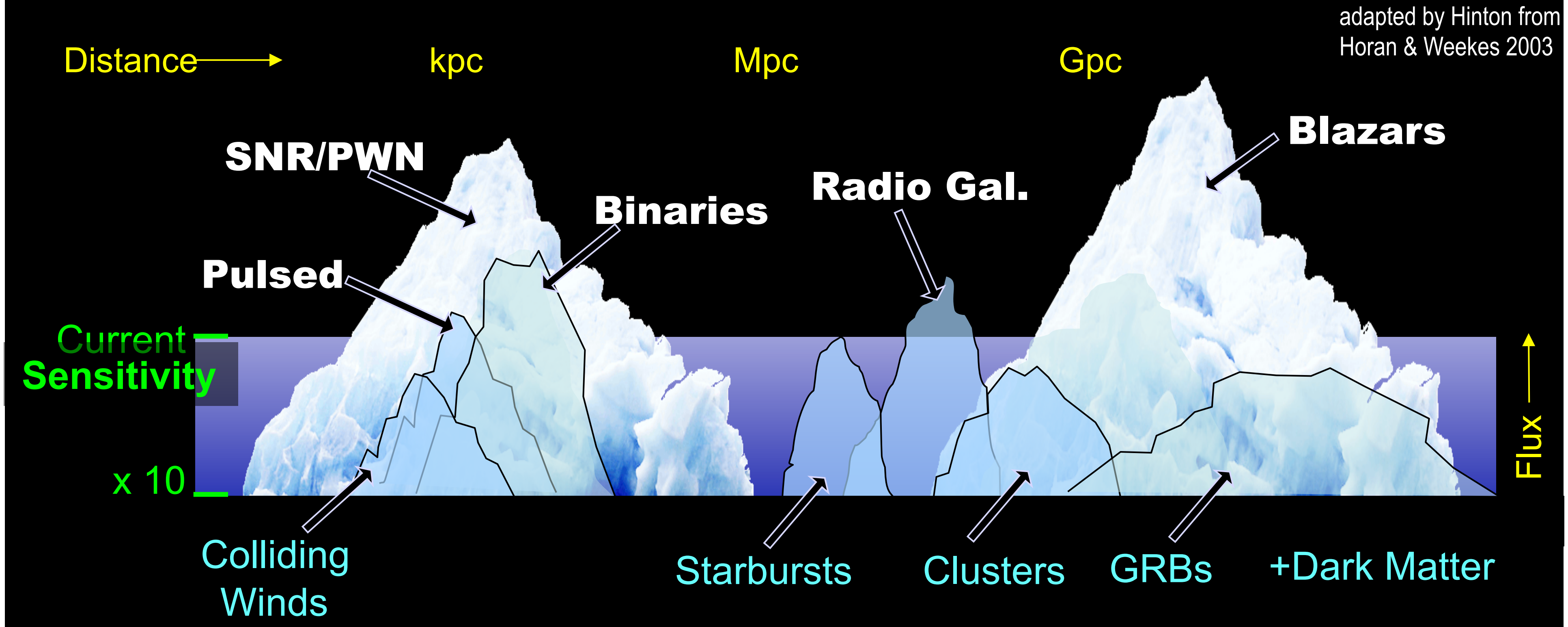
- *Microquasars:* Science 309, 746 (2005), Science 312, 1771 (2006)
- *Pulsars:* Science 322, 1221 (2008)
- *Supernova remnants:* Nature 432, 75 (2004)
- *The Galactic Centre:* Nature 439, 695 (2006)
- *Galactic Survey:* Science 307, 1839 (2005)
- *Starbursts:* Nature 462, 770 (2009), Science 326,1080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



Results from **H.E.S.S.**, **MAGIC** and **VERITAS**

Science Potential

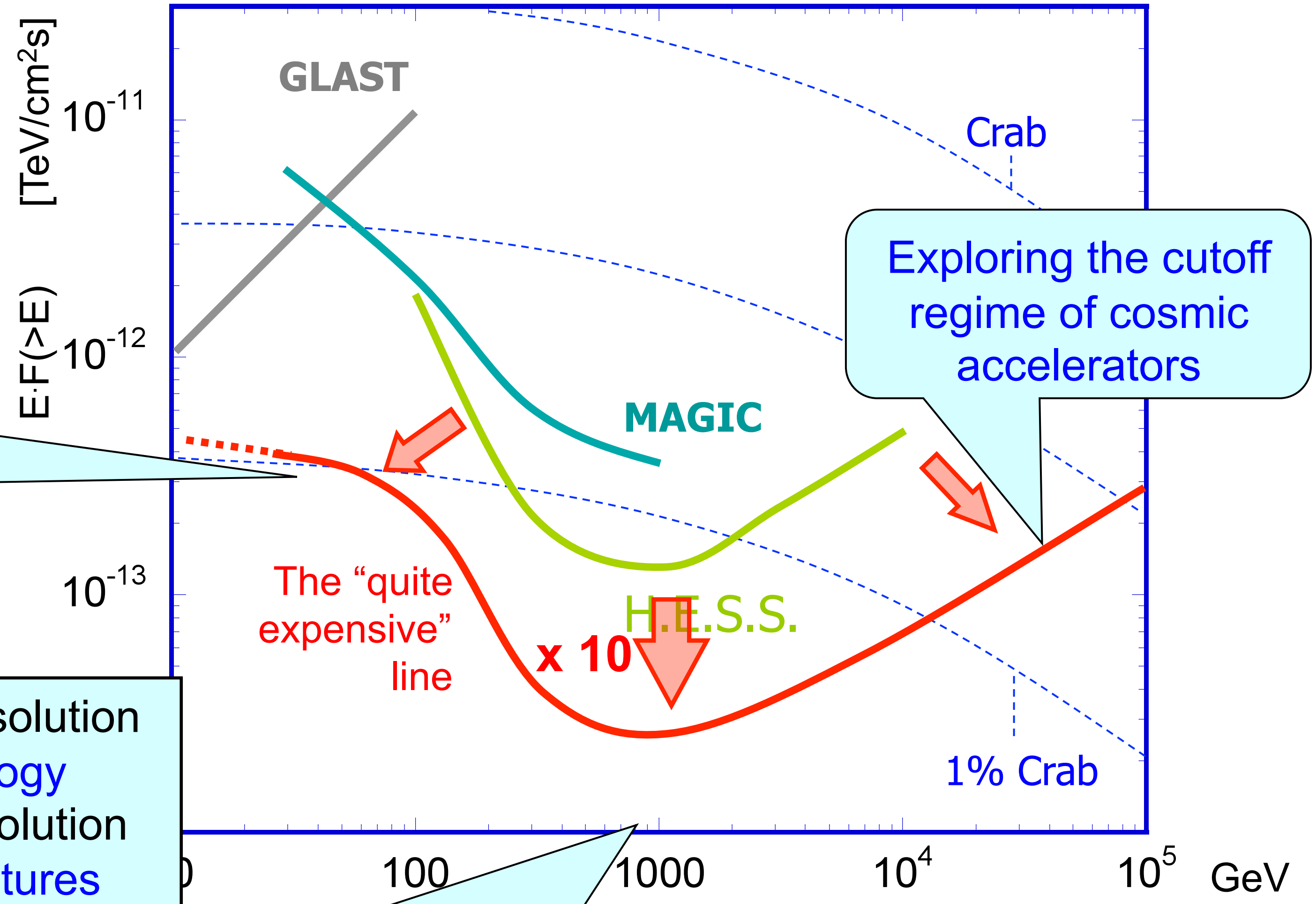
CTA



- Current instruments have passed the critical sensitivity threshold and reveal a rich panorama, **but this is clearly only the tip of the iceberg**

CTA: Wish list

An advanced facility for ground-based high-energy gamma ray astronomy



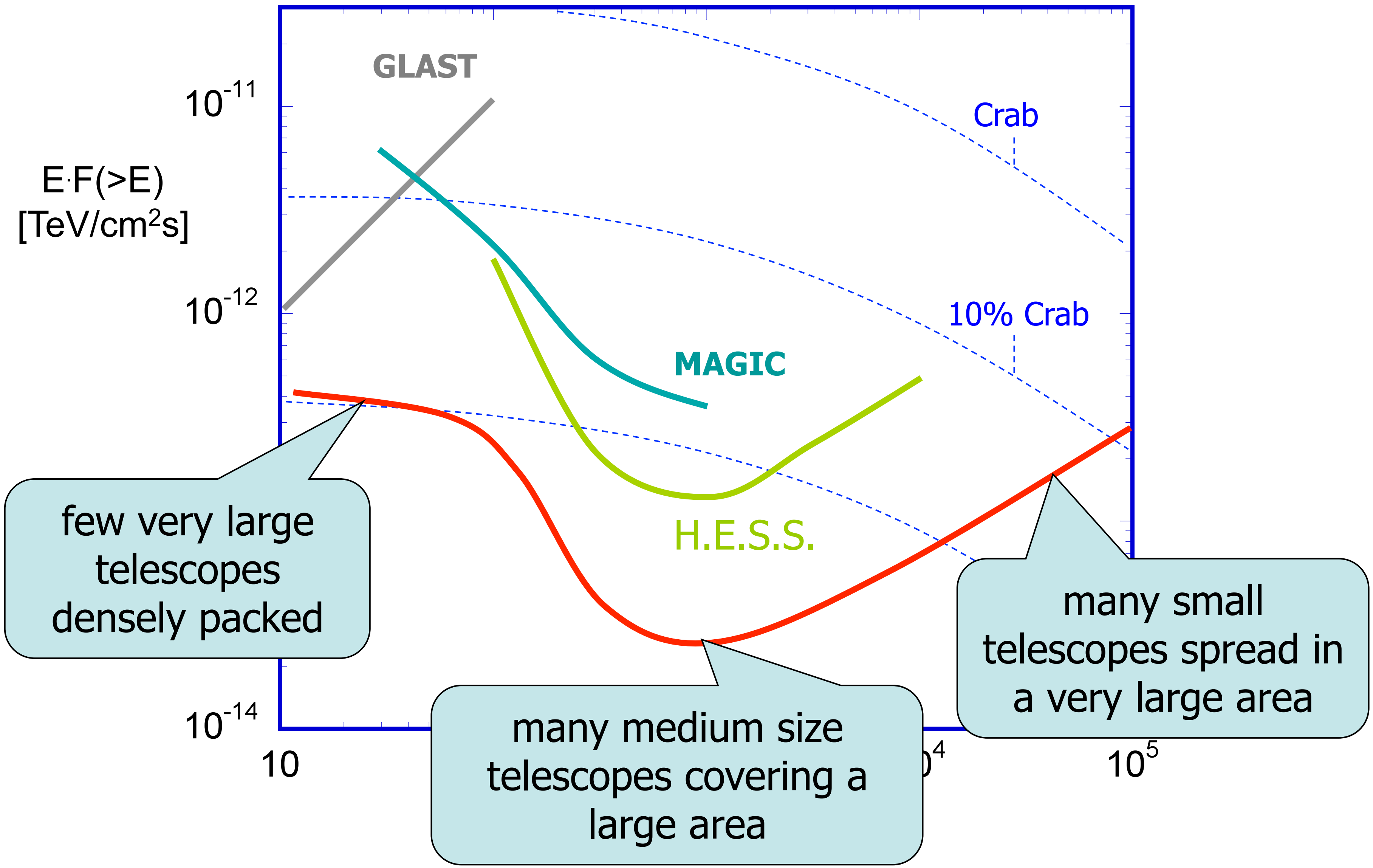
Hi-z AGN, GRBs, pulsars, dark matter

+ Improved angular resolution
  source id. & morphology
+ Improved energy resolution
  cutoffs & spectral features
+ large FoV (6-8 deg)
  extended sources, survey
+ multiple observation modes

Population studies, extended sources, variability, precision TeV astronomy

Possible CTA sensitivity

An advanced facility for ground-based high-energy gamma ray astronomy



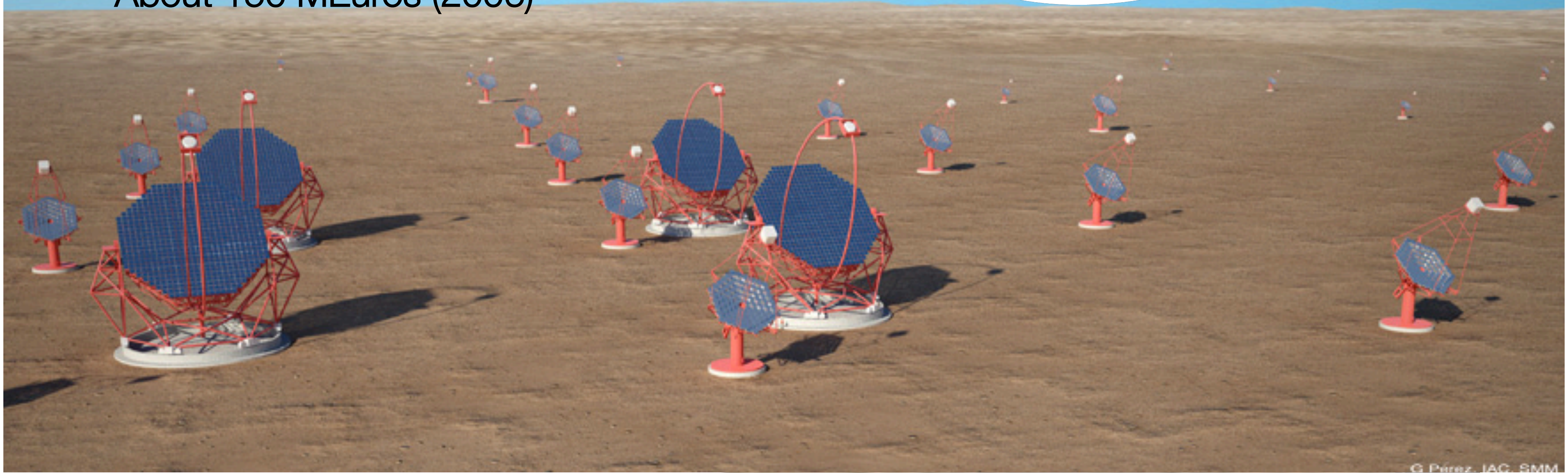
The future in VHE gamma ray astronomy:

cta
cherenkov telescope array

10 fold sensitivity of current instruments
10 fold energy range
improved angular resolution
two sites (North / South)

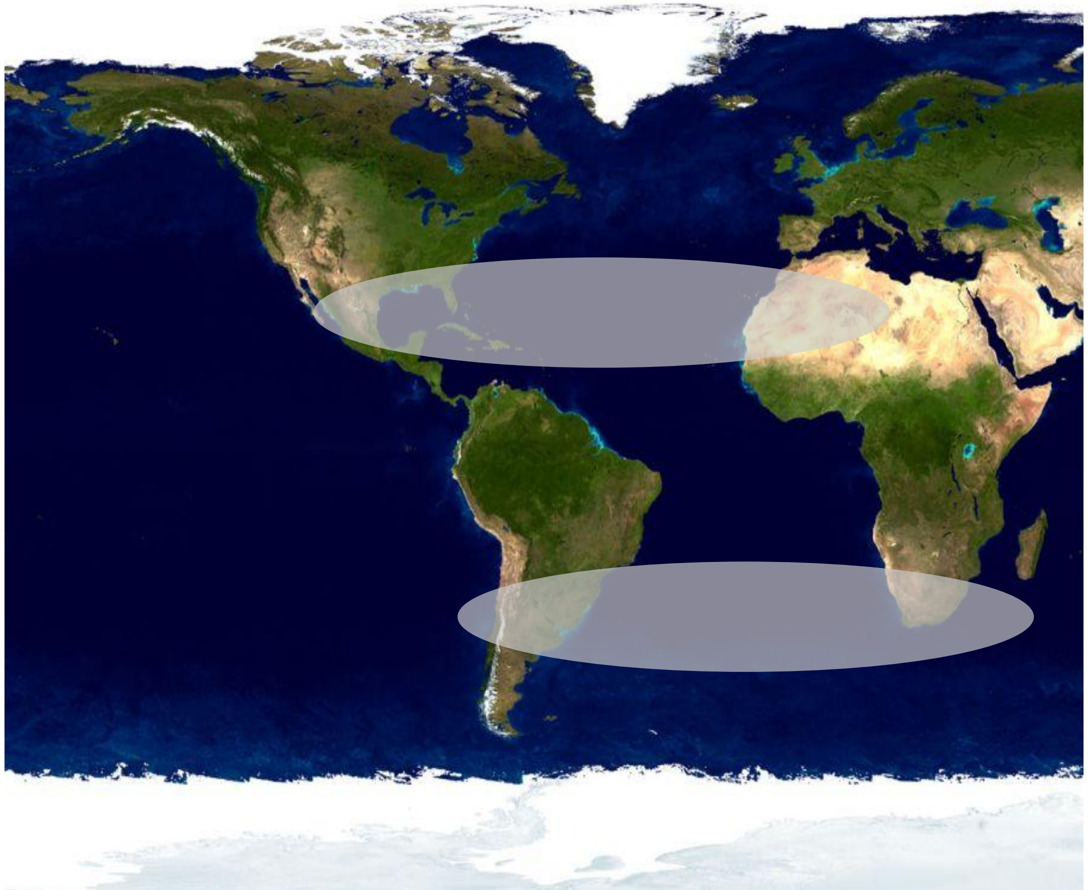
operated as **open observatory**

Over hundred telescopes
About 150 MEuros (2006)



What is CTA ?: Cherenkov Telescope Array

One observatory with two (asymmetric) sites for all-sky coverage operated by one consortium



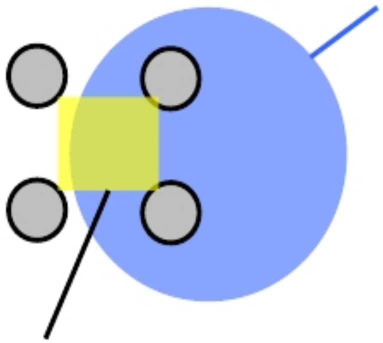
Northern Array
- complementary to SA for full sky coverage
- Energy range: some 10 GeV to few TeV
- Limited field of view

Mainly Extragalactic Sources

Southern Array
- Full energy and sensitivity coverage: some 10 GeV to above 100 TeV
- Angular resolution: 0.02 to 0.2 deg
- Large field of view

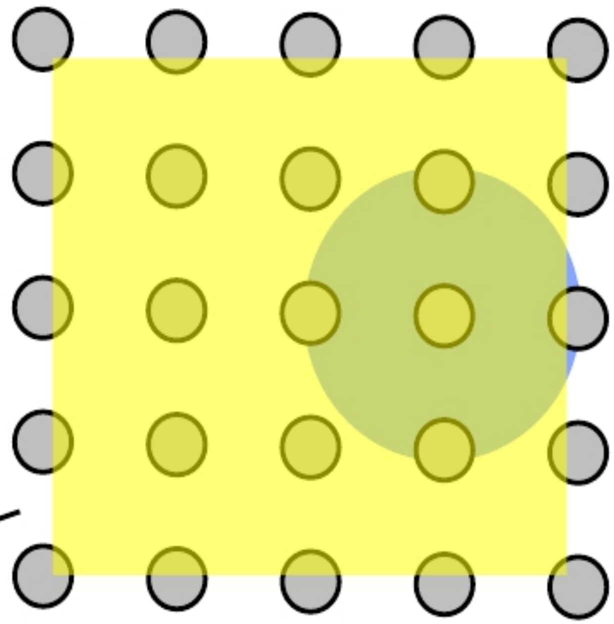
Galactic + Extragal. Sources

Why so many telescopes
From current arrays to CTA



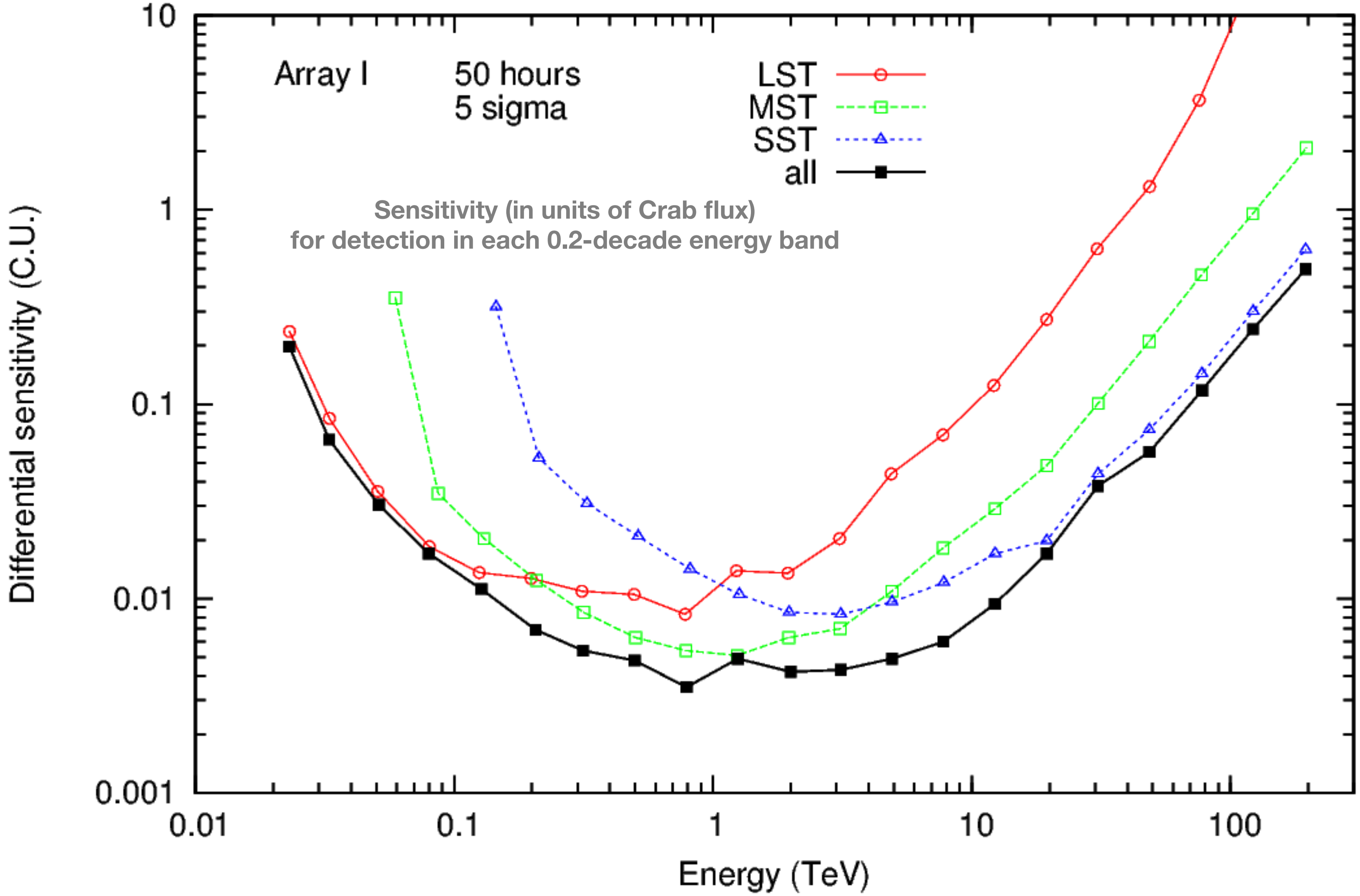
light pool radius
R ≈100-150 m
≈ typical telescope spacing

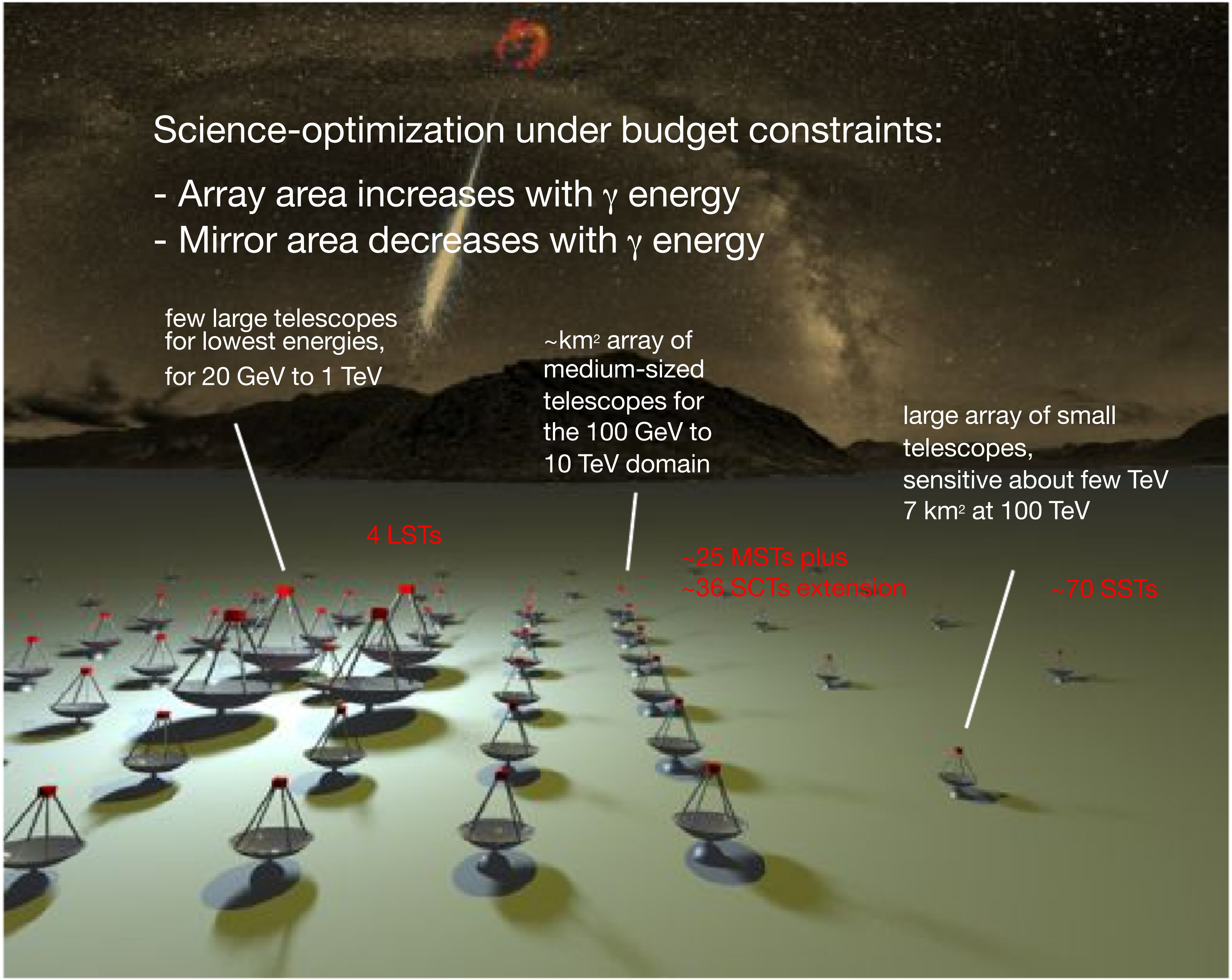
Sweet spot for
best triggering
and reconstruction:
most showers miss it!

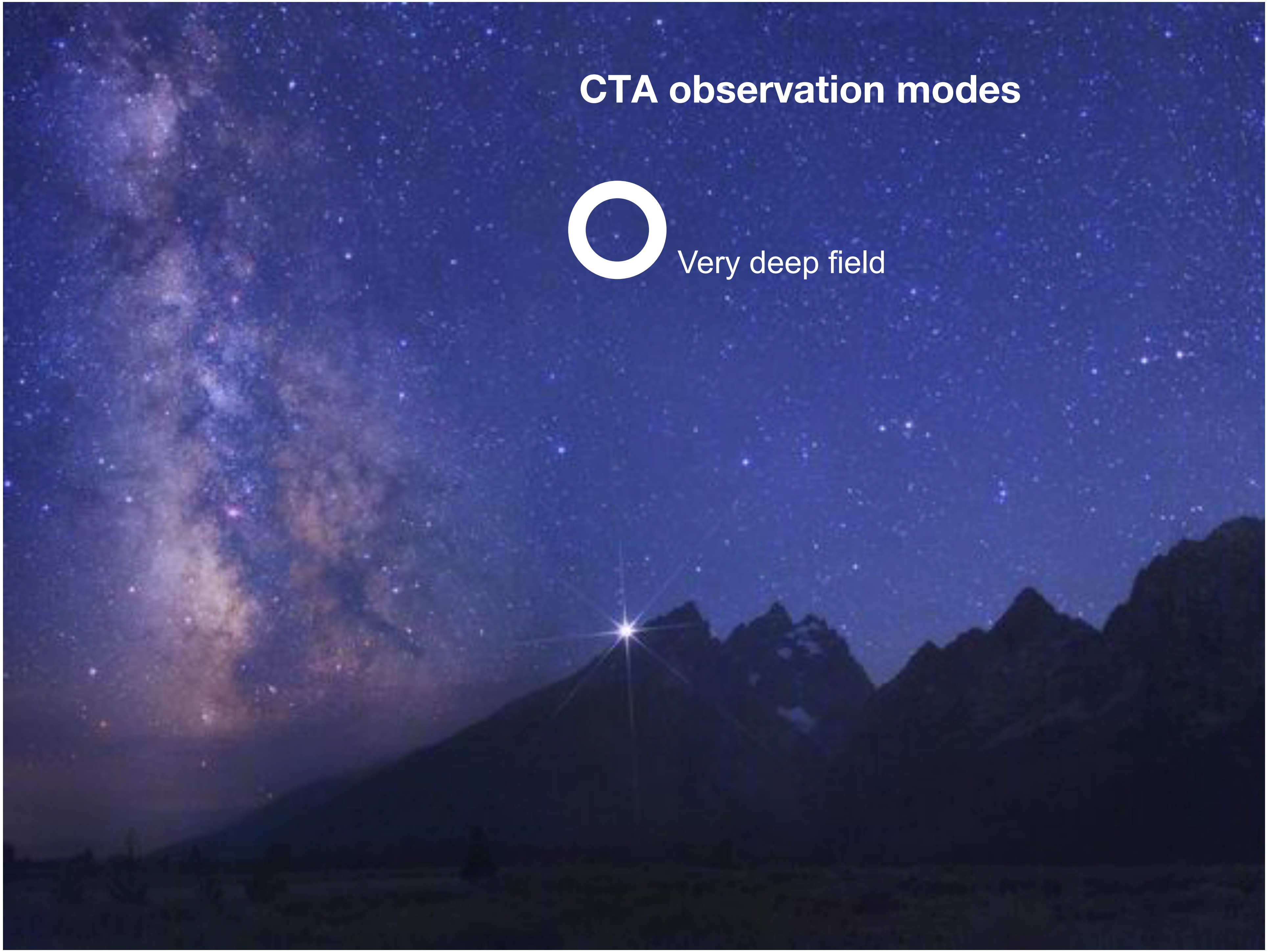


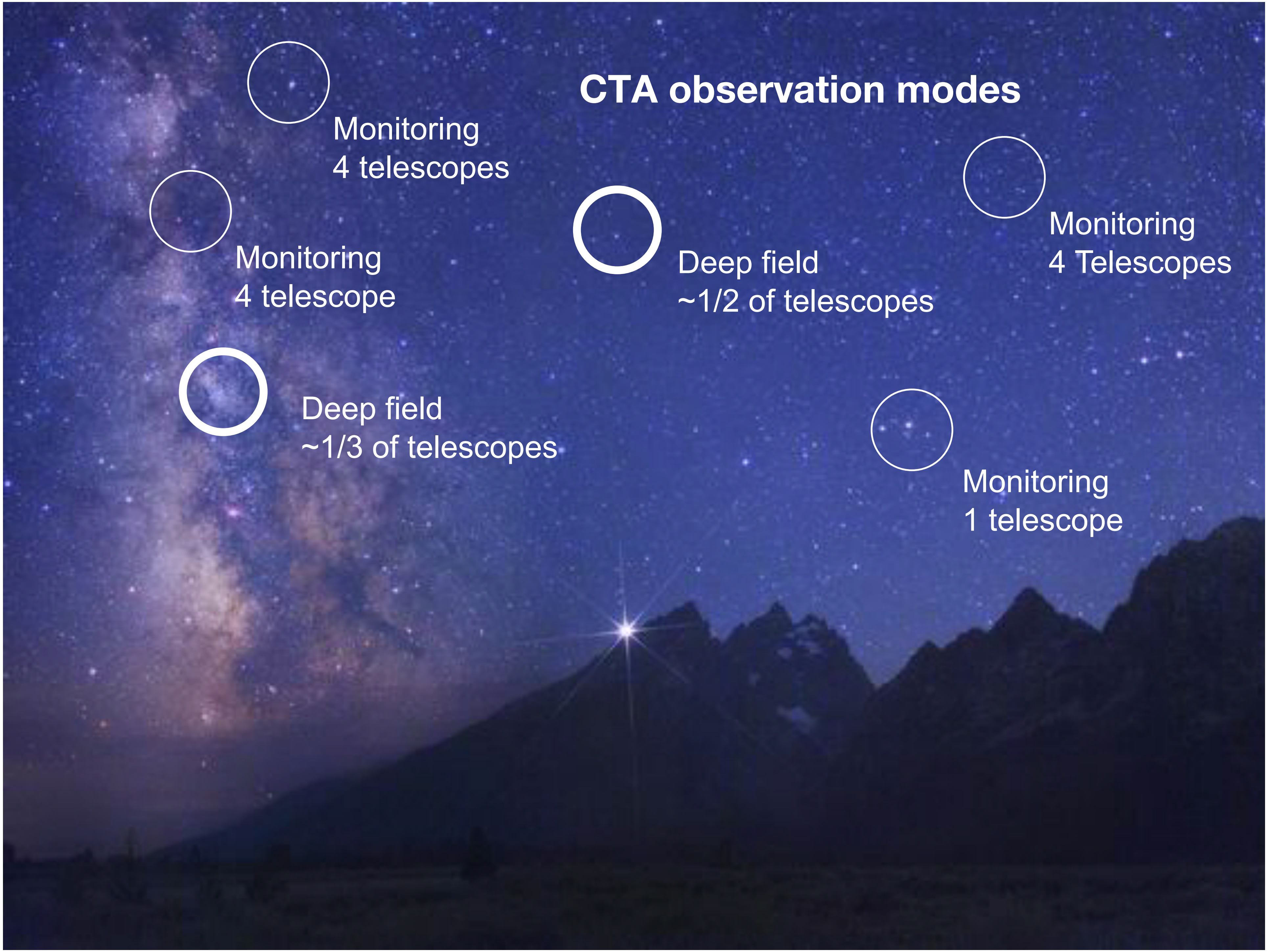
large detection area
more images per shower
lower trigger threshold

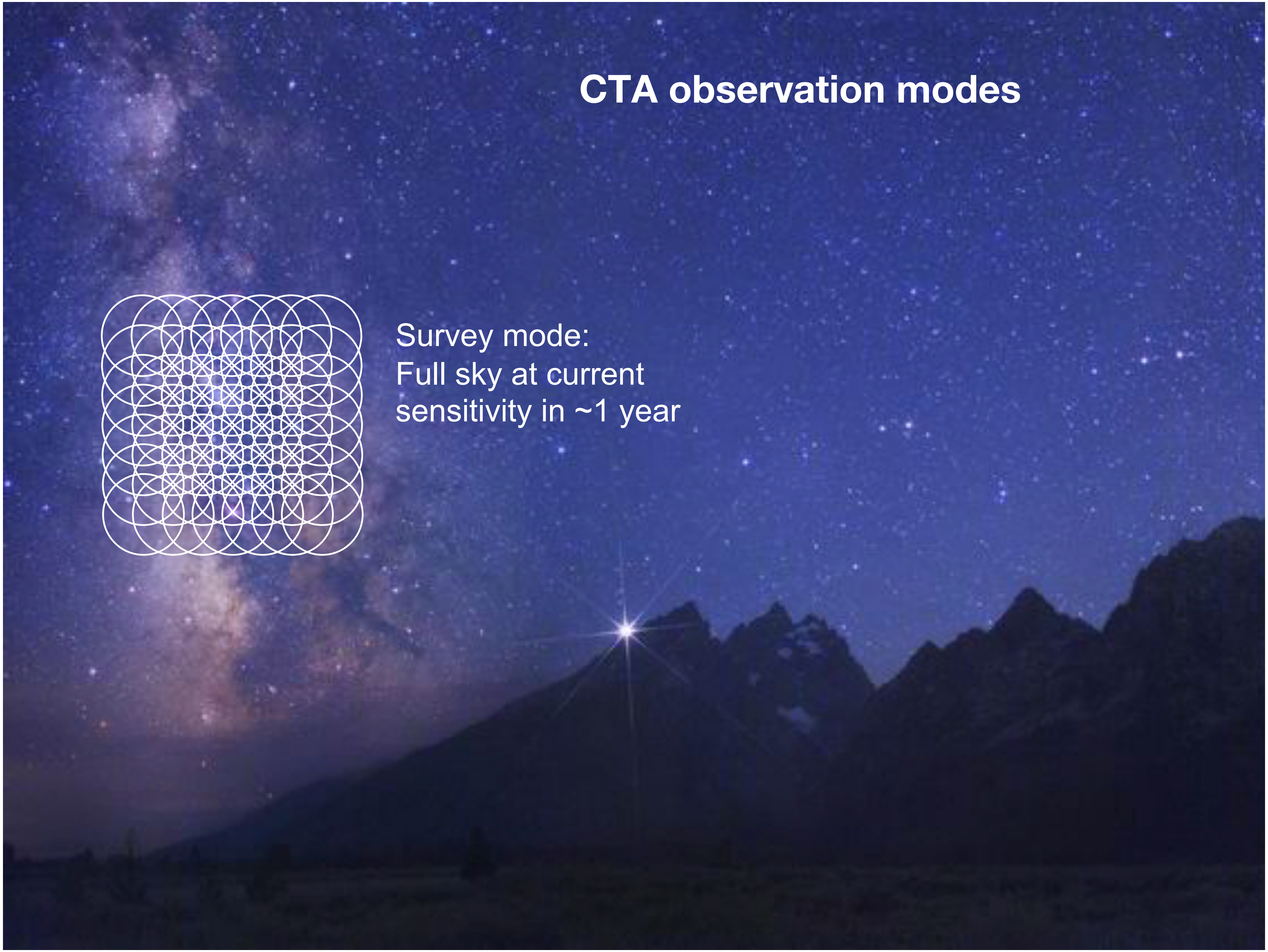
Why different telescope sizes?




Science-optimization under budget constraints:
- Array area increases with γ energy
- Mirror area decreases with γ energy
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
~25 MSTs plus ~36 SCTs extension
~70 SSTs

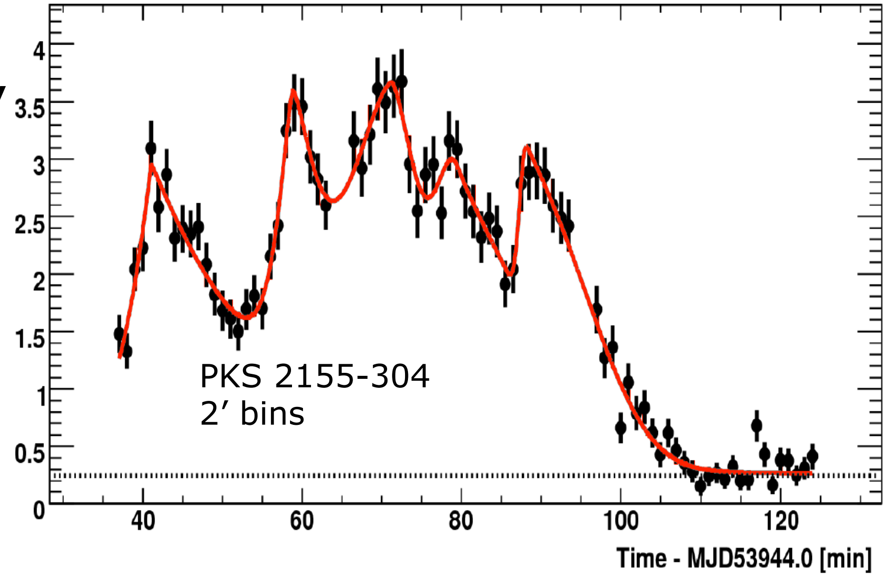

CTA observation modes
Very deep field


CTA observation modes
Monitoring
4 telescopes
Monitoring
4 telescope
Deep field
~1/3 of telescopes
Deep field
~1/2 of telescopes
Monitoring
4 Telescopes
Monitoring
1 telescope


CTA observation modes
Survey mode:
Full sky at current
sensitivity in ~1 year

Main characteristics of CTA

- High sensitivity
  - >4 orders of magnitude dynamic range in flux between strongest and faintest sources
- Wide spectral range
  - >4 orders of magnitude coverage in energy, up to 100s of TeV
  - 10-15% energy resolution
- Resolved source morphology
  - Up to 0.02 deg. angular resolution
  - 10-20" source localization
- Well-resolved light curves
  - Minute-scale variability of AGN



Main characteristics of CTA (2)

- Large field of view

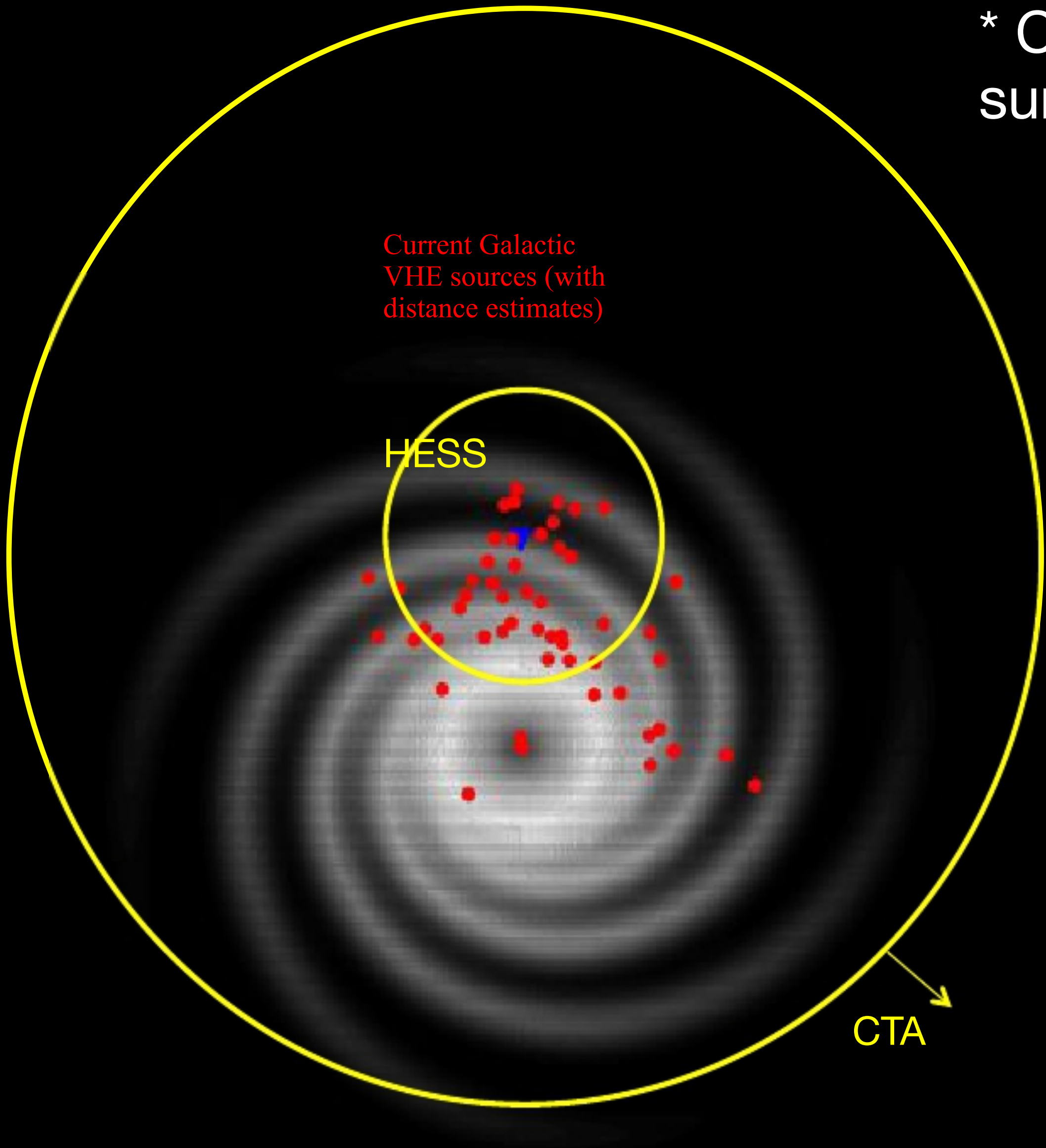
  serendipitous AGN discoveries

- Surveying capabilities

  full-sky survey at O(1%) Crab in about 1 year

- Monitoring capabilities

  possible use of single telescopes or sub-arrays for AGN monitoring

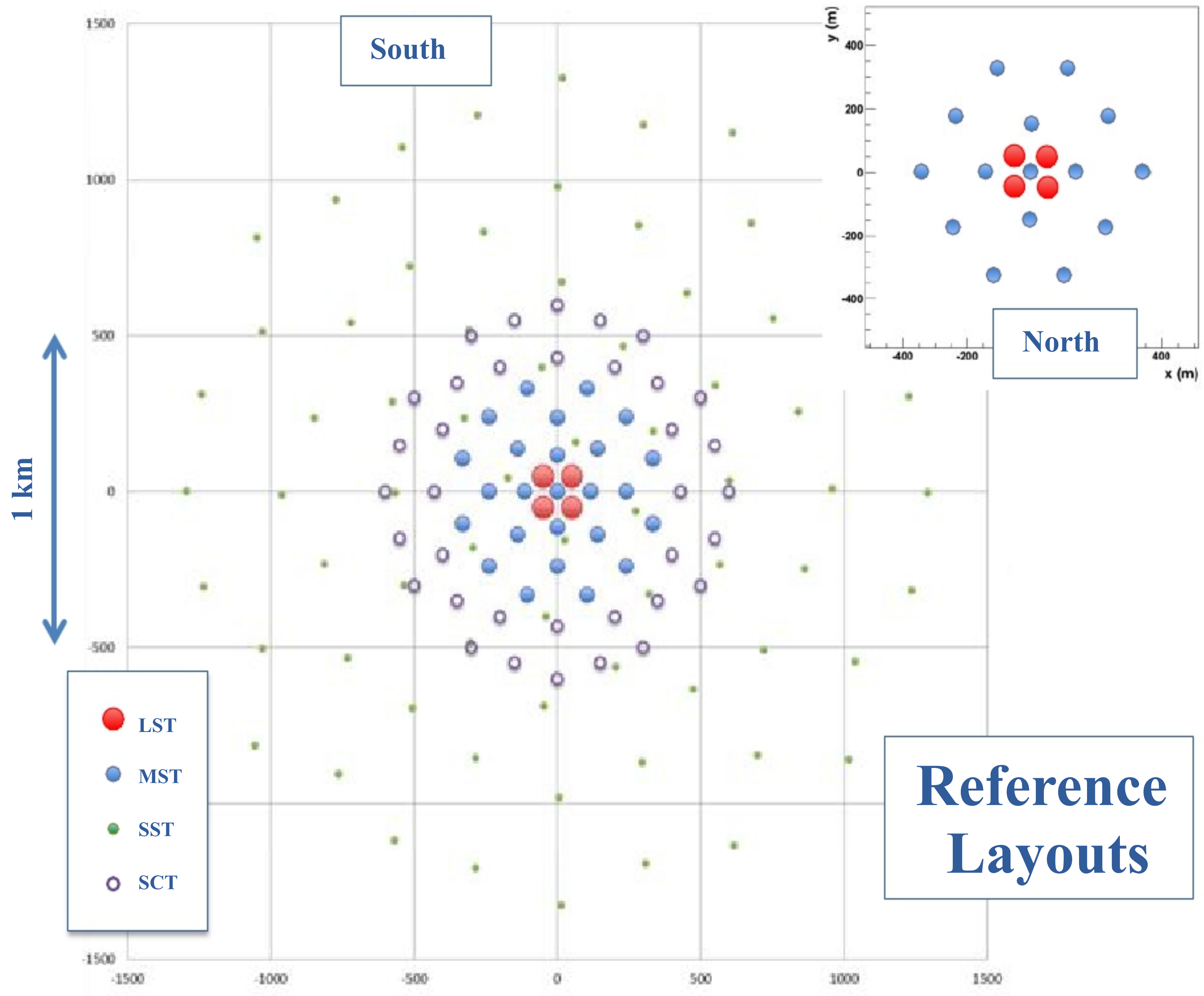


* CTA as ultimate survey machine

* CTA as ultimate flare machine

at 25 GeV, for flares 10000 times more sensitive than Fermi

* Coherent full-sky coverage from two sites



South
North
1 km
LST
MST
SST
SCT
Reference Layouts
y (m)
x (m)

TELESCOPES

	SST "small"	MST "medium"	LST "large"	SCT "medium 2-M"
Number	70 (S)	25 (S) 15 (N)	4 (S) 4 (N)	36 (S)
Spec'd range	> few TeV	200 GeV to 10 TeV	20 GeV to 1 TeV	200 GeV to 10 TeV
Eff. mirror area	> 5 m^2	> 88 m^2	> 330 m^2	> 40 m^2
Field of view	> 8°	> 7°	> 4.4°	> 7°
Pixel size ~PSF θ_{80}	< 0.25°	< 0.18°	< 0.11°	< 0.075°
Positioning time	90 s, 60 s goal	90 s, 60 s goal	50 s, 20 s goal	90 s, 60 s goal
Availability	> 97% @ 3 h/week	>97% @ 6 h/week	>95% @ 9 h/week	>97% @ 6 h/week
Target capital cost	420 k€	1.6 M€	7.4 M€	2.0 M€

LARGE 23 M TELESCOPE

OPTIMIZED FOR THE RANGE BELOW 200 GEV

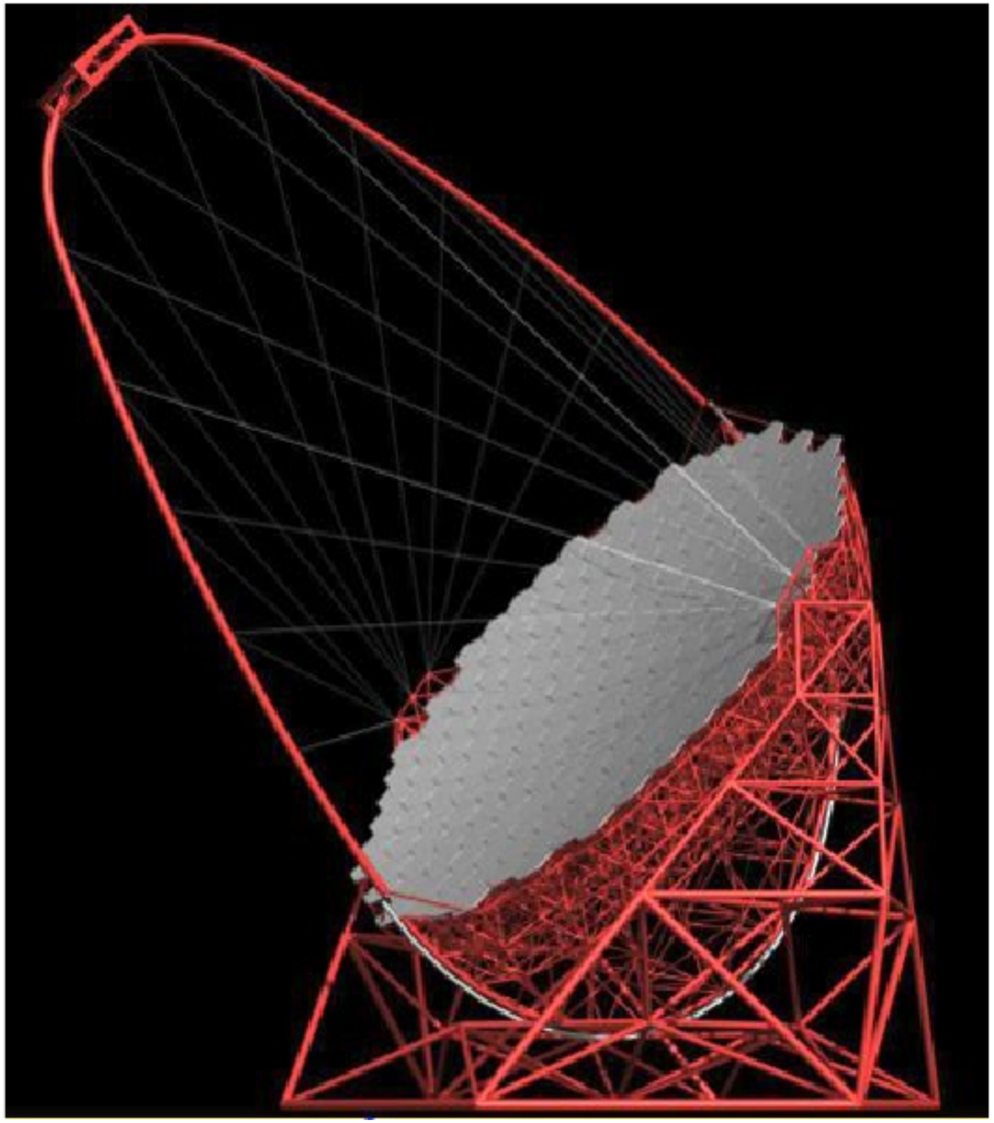
400 m^2 dish area
27.8 m focal length
1.5 m mirror facets

4.5 deg. field of view
0.1 deg. pixels
Camera diameter over 2 m

Carbon-fibre structure

Active mirror control

4 LSTs on each site



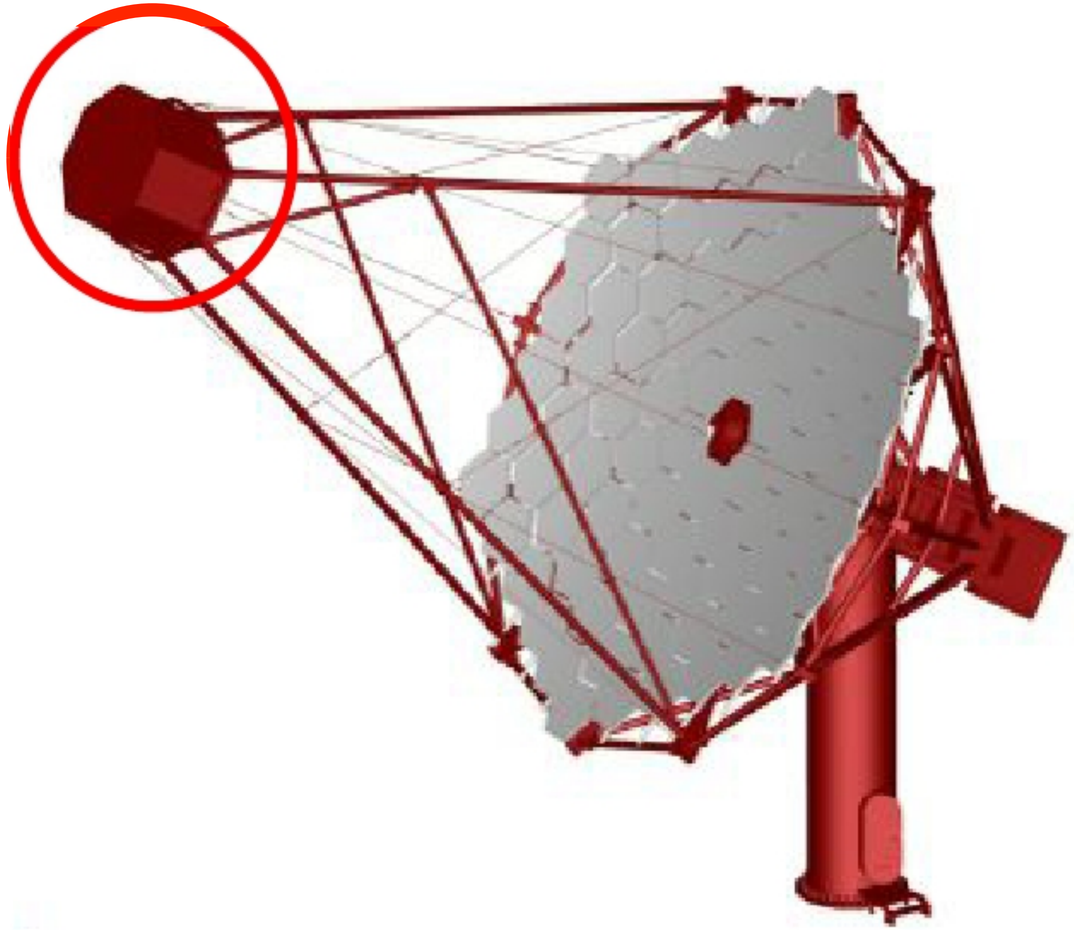
MEDIUM-SIZED 12 M TELESCOPE

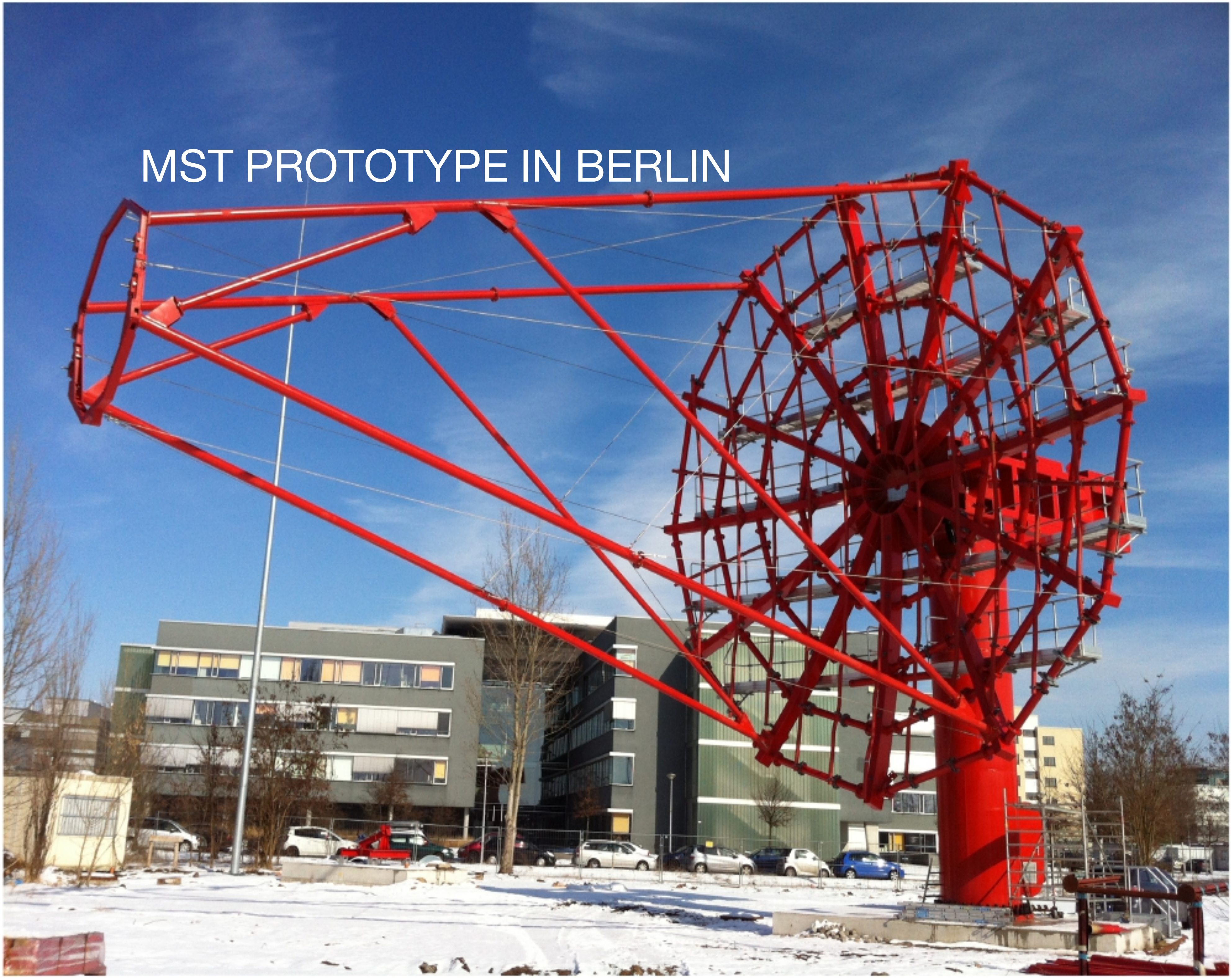
OPTIMIZED FOR THE 100 GEV TO ~10 TEV RANGE

100 m^2 dish area
16 m focal length
1.2 m mirror facets

7-8 deg. field of view
~2000 x 0.18 deg. pixels

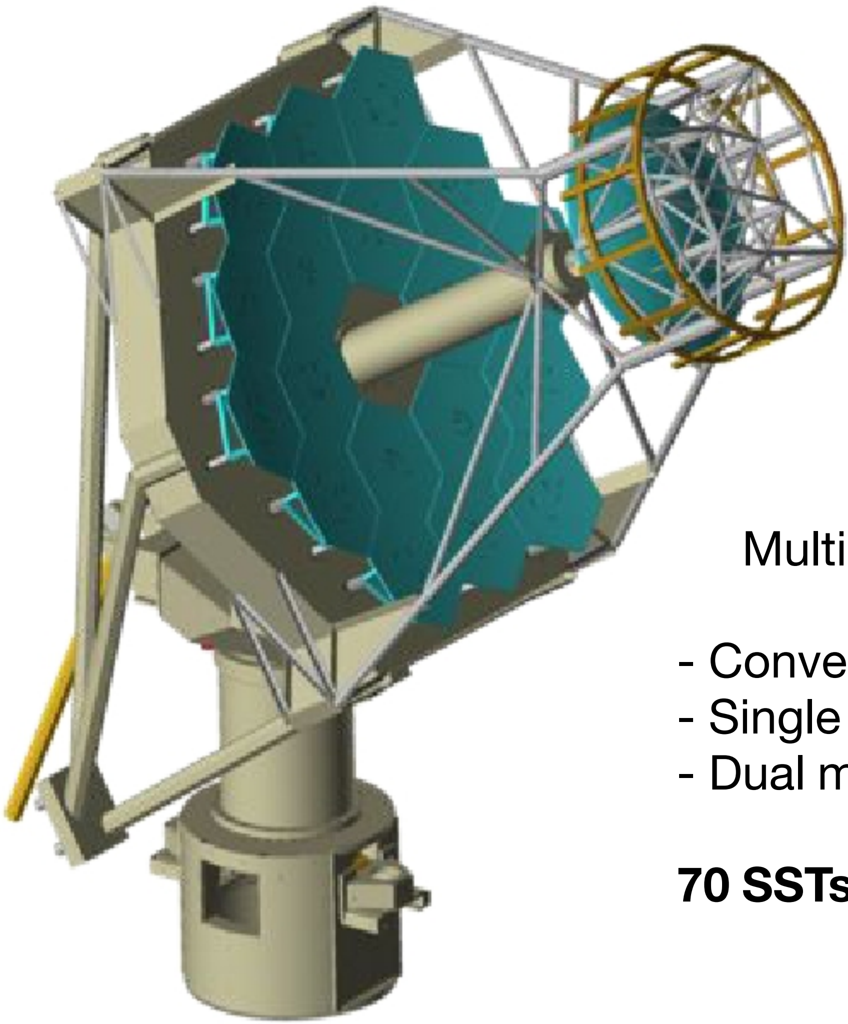
25 MSTs on South site
15 MSTs on North site




MST PROTOTYPE IN BERLIN

SMALL TELESCOPE

OPTIMIZED FOR THE RANGE ABOVE 10 TEV



ASTRI Design
4.3 m mirror
9.6 deg. foV
0.25 deg. pixels

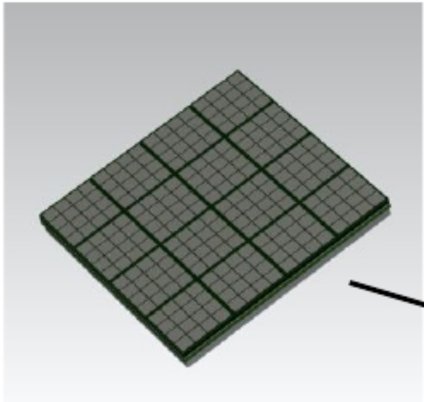
Multiple options under study:

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

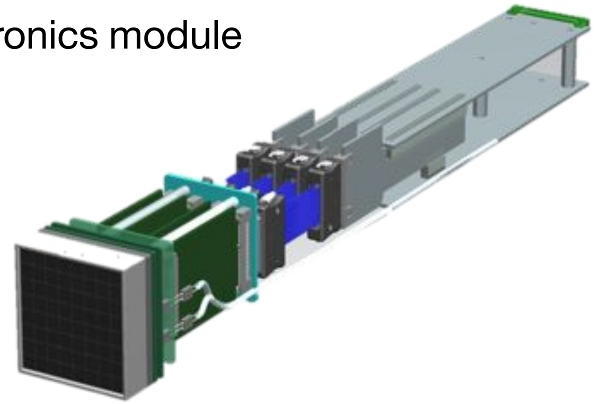
70 SSTs on Southern site

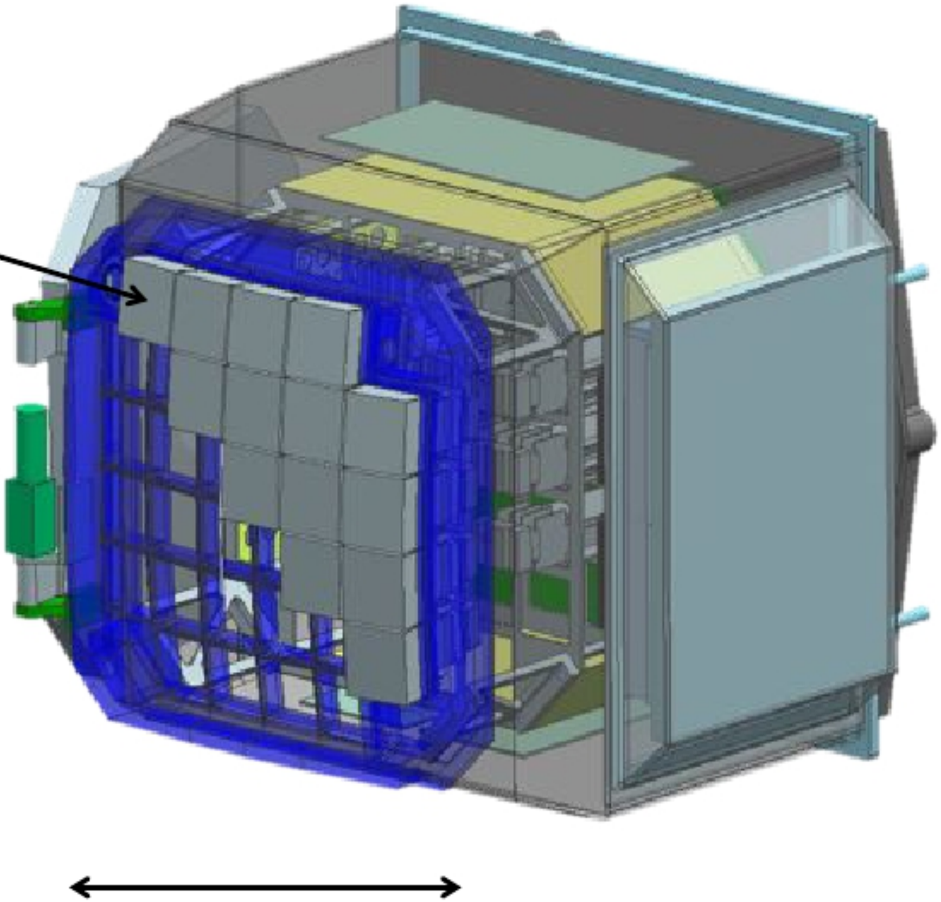
COMPACT SILICON CAMERAS

Hamamatsu
SiPM
50 x 50 mm^2
16 x 16 pixels
(grouped 2 x 2)



64 Channel
TARGET-based
electronics module

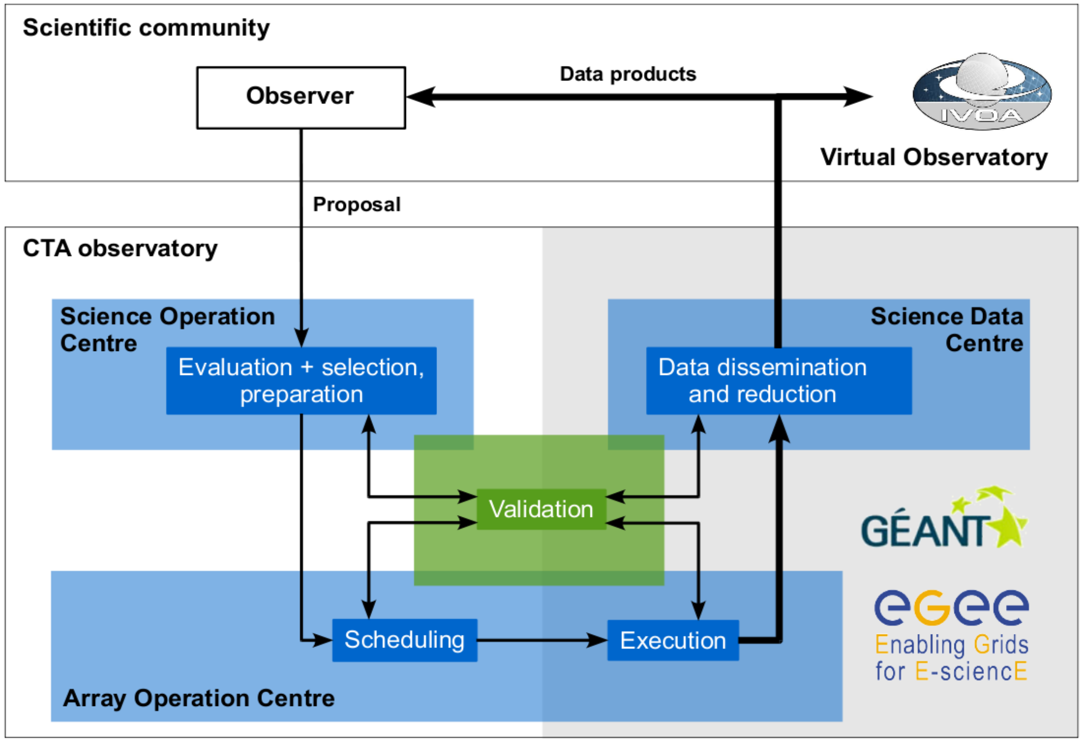




30 cm

CTA, an open observatory
(for the first time in the field)

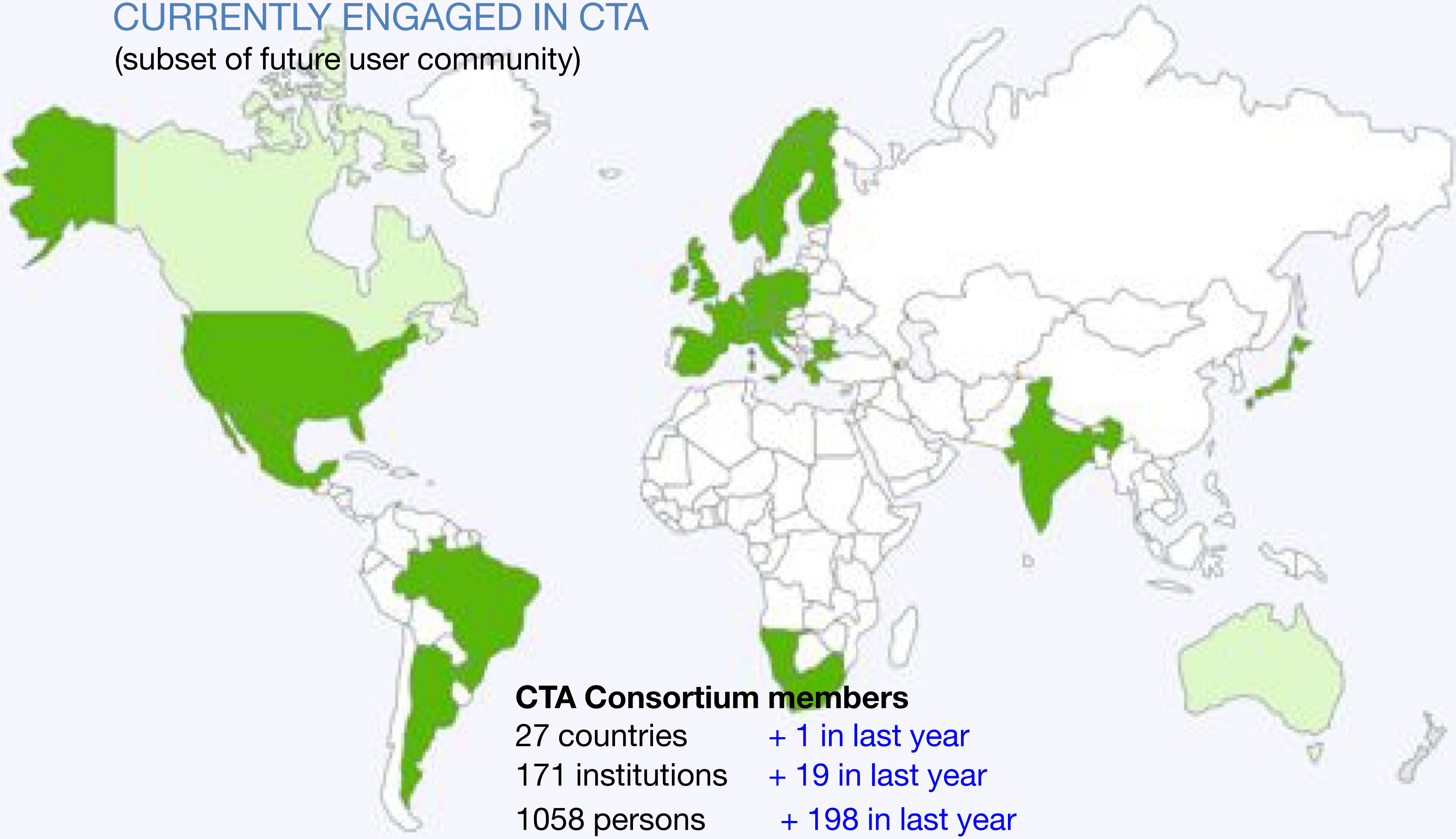
- Large number of detectable objects and maximizing scientific outcome main motivation to operate CTA as an open observatory
- Provide tools for data dissemination and data analysis
- Large number of users from astronomy, astroparticle and particle physics, cosmology, …



COMMUNITY

Members (27 countries)
Interested to join
Canada, Australia, Israel

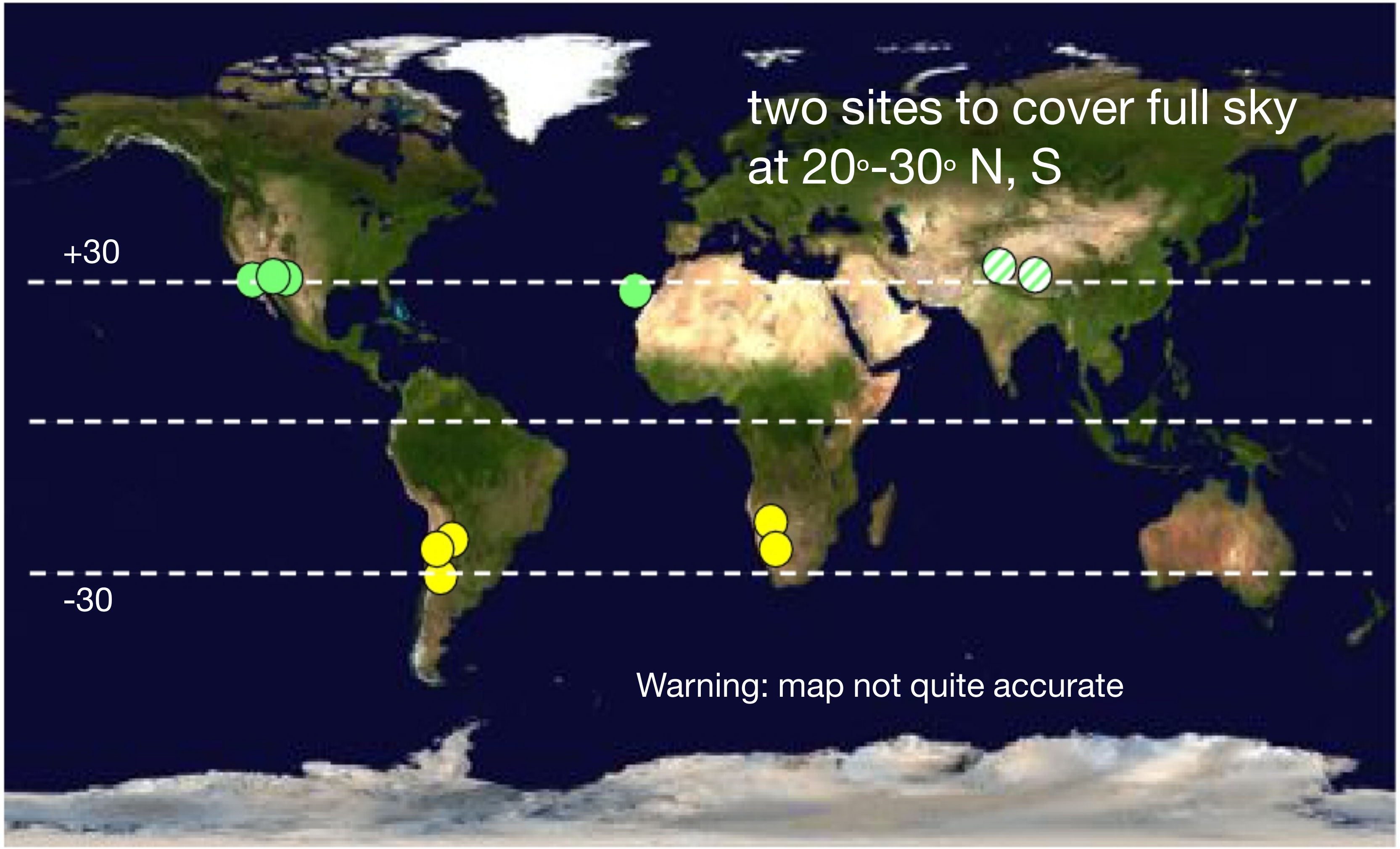
CURRENTLY ENGAGED IN CTA
(subset of future user community)



CTA Consortium members

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

SITE CANDIDATES



CTA Technical Concept

“ .

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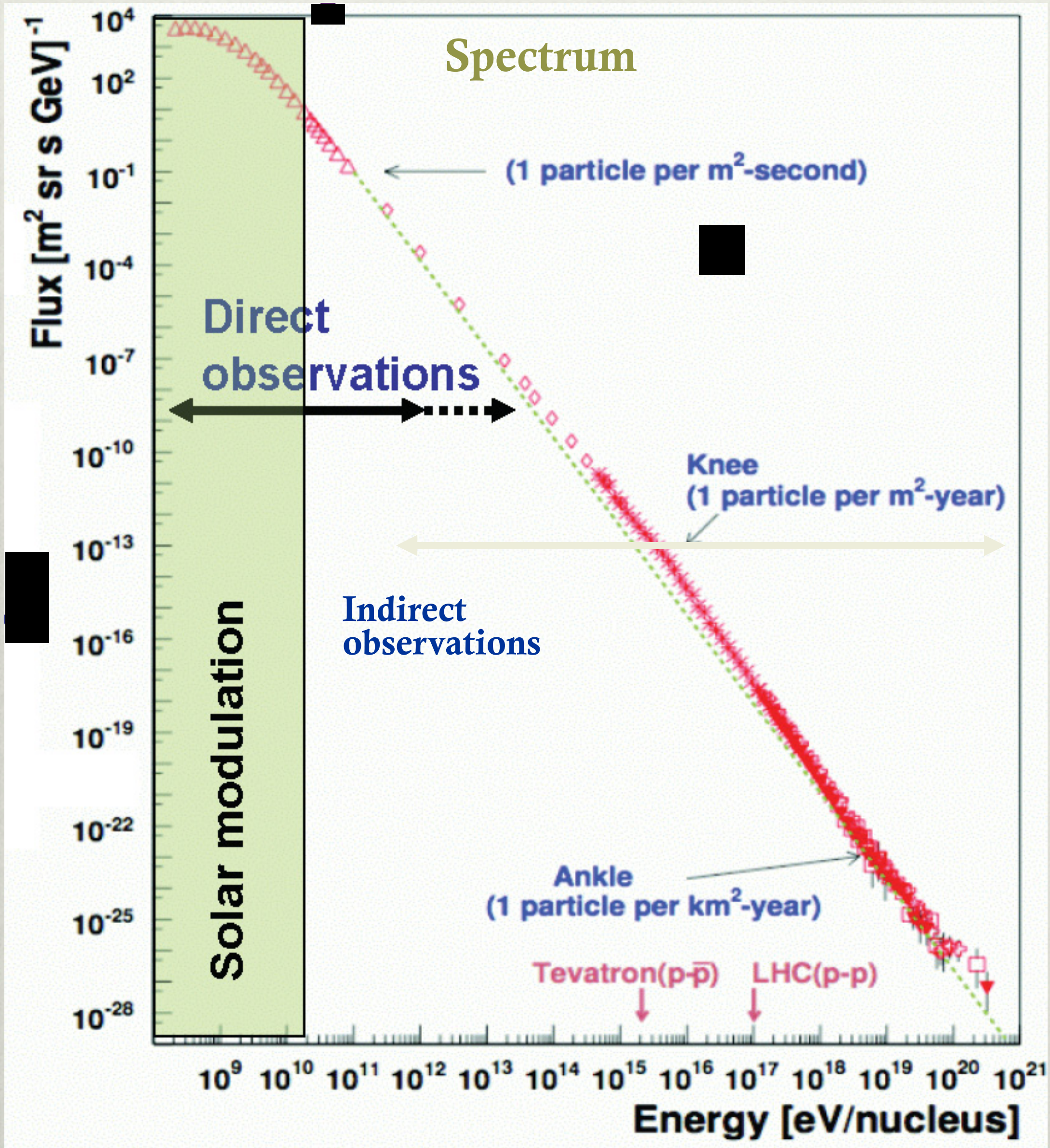
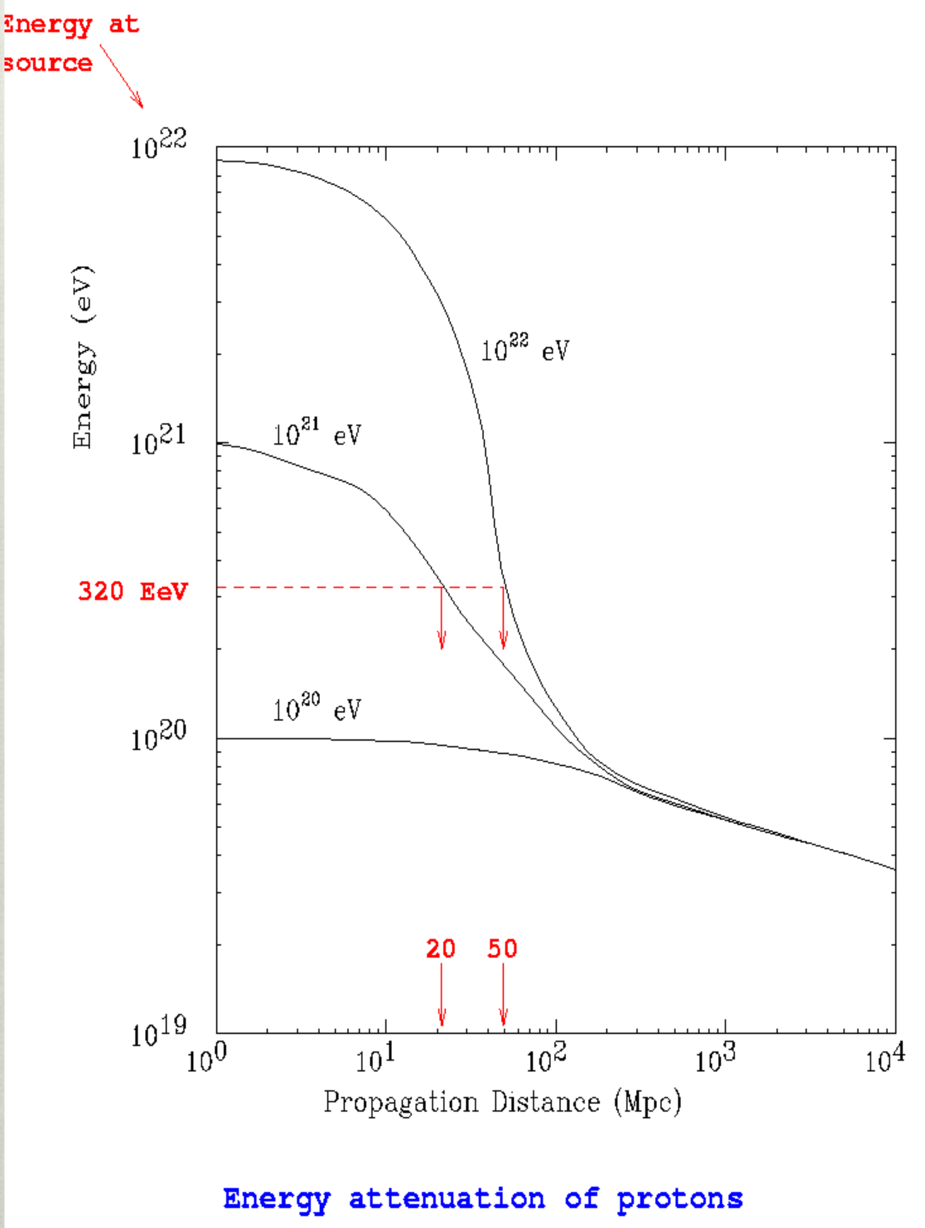
Ultra High energy Cosmic Rays

Charged cosmic rays



- Cosmic rays are extraterrestrial particles (mostly charged, mostly protons) continuously bombarding Earth
- Discovered by Victor HESS in 1912
- Several features (knee, ankle…) suggest different origins
- High energetic ones are detected indirectly ($E>10^{20}$eV 1 km^{-2} sr^{-1} century^{-1})

The highest energies: The particle horizon/ GZK effect



Pion photoproduction

$p + \gamma_{2.7\,K} \rightarrow N + \pi$

for $E_p > 5\ 10^{19}$ eV

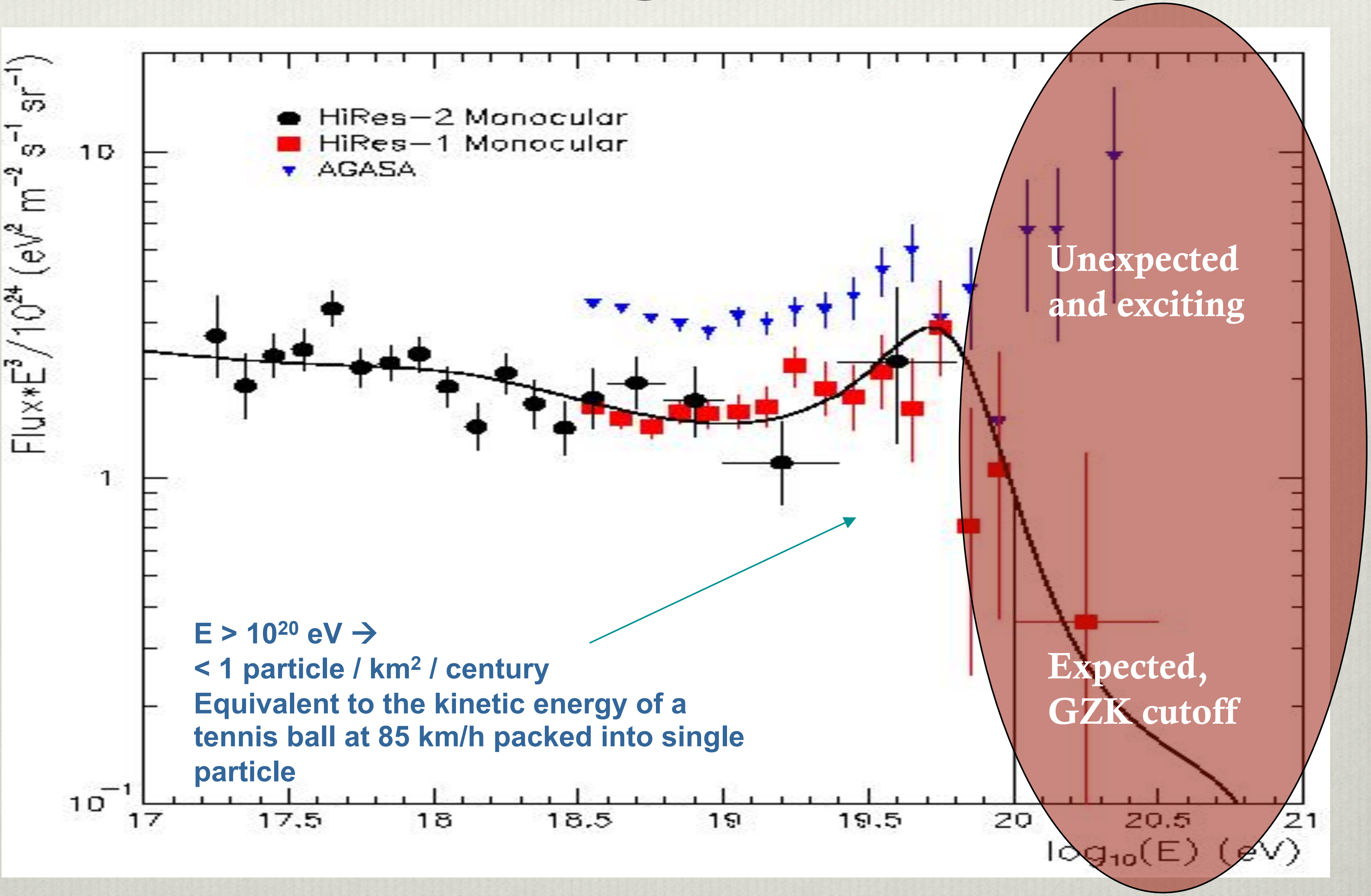
Interaction length $\approx$ 6 Mpc

Energy loss $\approx$ 20 %/interaction

nearby sources (<50 Mpc)

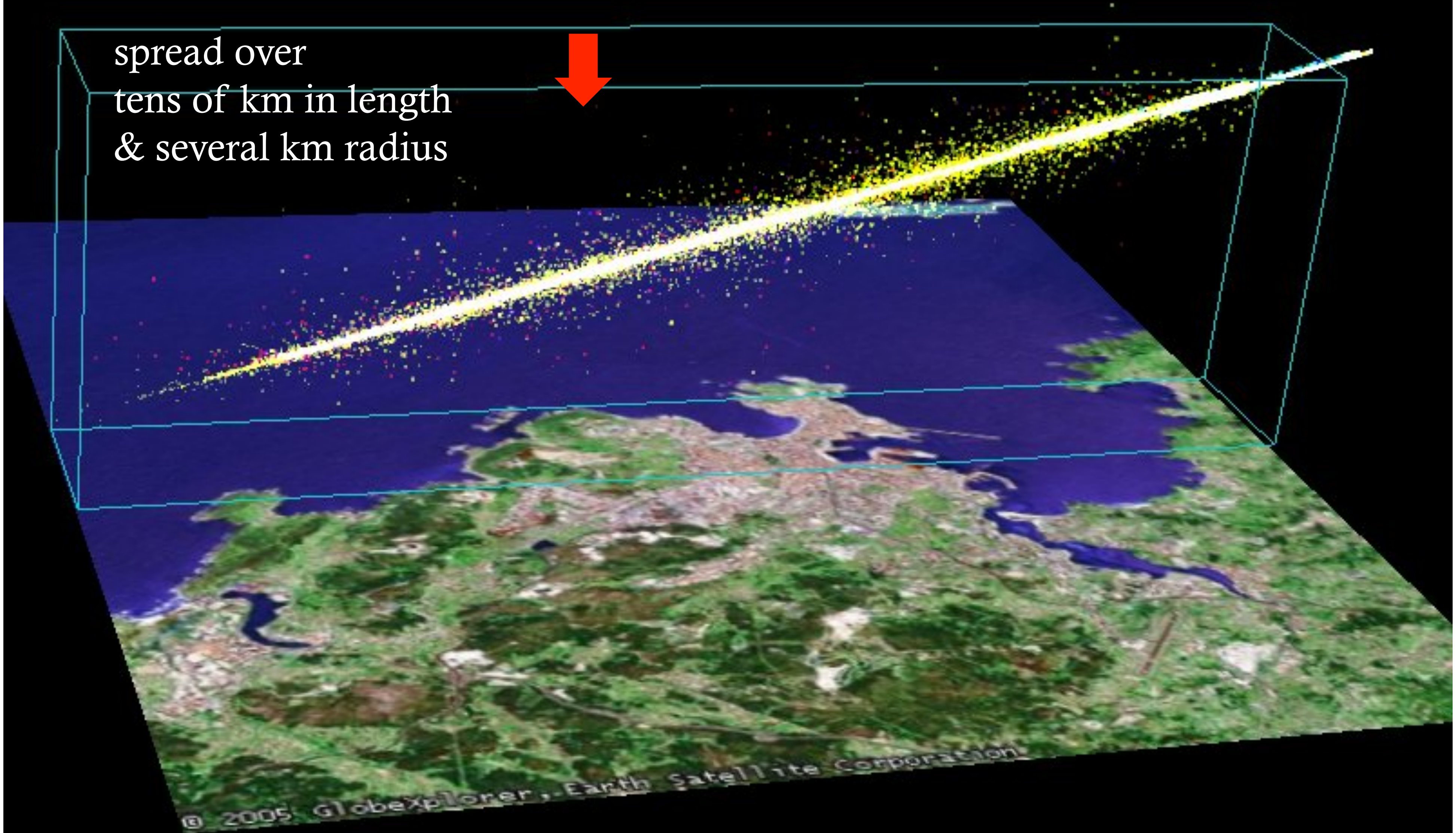
J. Cronin

CR at the highest energies



At UHE Only *Extensive Air Showers* detected

spread over
tens of km in length
& several km radius



The atmosphere is a calorimeter 30 X_0 (vertical) / 1000 X_0 (horizontal)

Composition inferred from shower development=>Extrapolate HE

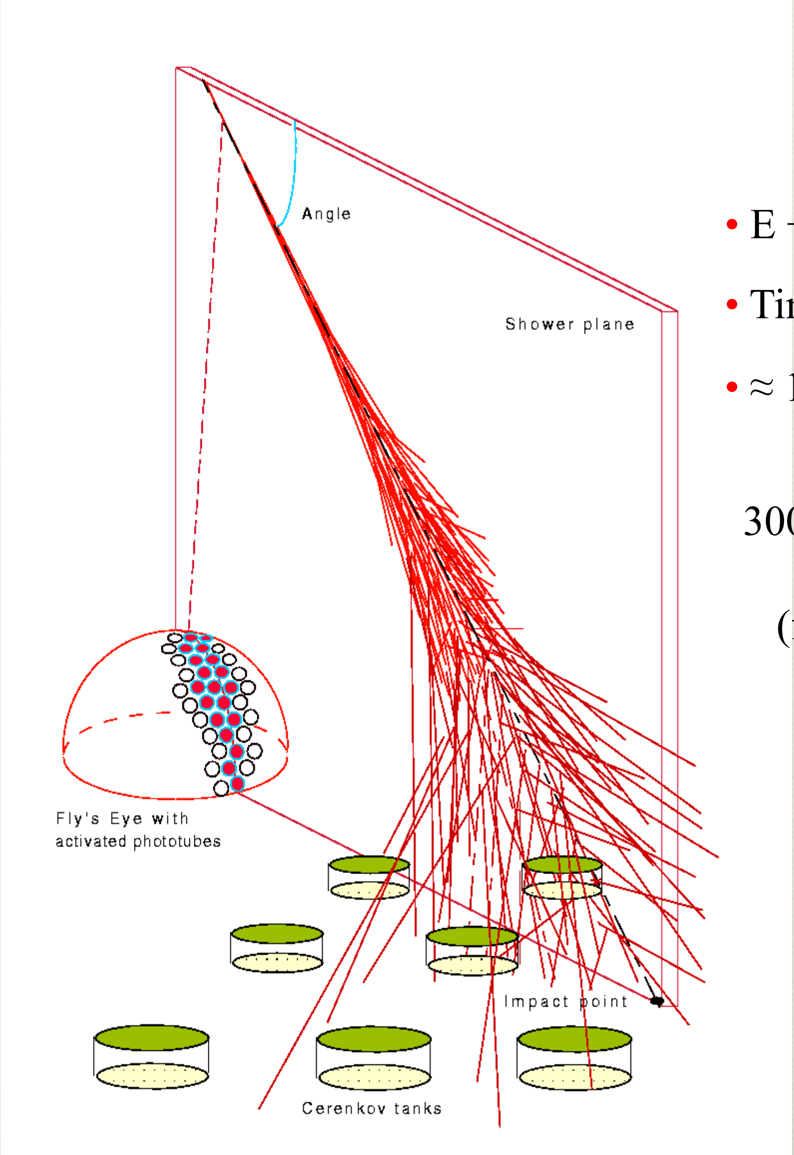
The Detector: Pierre Auger Observatory

HIBRID DETECTOR:

- cross-calibration,

- improved resolution,

- control of systematic errors



Fluorescence Detector

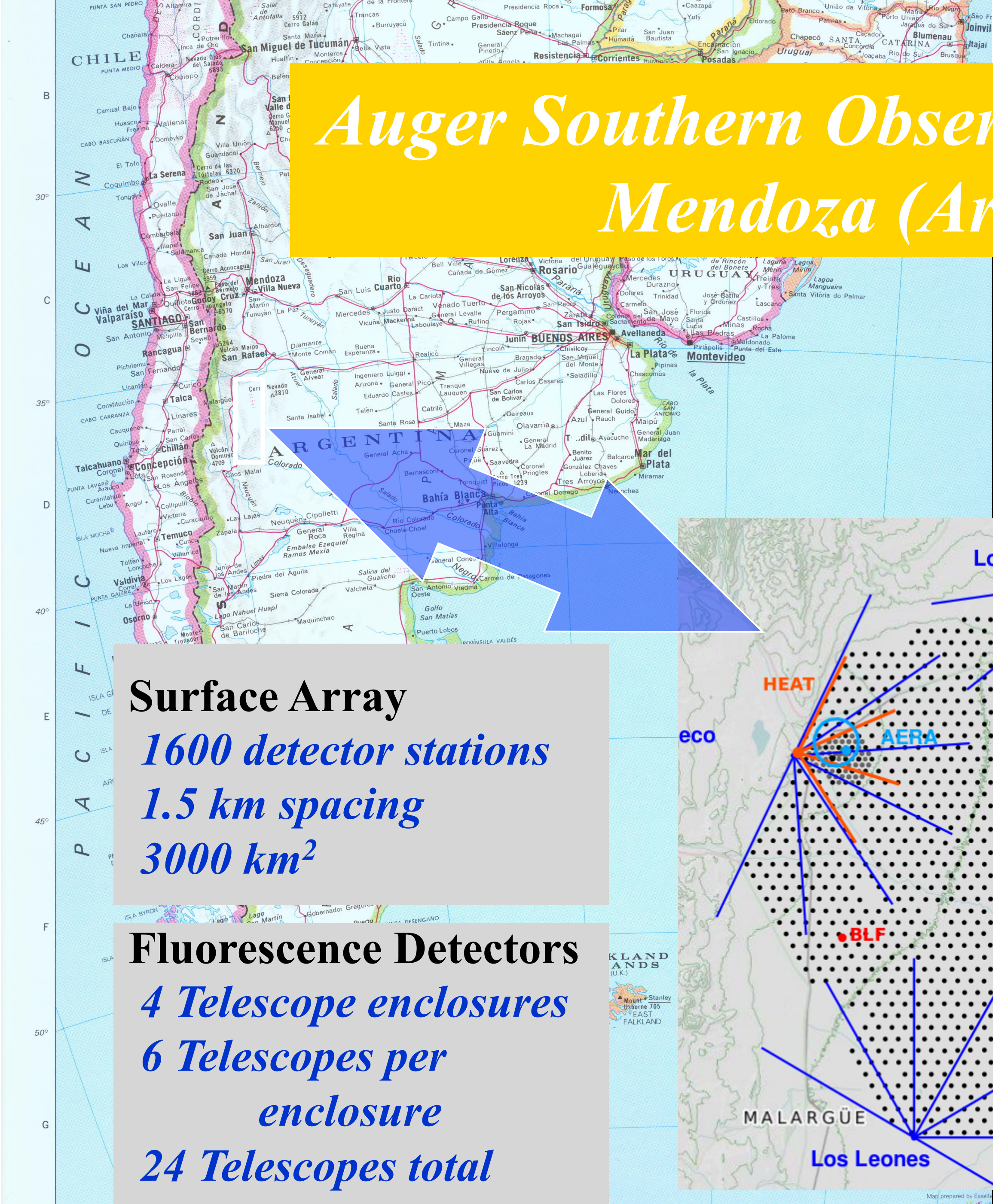
- E + longitudinal development
- Time ≈ direction
- ≈ 10% duty cycle

300-400 nm light from de-excitation of atmospheric nitrogen (fluorescence light) ≈ 4 γ's / m / electron

Surface Detector

- Shower size ≈ E
- Time ≈ direction
- 100% duty cycle

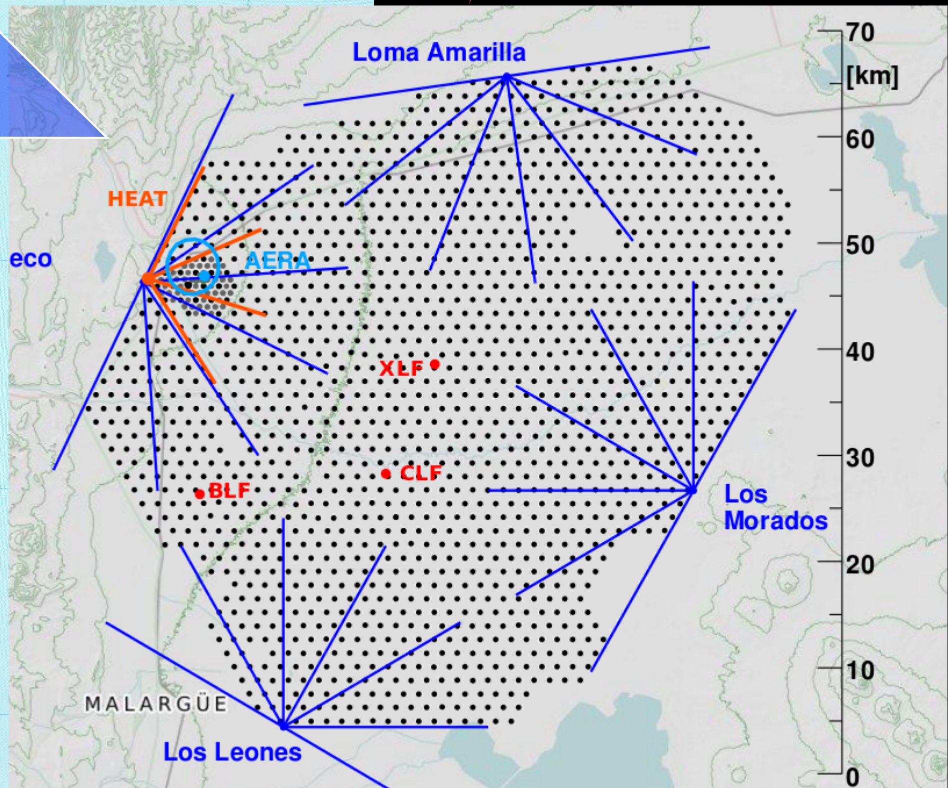
Auger Southern Observatory: Malargüe Mendoza (Argentina)



1600 tanks
4 Eyes

Surface Array
1600 detector stations
1.5 km spacing
3000 km²

Fluorescence Detectors
4 Telescope enclosures
6 Telescopes per enclosure
24 Telescopes total



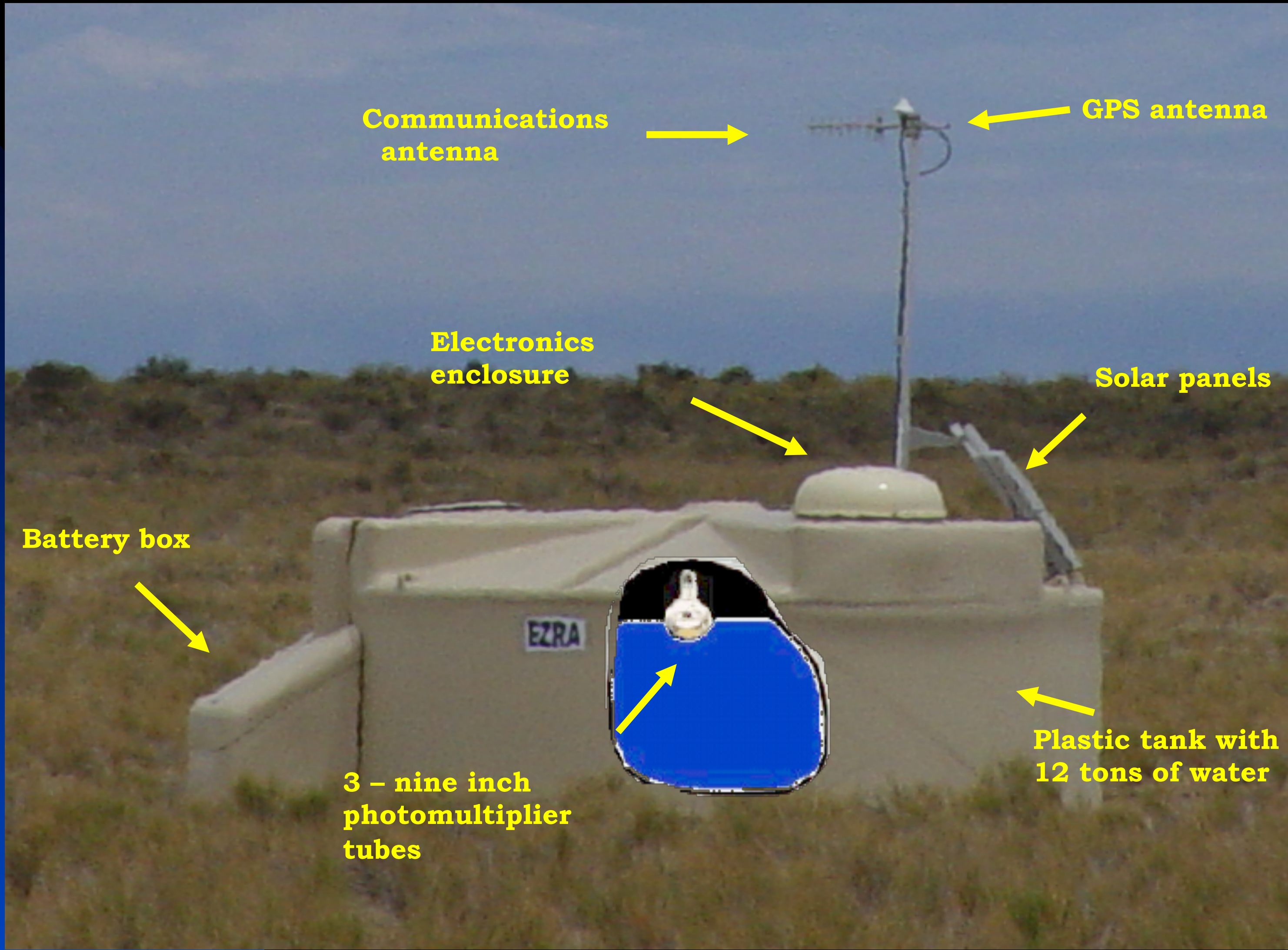
~3000 Km²

Observatori Pierre Auger in Catalunya ....

A hybrid observatory

Tanks aligned in La Pampa

The Surface Detectors



The Fluorescence Detector:

4 Eyes at the perimeter

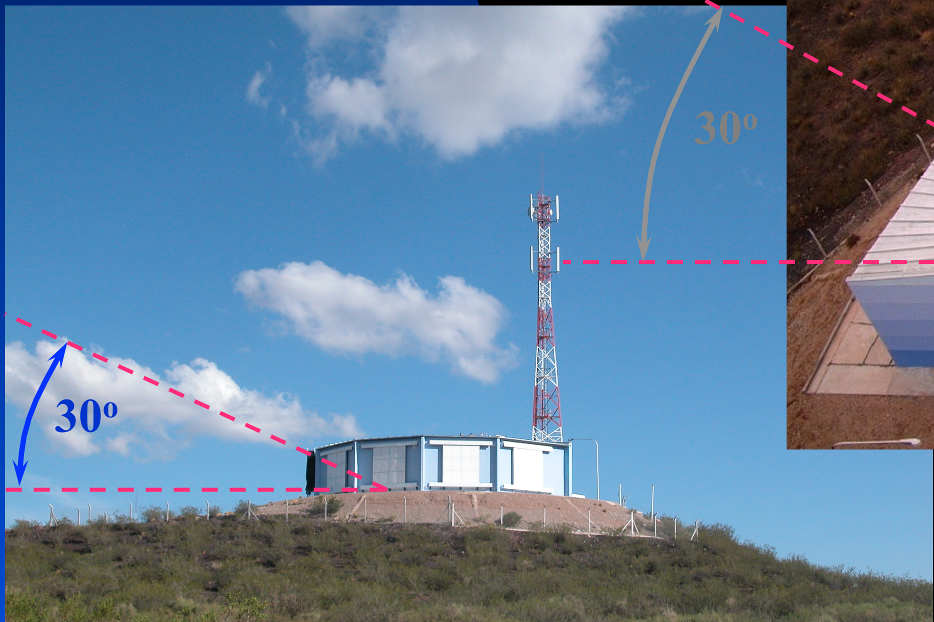
Each has 6 Telescopes (Schmidt optics):

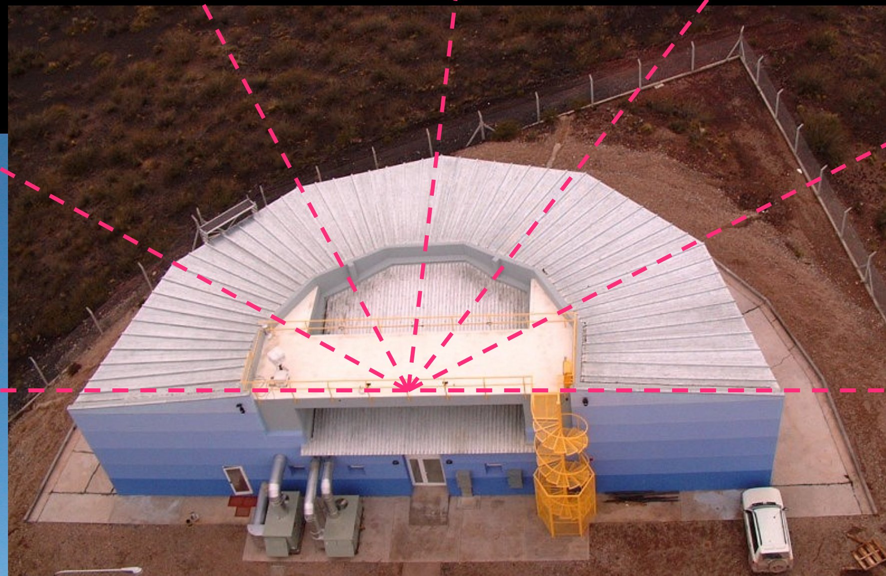
✓Spherical mirror, 3.4 m radius of curvature

✓2.2 m diameter diaphragm, corrector ring

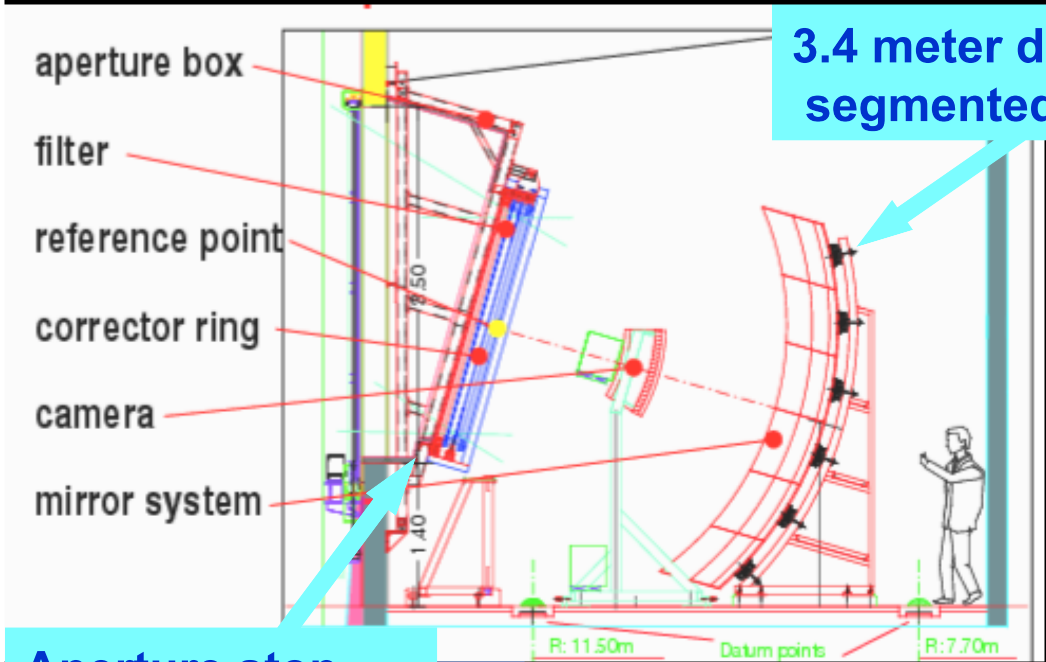
✓30°x30° FOV, 15 mm diameter spot

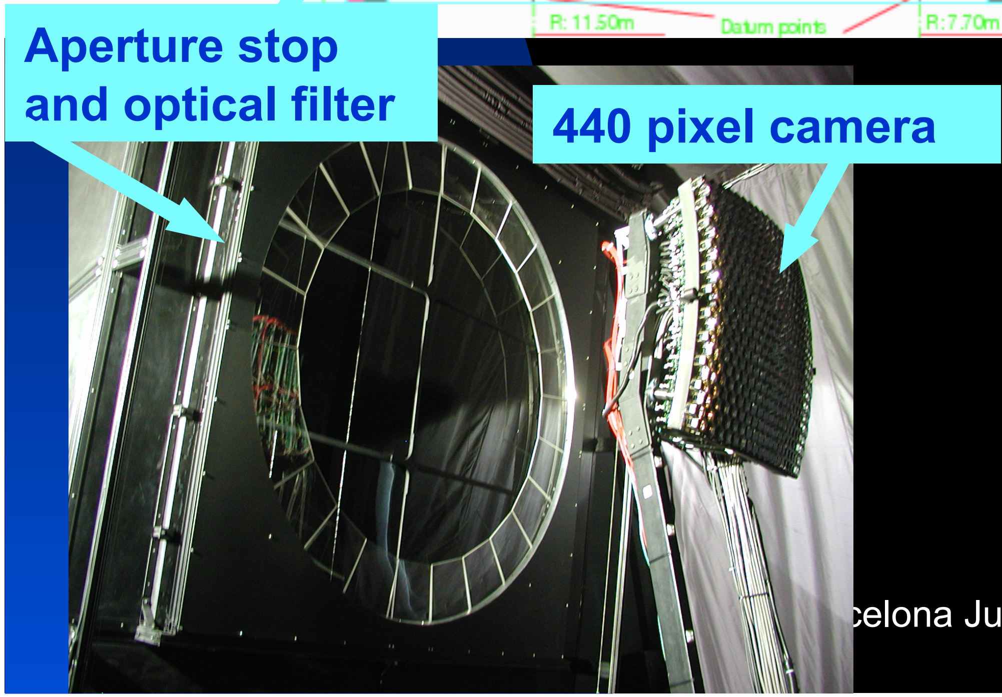
Los Leones

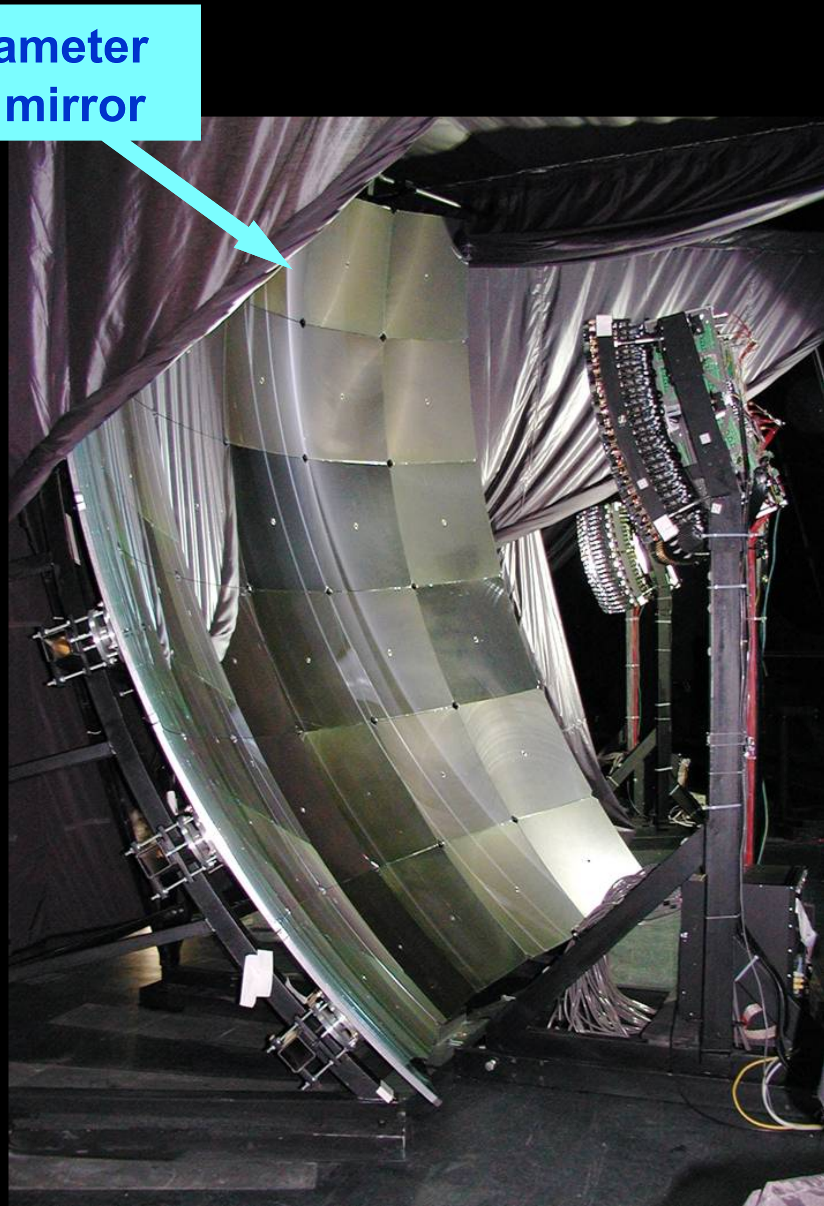




A Fluorescence Telescope

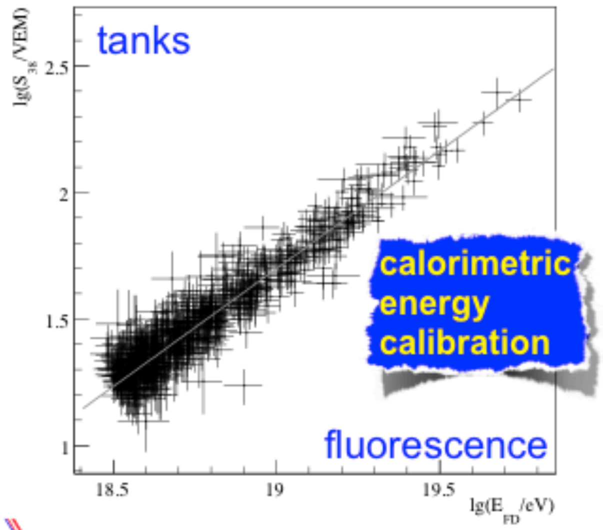


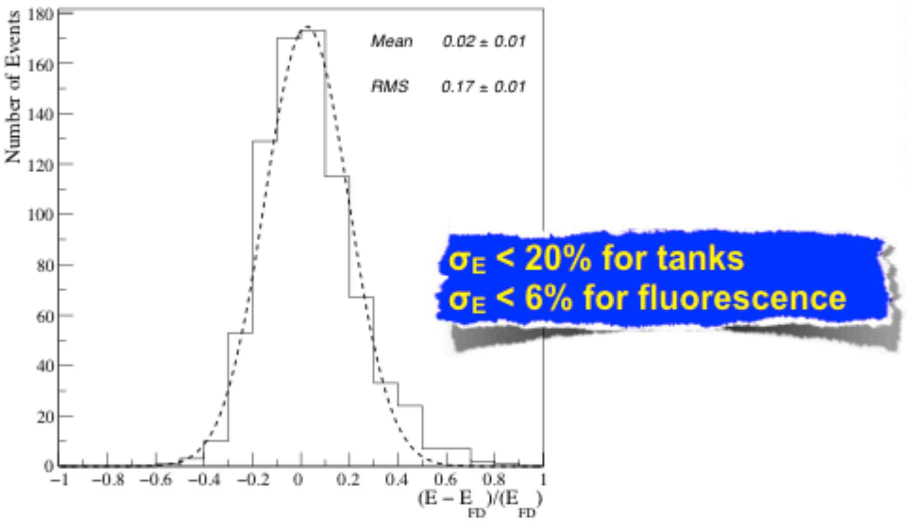


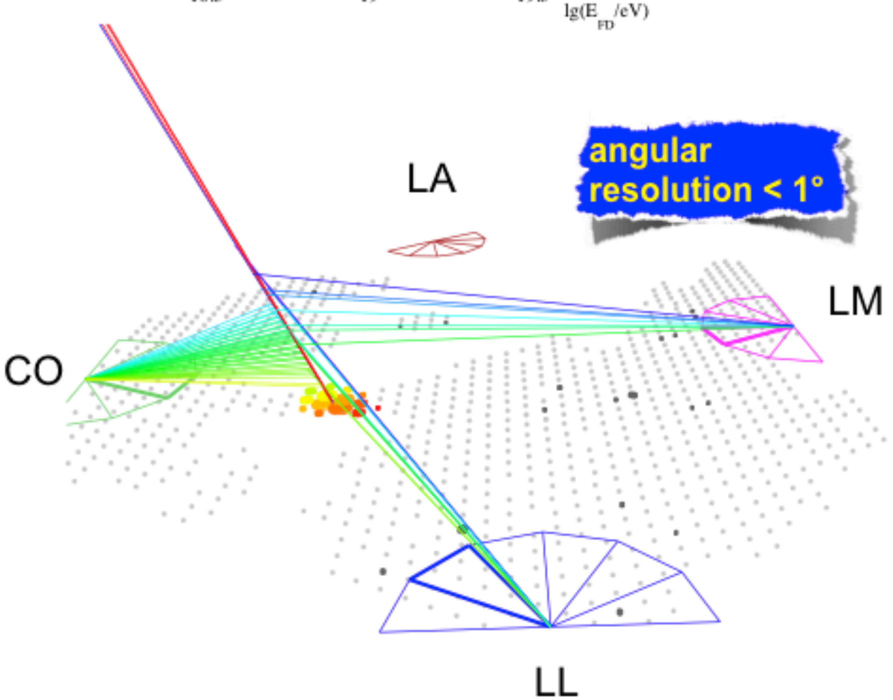


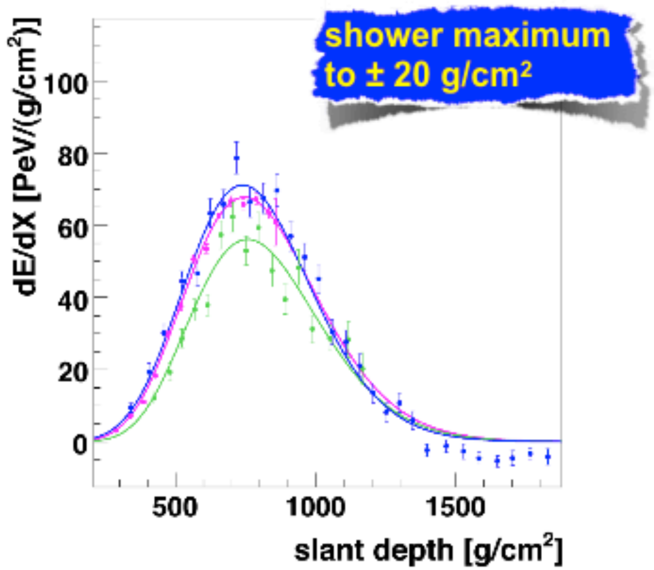
A wild environment...

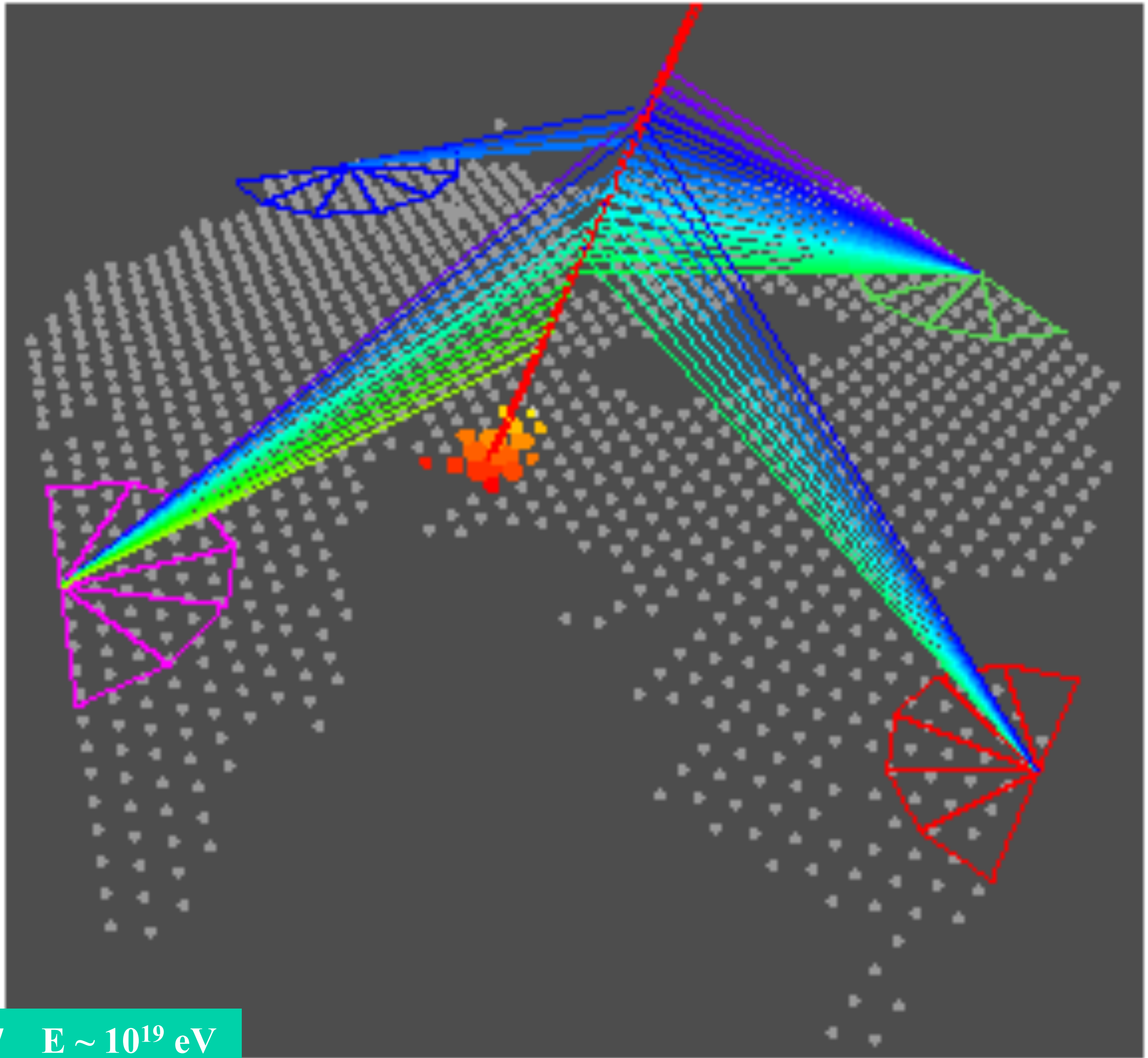
The first instrument: Auger South





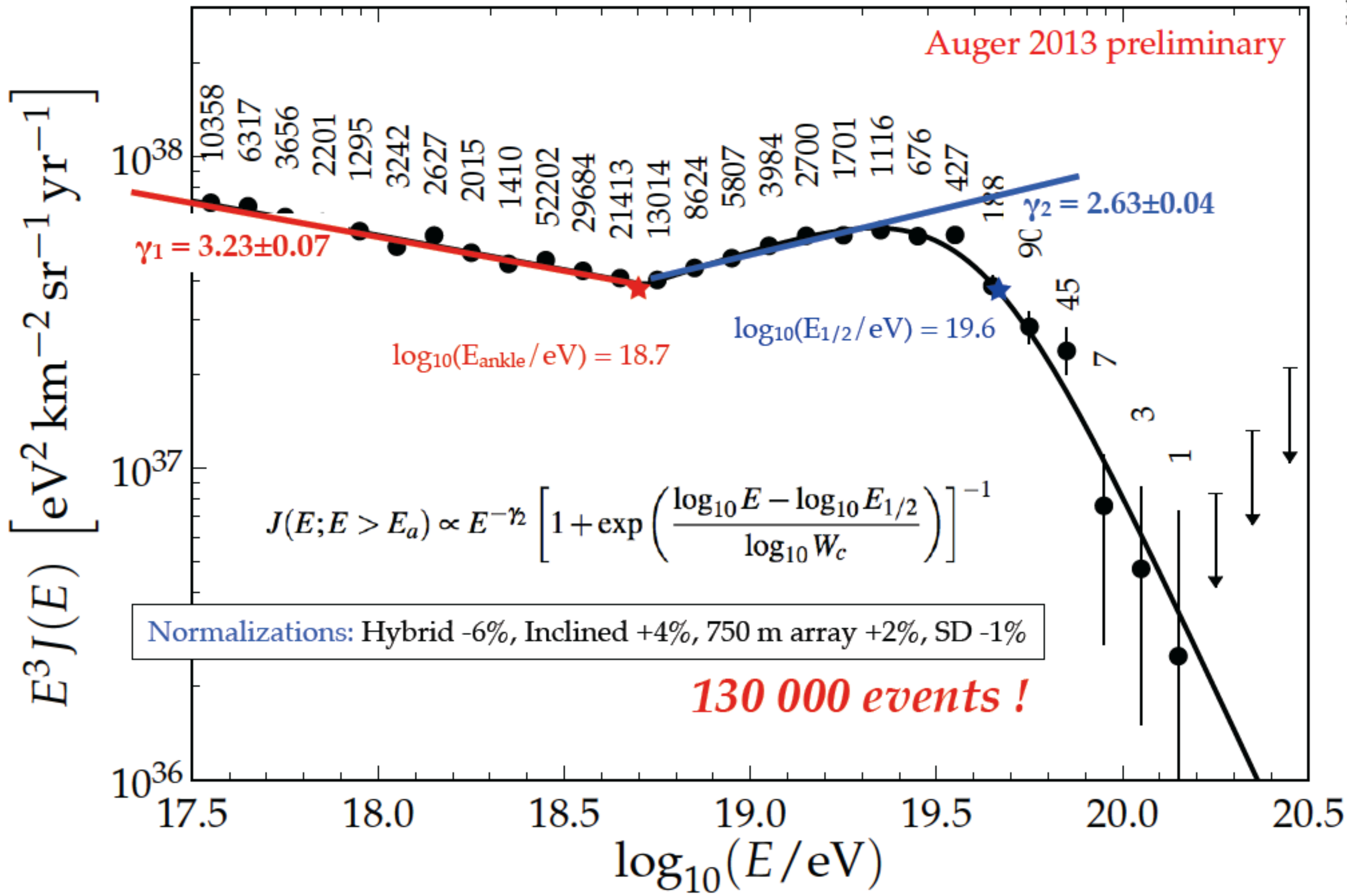






20 May 2007 E ~ 10^{19} eV

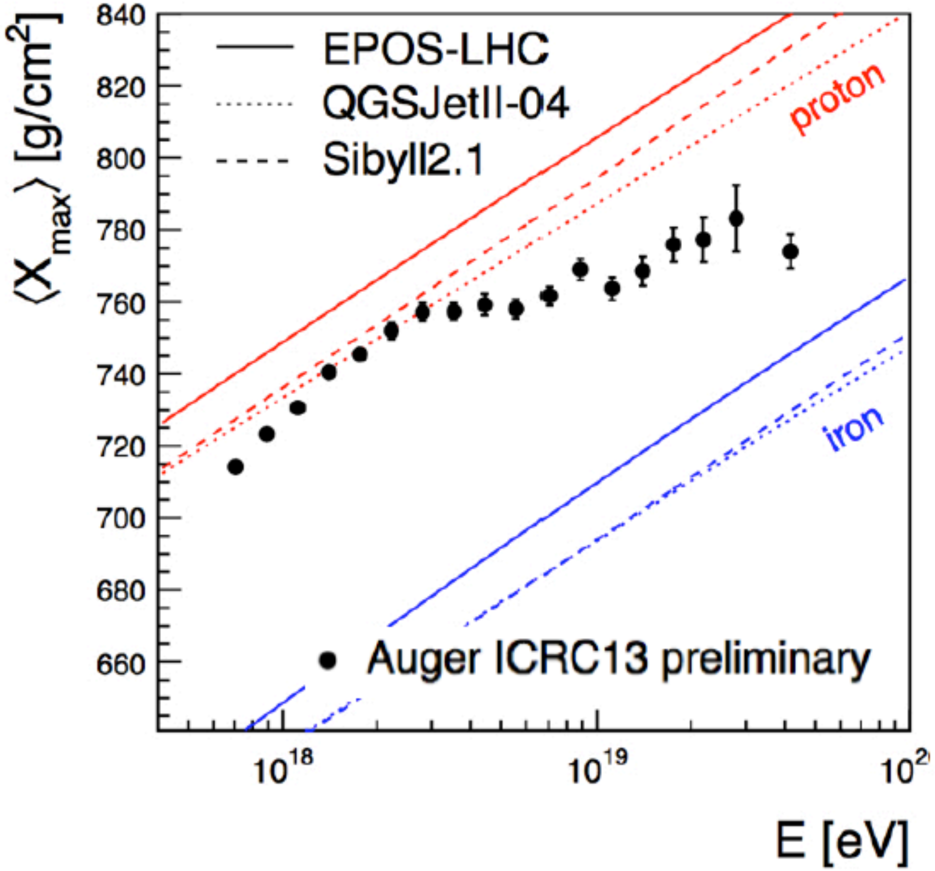
THE AUGER ENERGY SPECTRUM



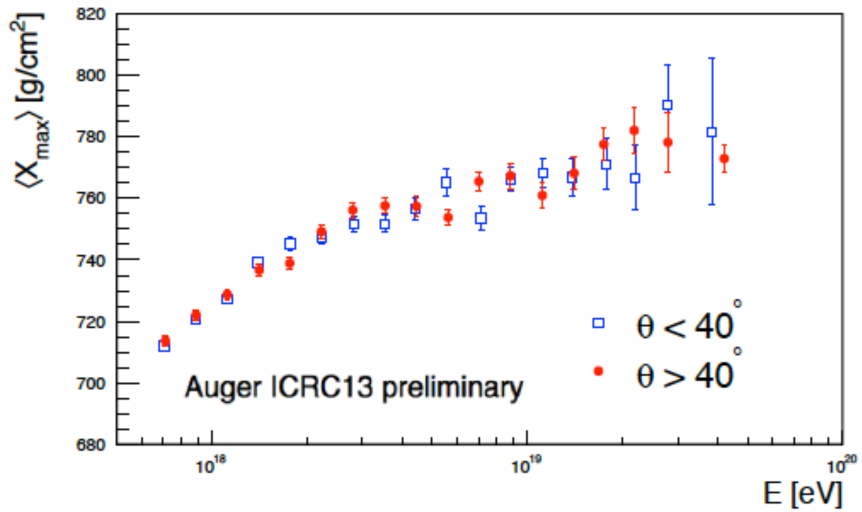
MASS COMPOSITION I

<X_{max}> and $\sigma(X_{max})$ data

PIERRE AUGER OBSERVATORY

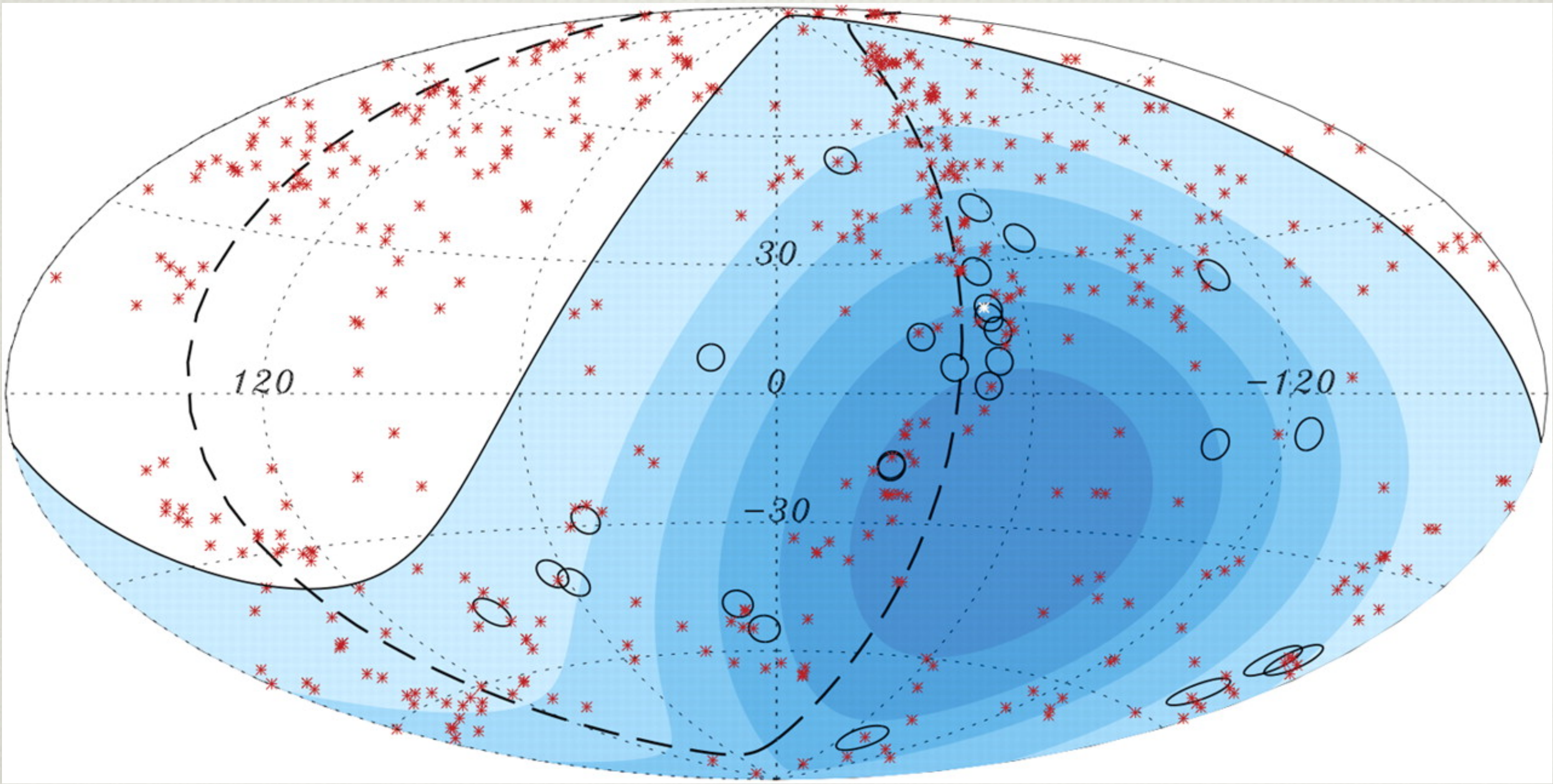


Extensive cross checks and verifications

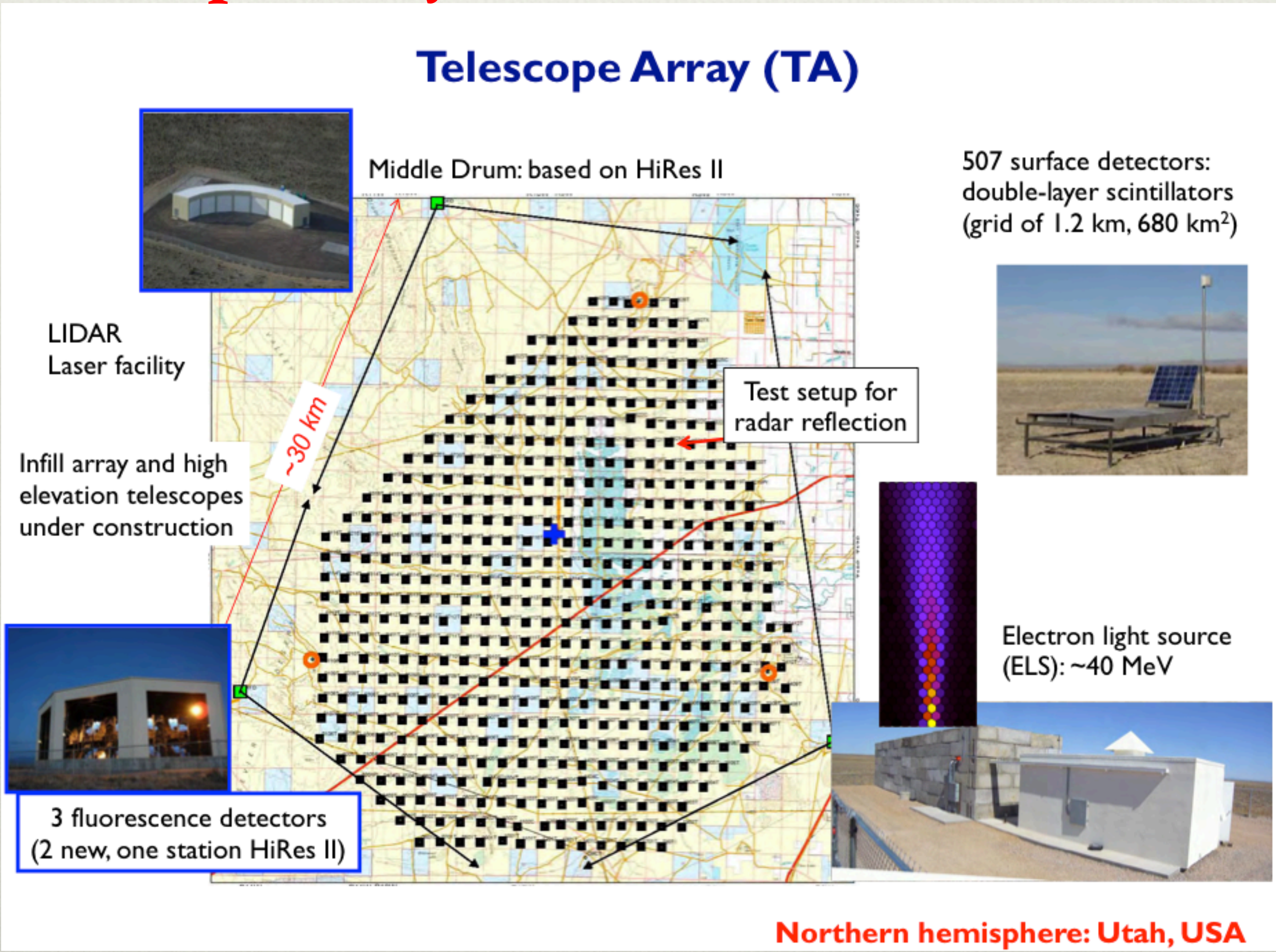


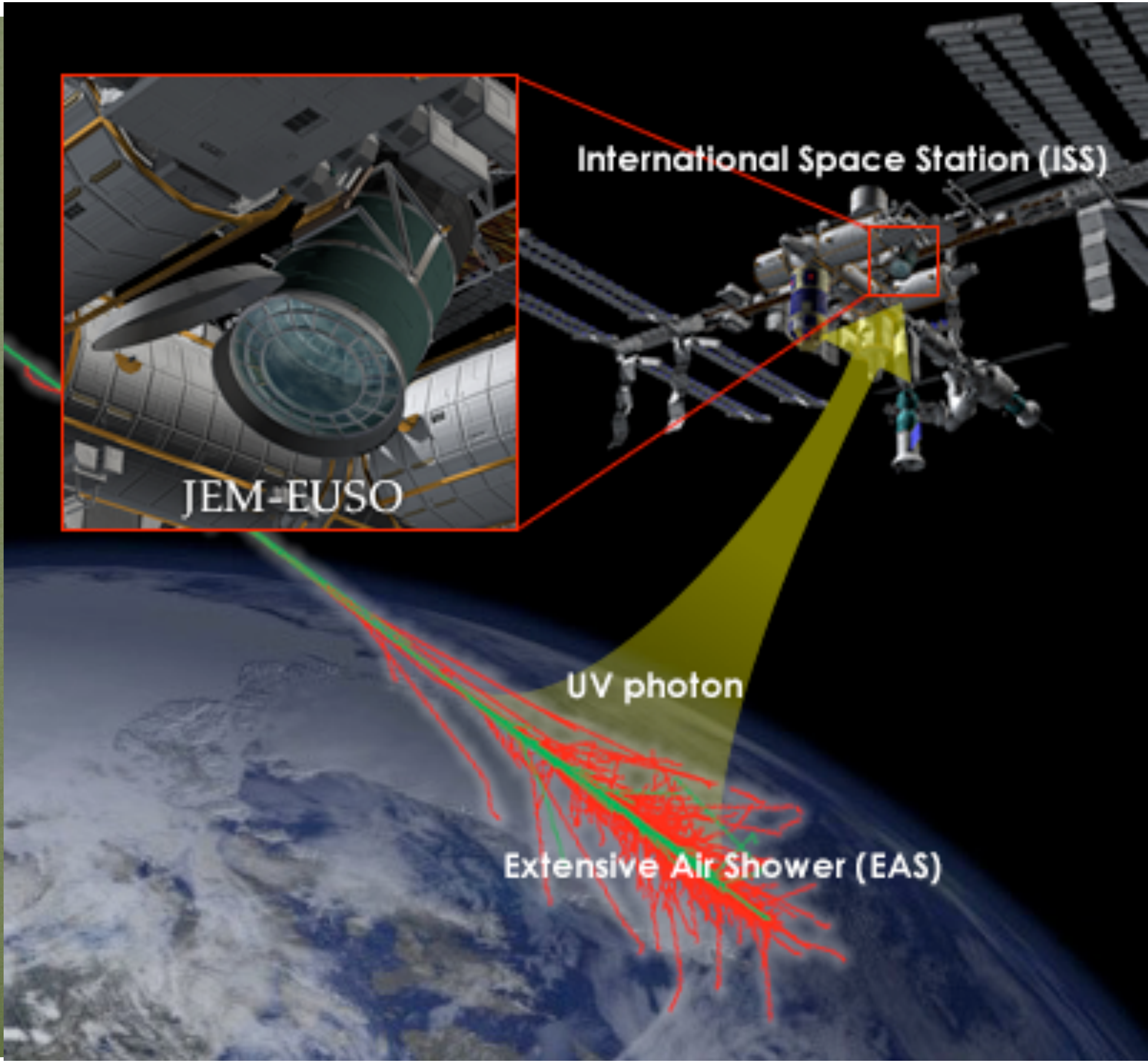
Look for anisotropies

- First step to find origin is to prove CR's do not arrive isotropically
- In 2007, Auger found correlation between 27 events $E>6\times10^{19}$eV (not deflected by intergalactic magnetic field) and AGN catalogue
- Correlation level seems to have reduced with time → claim has been softened



Telescope Array: Construction reaching completion.




International Space Station (ISS)
JEM-EUSO
UV photon
Extensive Air Shower (EAS)

JEM-EUSO

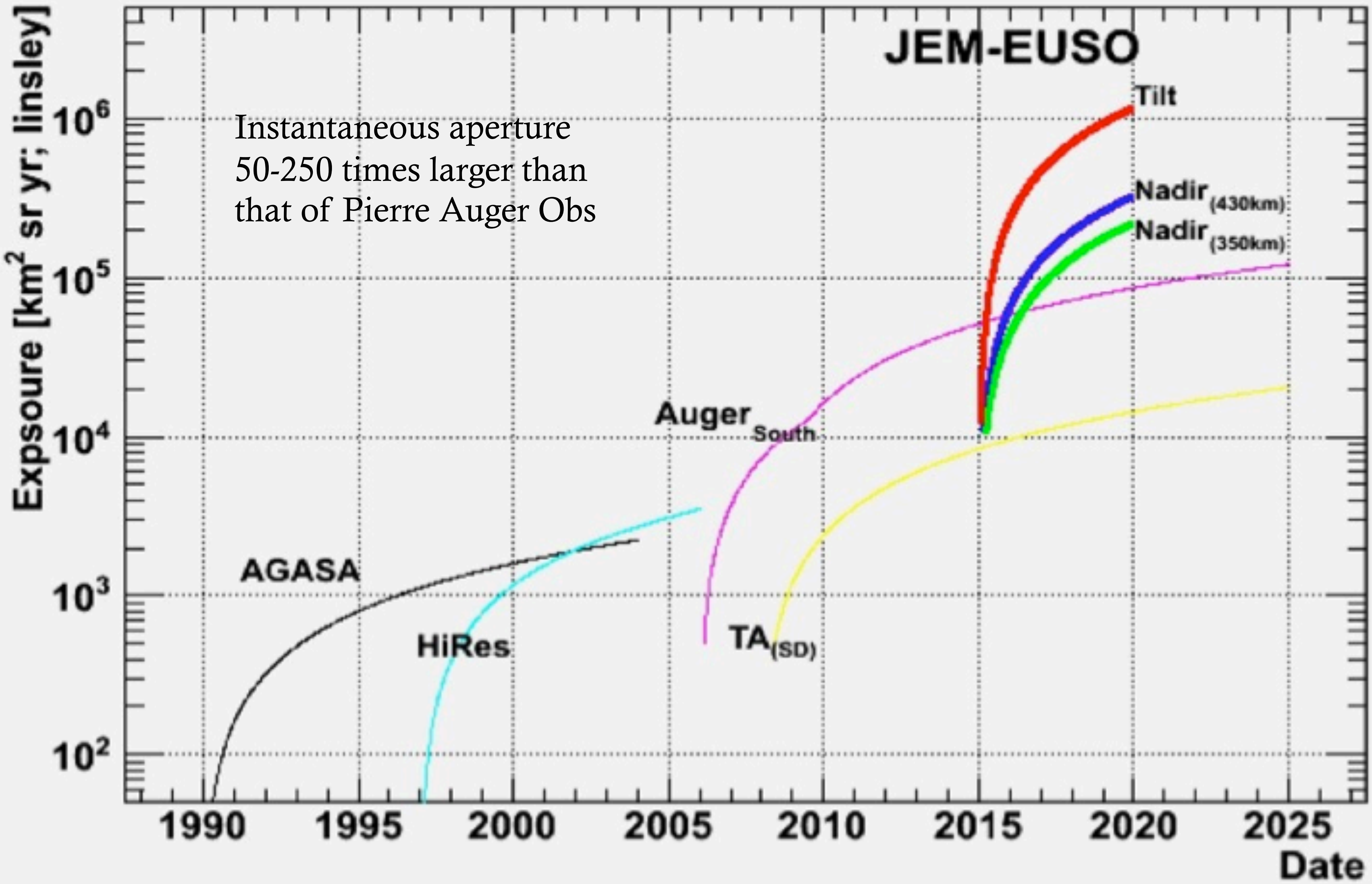
- The JEM-EUSO experiment shall be the first space mission devoted to the scientific research of cosmic rays of highest energies.

- **Technology:** The JEM-EUSO telescope, made of three Fresnel lenses and a fast, high-pixelized, large-aperture and large field-of-view digital camera, looks down from the ISS to detect UV photons emitted from air showers generated by UHECRs in the atmosphere. The atmosphere monitoring is made by an Infrared Camera and a LIDAR.

- **Goals:** Identification of UHE sources, measurement of the trans-GZK spectrum of the Cosmic Rays, discovery of UHE neutrinos and gammas and atmospheric science are the main goals of the mission.

- **Plan** to be launched in 2017 by Japanese heavy liftrocket, H2B, and then conveyed to the ISS

Why a Space-based experiment for CR detection ?



Instantaneous aperture
50-250 times larger than
that of Pierre Auger Obs

HAWC - High Altitude Water Cherenkov Observatory

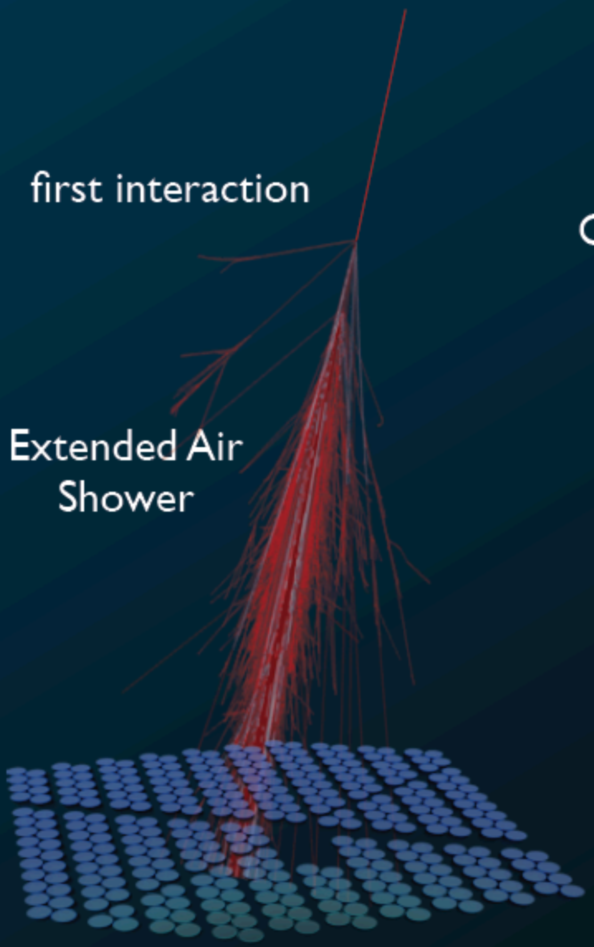
location: saddle point between Volcán Sierra Negra (also site of Large Millimeter Telescope) and Pico de Orizaba

Collaboration of ~100 scientists from US & Mexico

7.3 m dia x 4.5 m tall

Operation principle

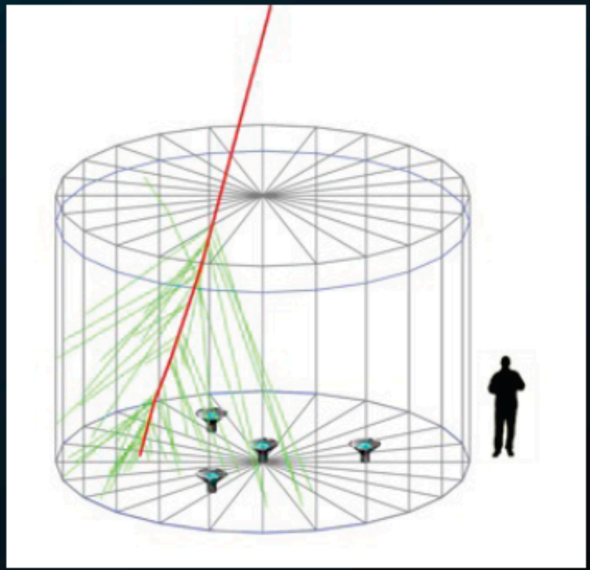
gamma ray or cosmic ray



secondary particles
reach ground level

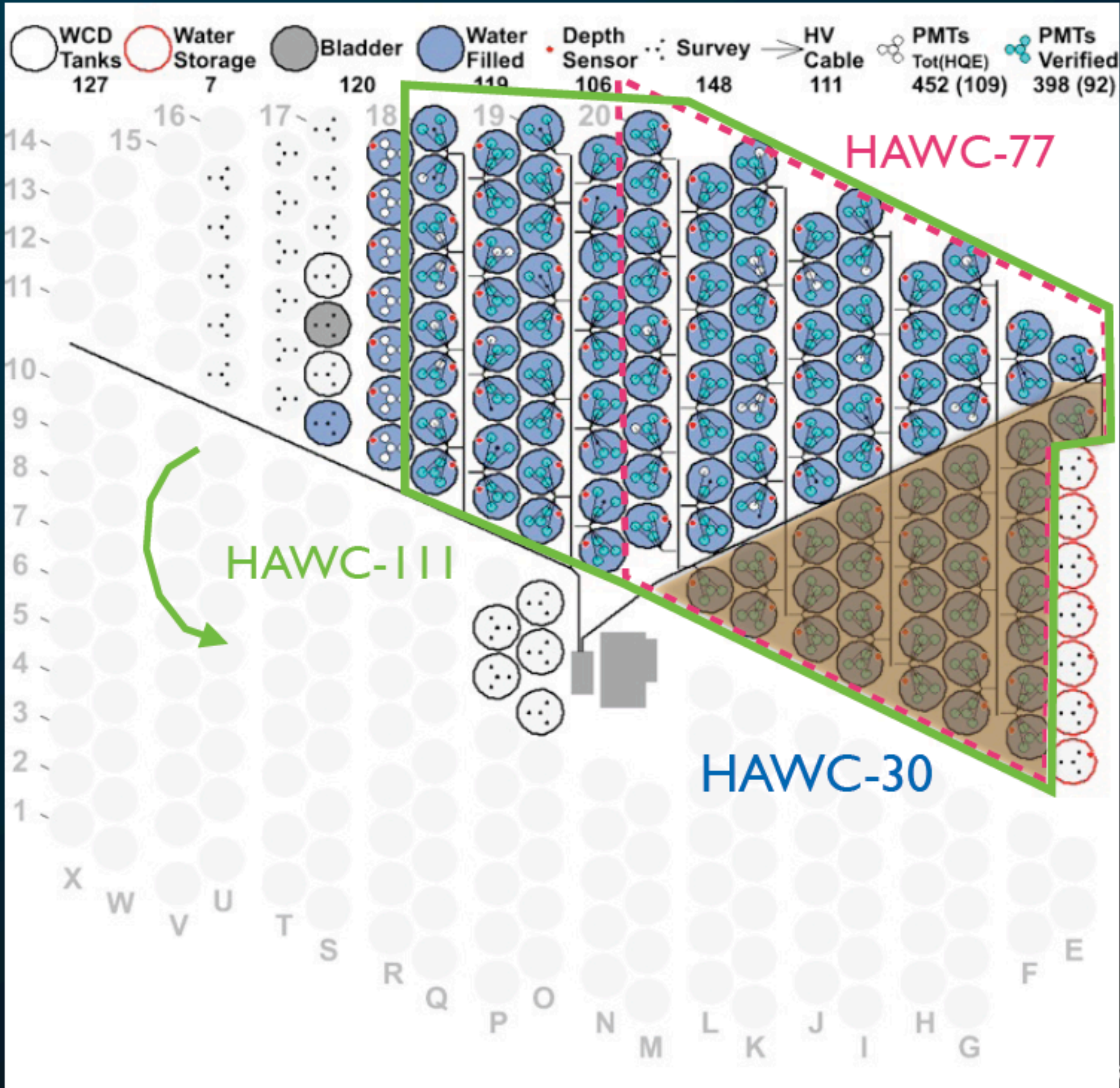
charged particles produce
Cherenkov light in HAWC tanks

light is detected by
photomultiplier tubes (PMT)



4 upward looking PMTs per tank: three 8" PMTs (Hamamatsu R5912, re-used from Milagro) and one high quantum efficiency 10" PMT in the center (Hamamatsu R7081-MOD)

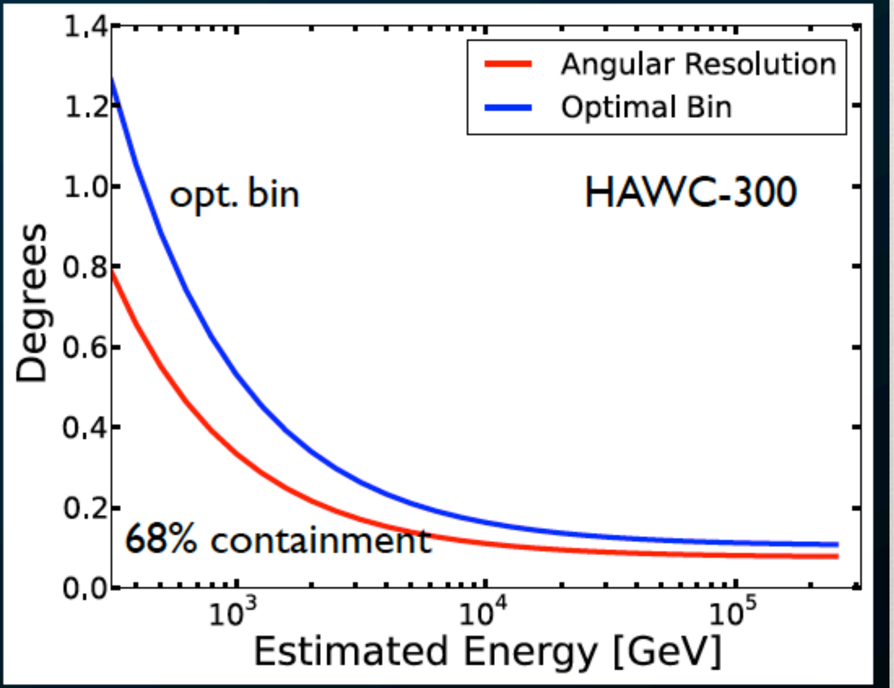
HAWC construction progress

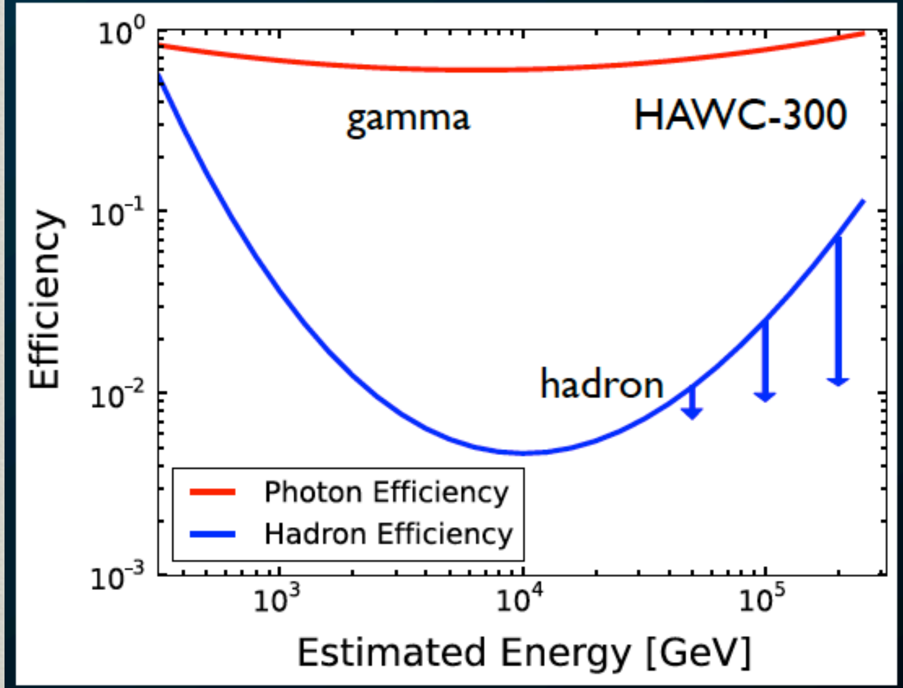


- Sep 2012: first 29 tanks completed; regular data taking begins
- January-March 2013: high QE PMTs added
- mid-May: 77 tanks operational
- June: >90% uptime reached (automatic running)
- Now: operating with 111 tanks / 400 PMTs
- summer 2014: expect complete detector

Also a gamma-ray telescope

- Reconstruct shower core position from hit amplitudes and shower plane / direction from hit timing
- Angular resolution up to 0.1° at TeV energies

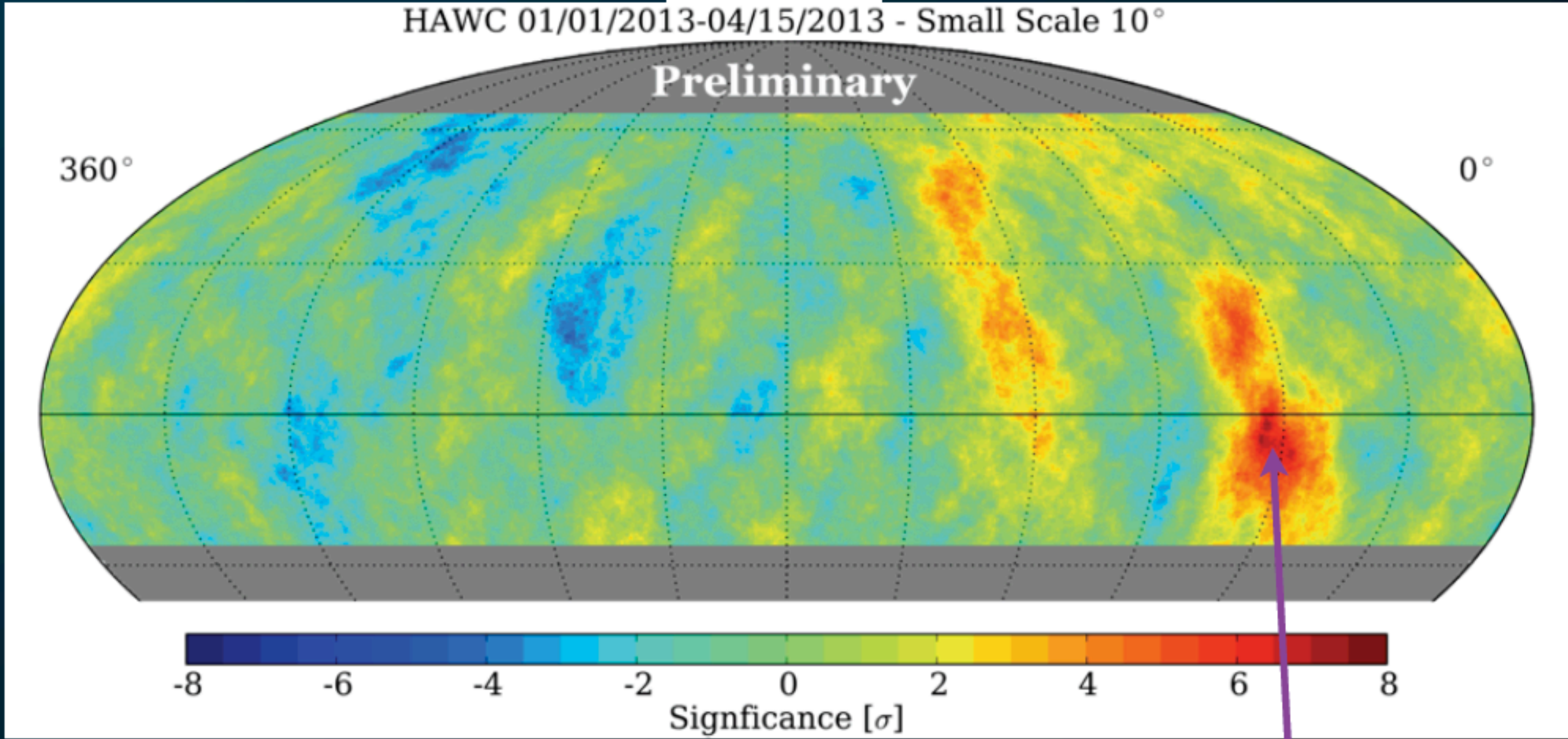




- Gamma-hadron separation is based on shower lateral size, clumpiness, and high amplitude pulses produced by muons
- > 100-fold hadron rejection while retaining >50% of photon-induced events

Small scale Cosmic Ray anisotropy

95 days live



2 hr integration window, 10 deg smoothing applied
median energy the event sample ~ 2 TeV

> 5 sigma excess region

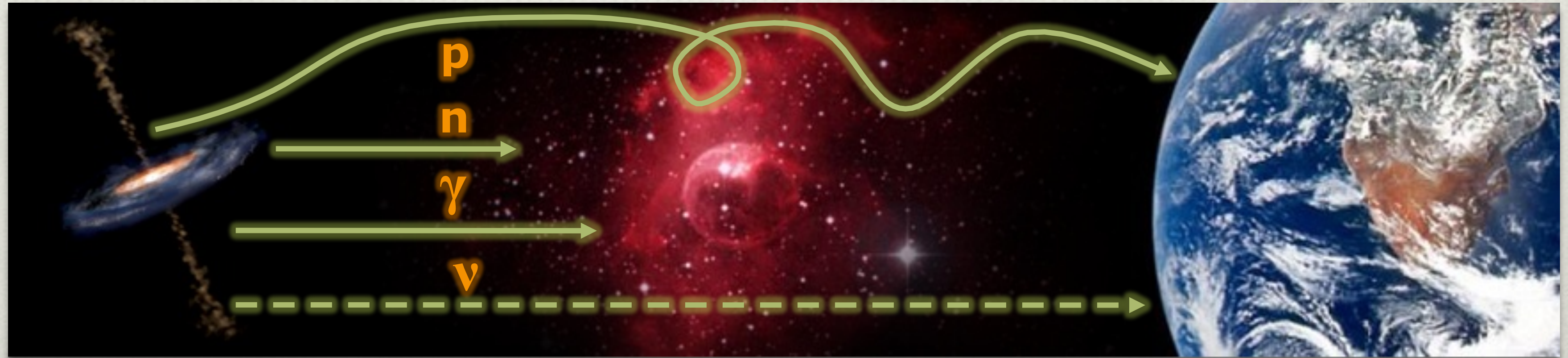
A confirmation of CR anisotropy regions discovered by Milagro (PRL 101:221101, 2008)

S. BenZvi et al., Observation of the Anisotropy of Cosmic Rays with HAWC, ICRC 2013

High energy neutrinos

Cosmic messengers

- Why neutrino astronomy?

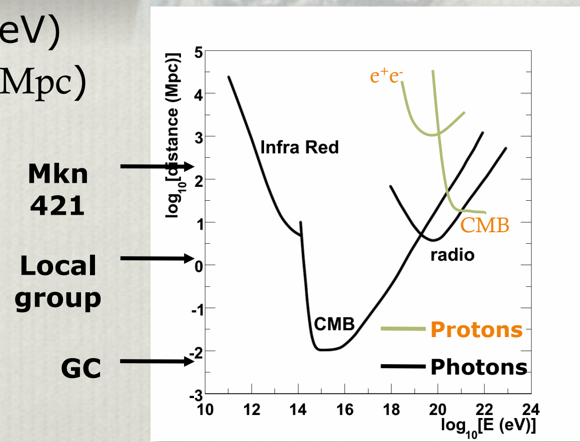


- Protons are deflected by magnetic fields ($E_p < 10^{19}$ eV)
  UHE protons interact with the CMB ($E_p > 10^{19}$ eV → 30 Mpc)

- Neutrons decay (~10 kpc at E ~ EeV).

- Photons interact with the EBL (~100 Mpc) and CMB (~10 kpc).

- Neutrinos are neutral weakly interactive particles.



Where can high energy neutrinos come from?

Astrophysical objects

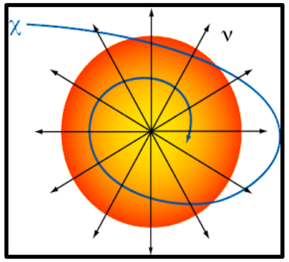
HE neutrinos appear as the sub-product of interactions of **accelerated protons** or nuclei with matter or radiation

$$p + A/\gamma \rightarrow \pi^{\pm} + \dots$$

$$\rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) + \dots$$

$$\rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \nu_{\mu}(\bar{\nu}_{\mu}) + \dots$$

WIMP decay products



HE neutrinos are the decay sub-products of the **annihilation** of **WIMPs** which may concentrate in astrophysical objects.

$$\chi + \chi \rightarrow q\bar{q}, \dots \rightarrow X + \nu\bar{\nu}$$

Detecting cosmic neutrinos

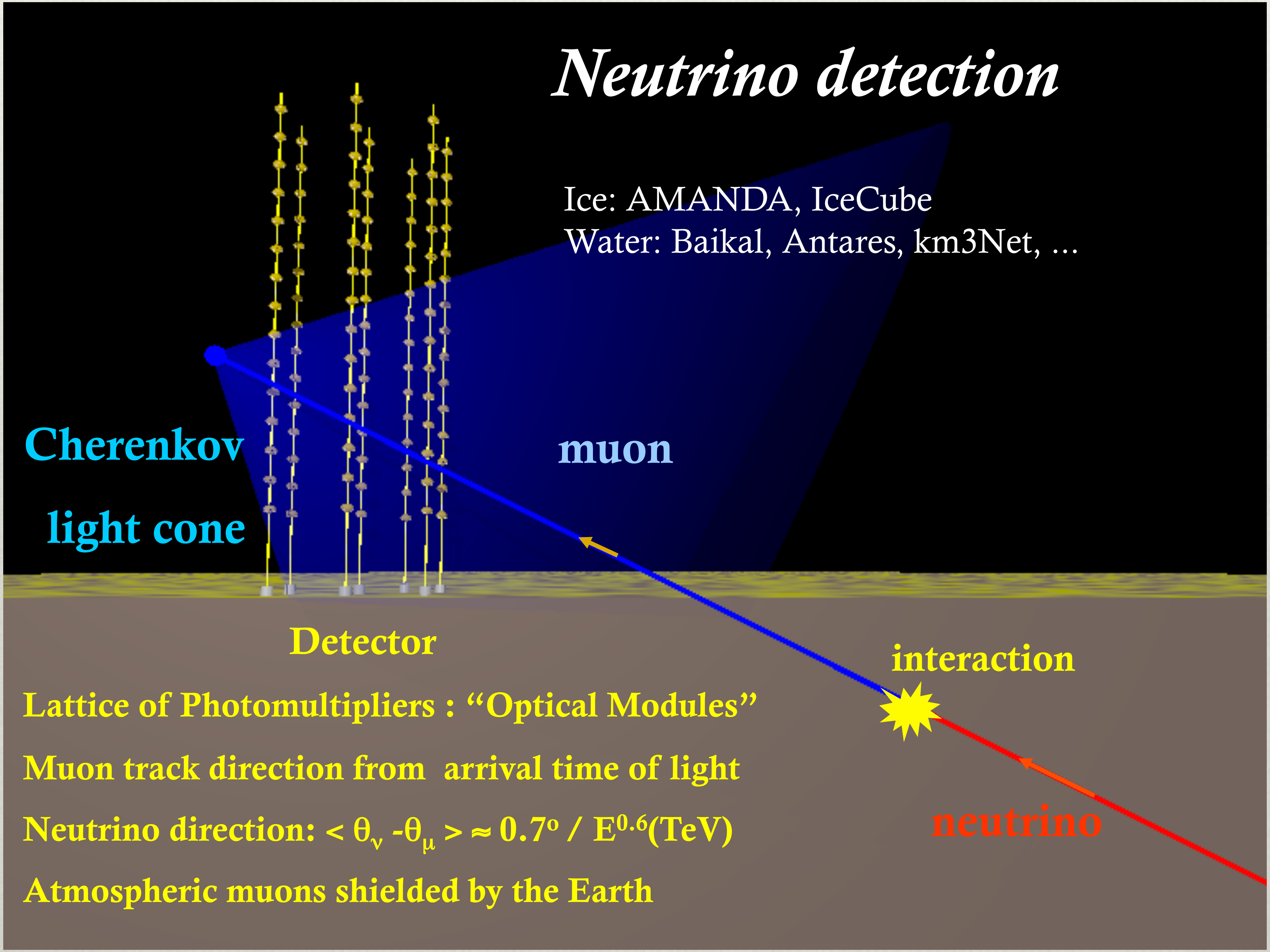
- The only extraterrestrial neutrinos detected until recenly come from:

  Sun and SN 1987A

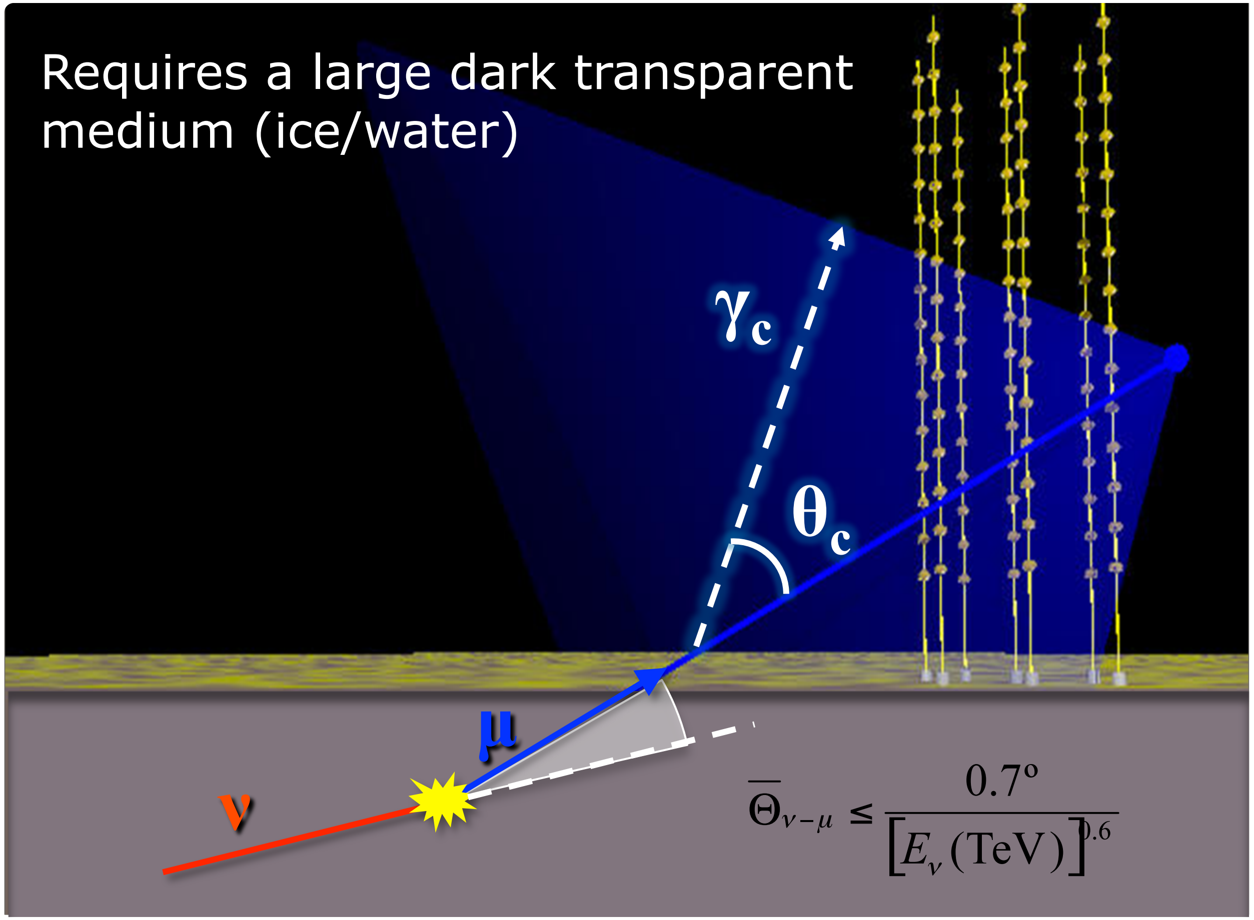
- Very, very, very weak interaction ->

1 lightyear (10^{13} Km) of lead needed to absorbe 50% of a neutrino beam

=> To build a “neutrino telescope” the whole earth is used as detector and the Cherenkov light from the secondary muons produced by the neutrino interaction is used as the signal


Neutrino detection
Ice: AMANDA, IceCube
Water: Baikal, Antares, km3Net, ...
Cherenkov
light cone
muon
Detector
interaction
neutrino
Lattice of Photomultipliers : "Optical Modules"
Muon track direction from arrival time of light
Neutrino direction: $< \theta_\nu - \theta_\mu > \approx 0.7^o / E^{0.6}(\mathrm{TeV})$
Atmospheric muons shielded by the Earth

Cherenkov Neutrino detection

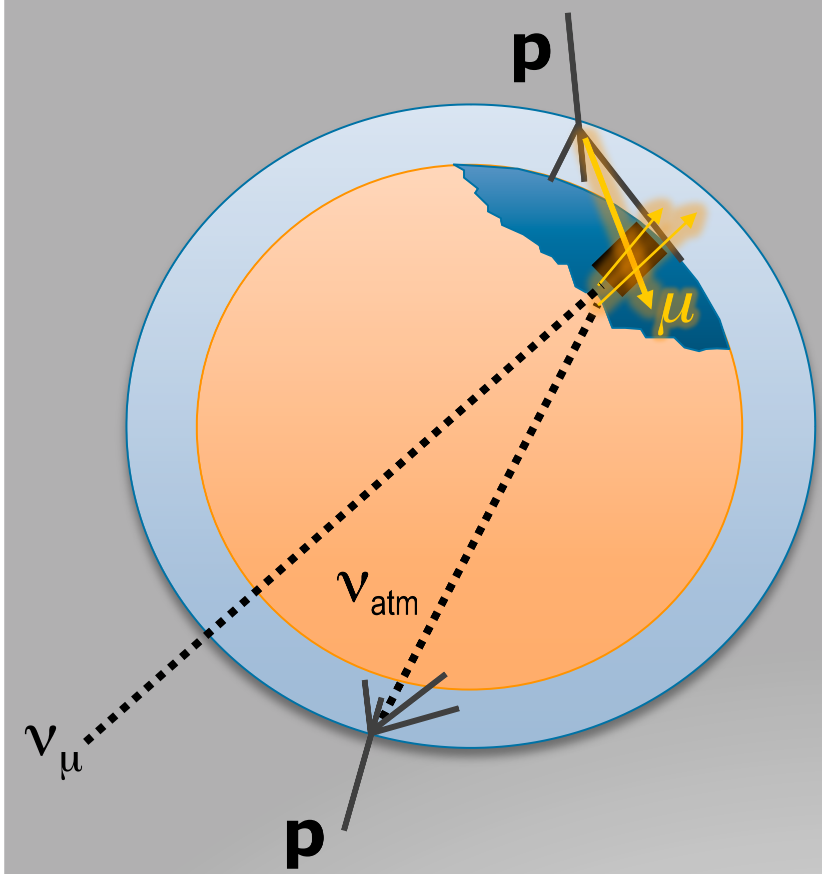


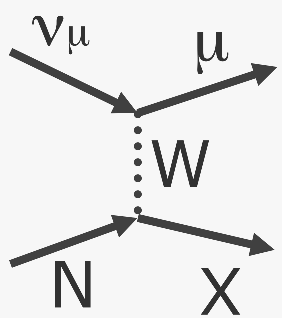
Muon neutrinos are well suited for HE detection (cross-section and muon range increase with energy)

Muons emit Cherenkov light collected by a lattice of PMTs.

Other signatures can also be detected.

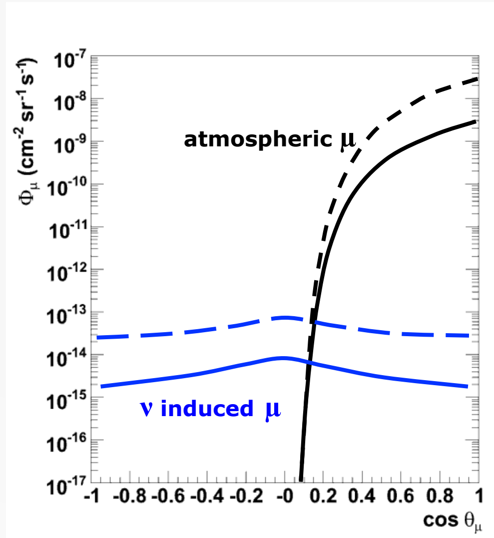
Long track $\longrightarrow$ angular resolution





Cosmic neutrinos can interact in the Earth and release a muon

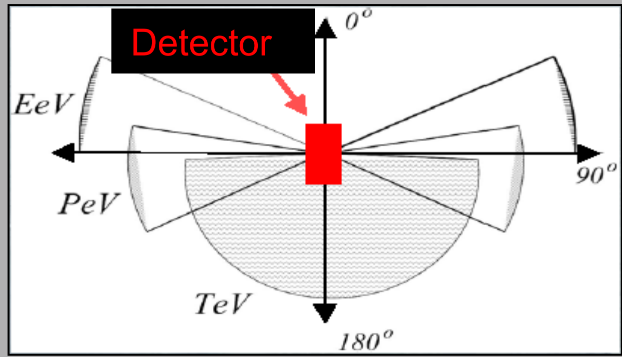
Atmospheric muons and neutrinos can also induce a signal at the detector



Detection principle

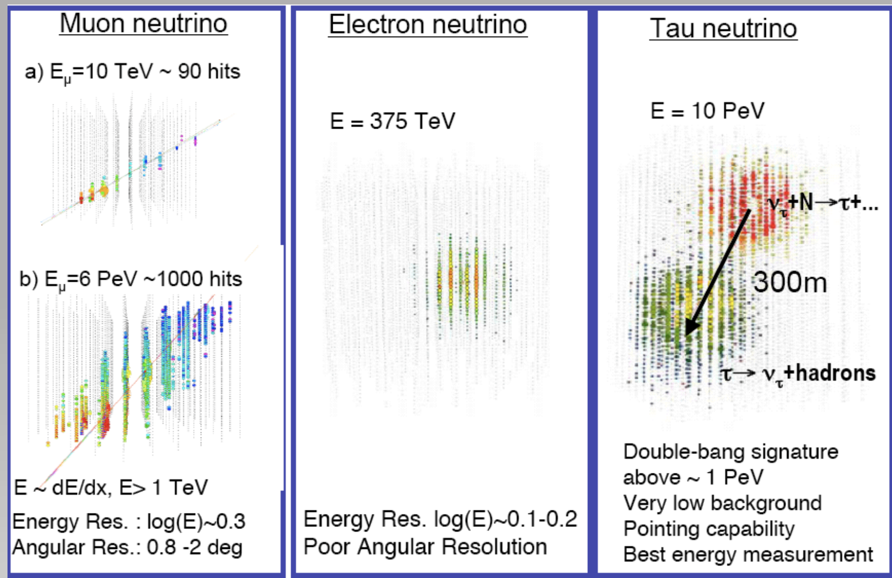
Different channels, different energy regions

Earth starts to become opaque at E~1 PeV
Below the horizon PeV neutrinos can be detected
Downgoing tracks at high energies (EeV) can only come from neutrinos

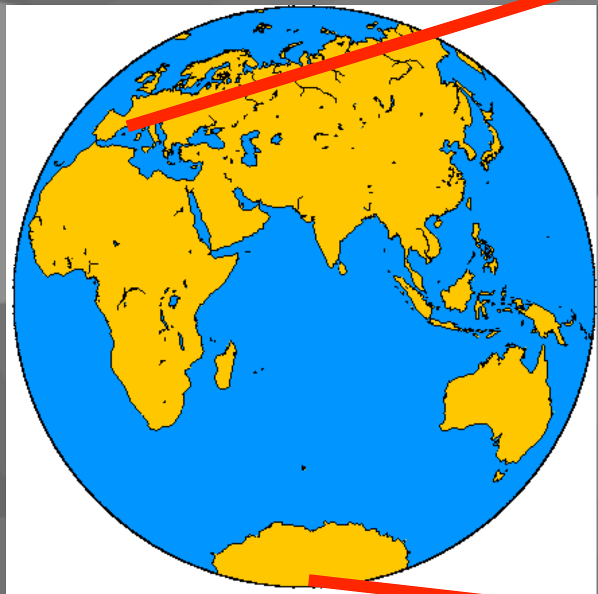


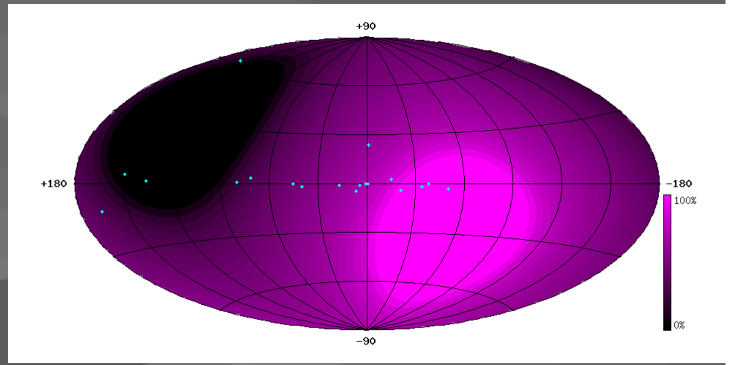
In addition to muons, EM showers can be identified.

Tau neutrinos can be identified by double bang events (production and decay).

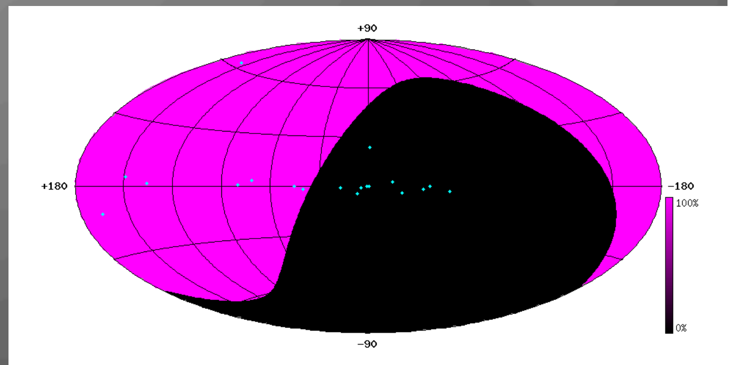


Present instruments for neutrino astronomy astronomy



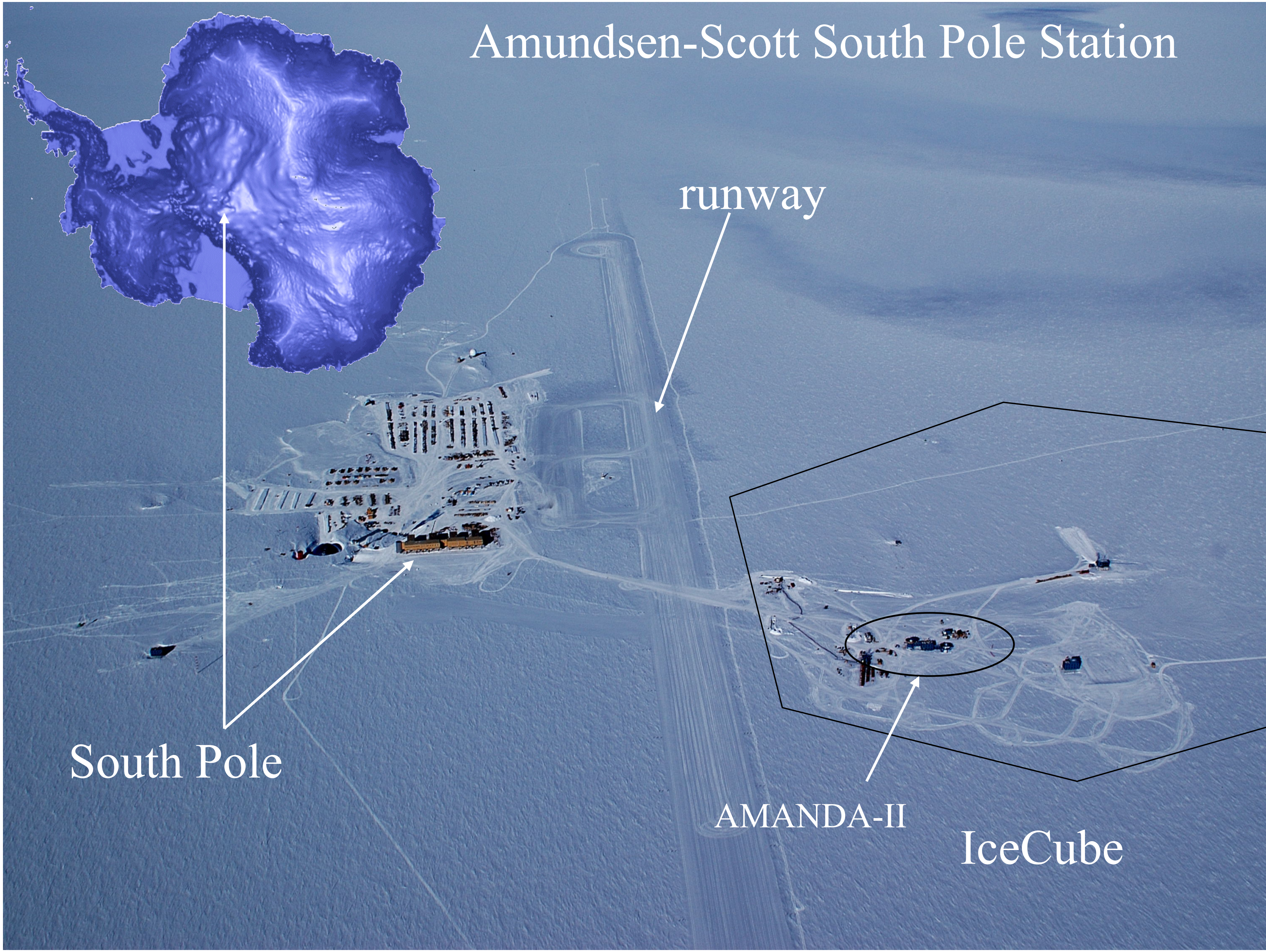


ANTARES
43° North
2/3 of time: Galactic Centre



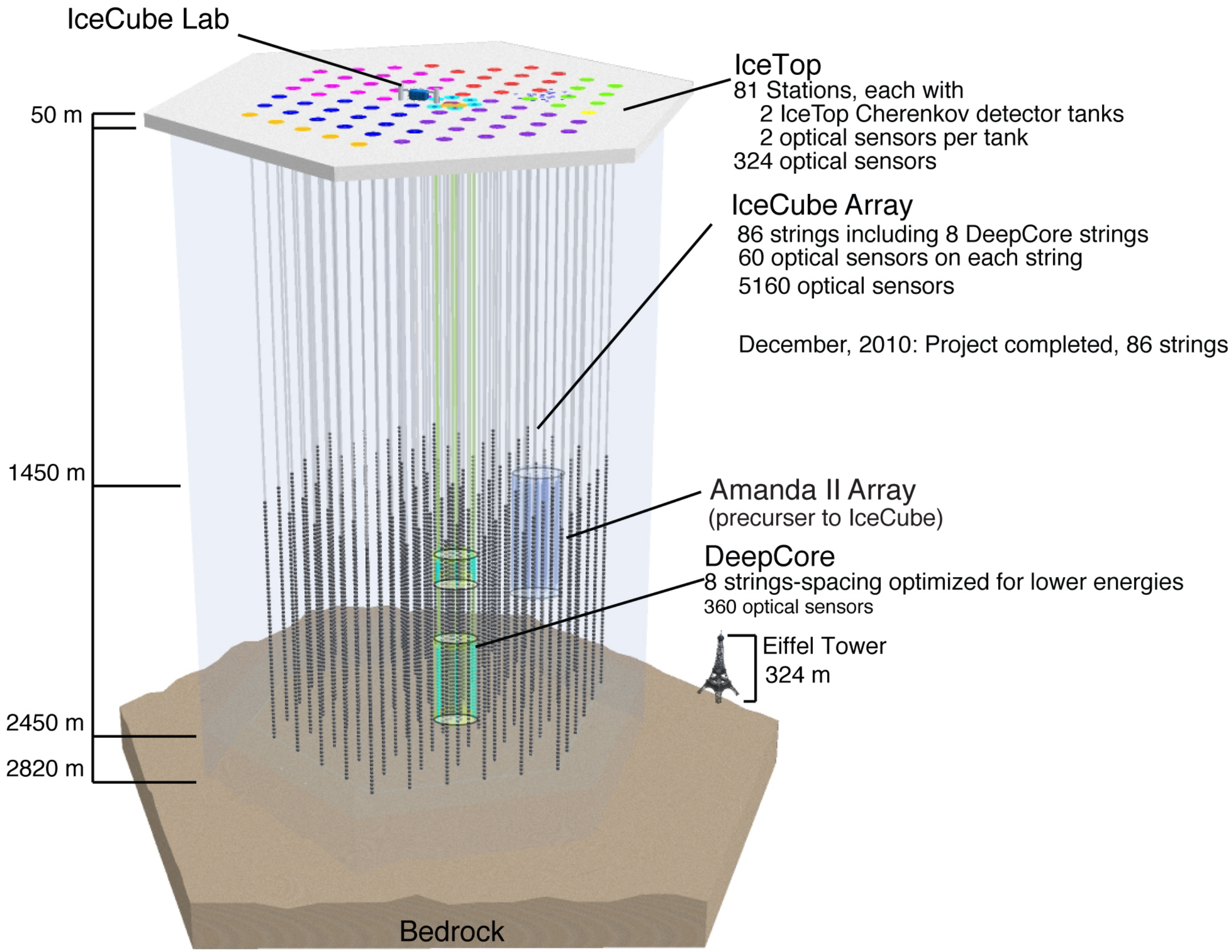
AMANDA/IceCube
South Pole

0.5 π sr instantaneous common view
1.5 π sr common view per day


Amundsen-Scott South Pole Station
runway
South Pole
AMANDA-II
IceCube

IceCube

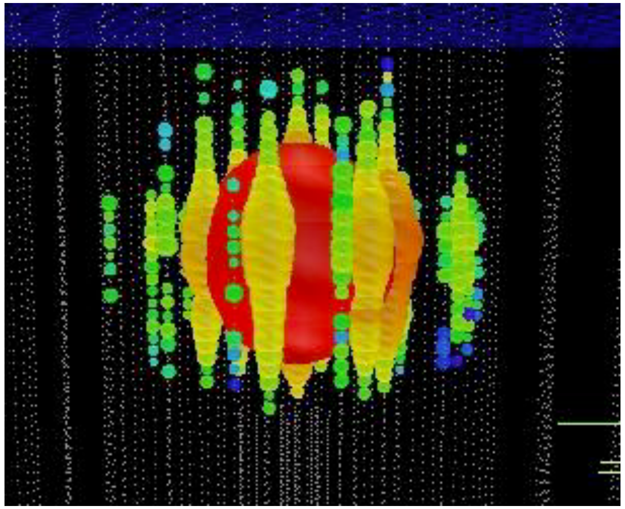
- Total of 86 strings and 162 IceTop tanks;
- Completion with 86 strings: December 2010
- Full operation with all strings since May 2011.
- 5160 DOM; ~1km^3

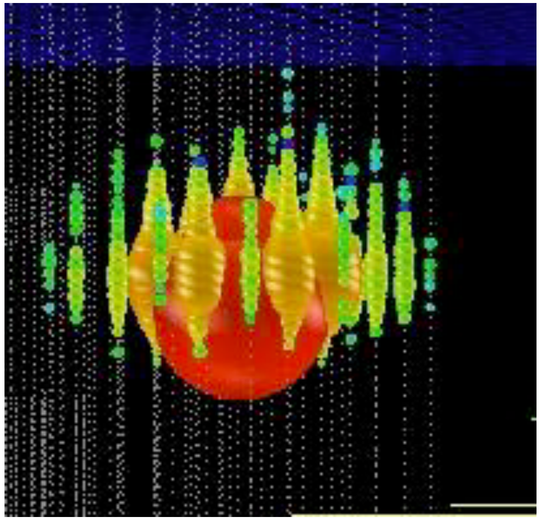


Digital Optical Modules

- 86 cables, each holding 60 digital optical modules (DOMs).
- Basic component of DOM are photomultiplier tubes + readout instrumentation
- DOMs attached to the cables at depth from 1,450 to 2,450 m.
- It took seven years (2004-2010) of work to complete the construction of IceCube.
- Average time to drill a hole for the cable was 48 h + 11 h to deploy a cable.
- IceCube frozen in optically clear ice that moves ~10 m/yr as single piece

Two events found at PeV energies





Preliminary

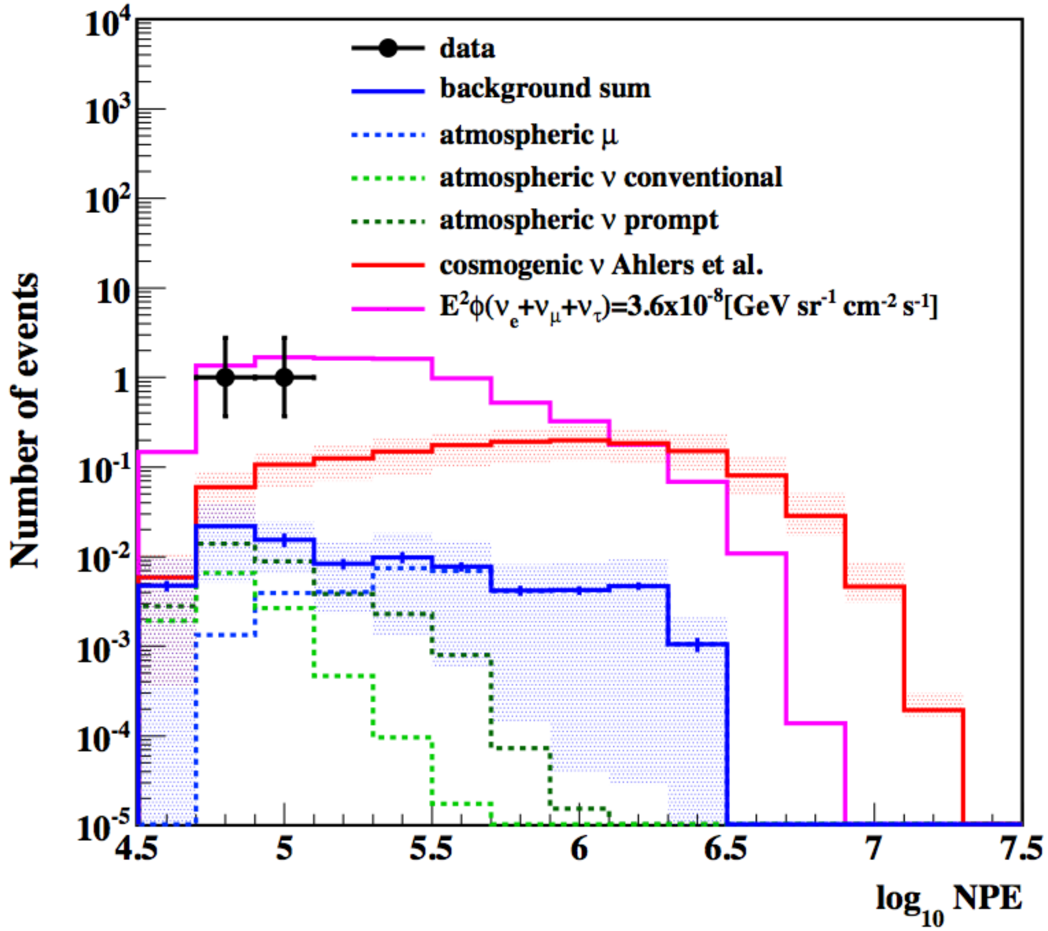
	Event 1	Event 2
date (GMT)	August 8, 2011	January 3, 2012
Number of Photoelectrons	7.0×10^4	9.6×10^4
number of recorded DOMs	312	354
reconstructed energy	1.0 ± 0.2 PeV	1.1 ± 0.2 PeV
reconstructed z vertex	121.8 m	24.6 m

Error on vertex position: ~ 5m

PeV Events Compared to Models

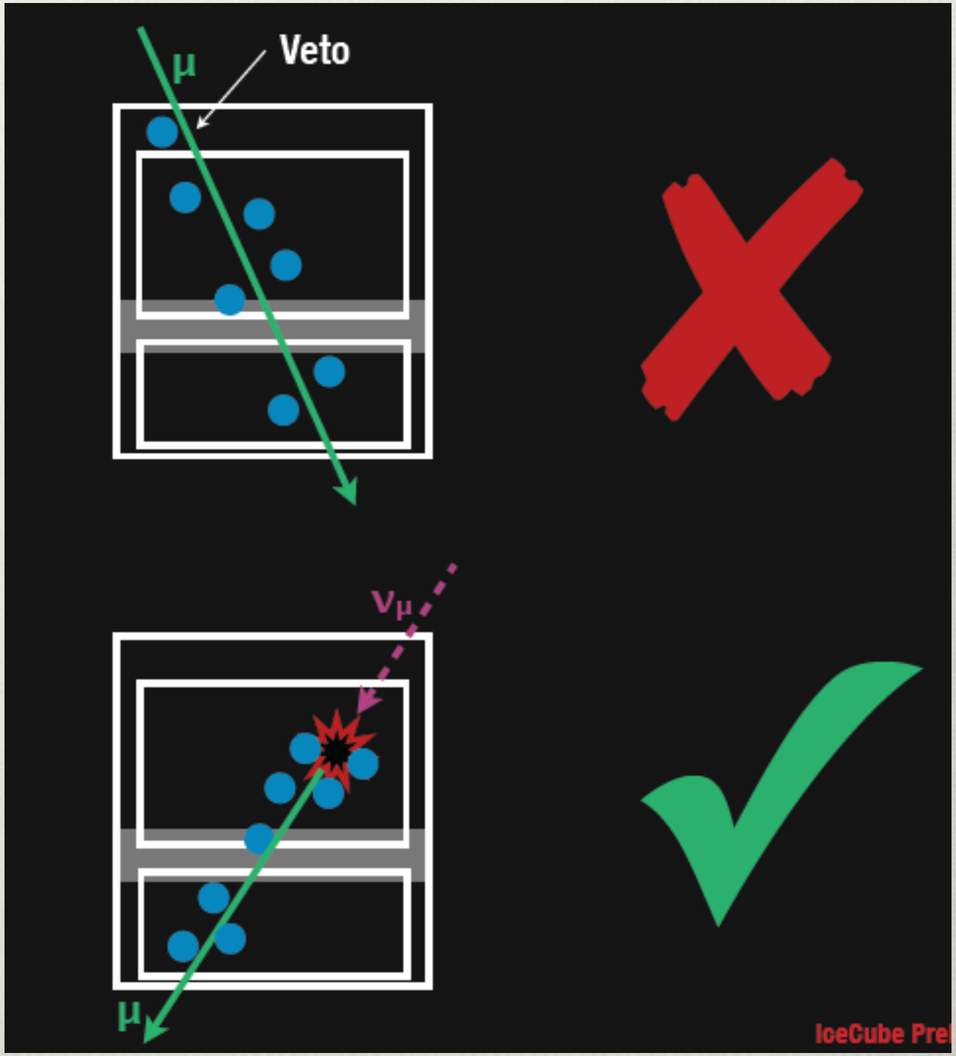
The two events are

- Not muon background (cascades)
- Difficult to explain as conventional atmospheric origin. (2.7σ tension to conventional atmospheric neutrino flux)
- Compatible with the diffuse E^{-2} limit, but such a spectrum would also predict additional events at higher energies.
- Seeing two such events would be relatively surprising for GZK fluxes which peak at higher energies.
- They are down-going, though

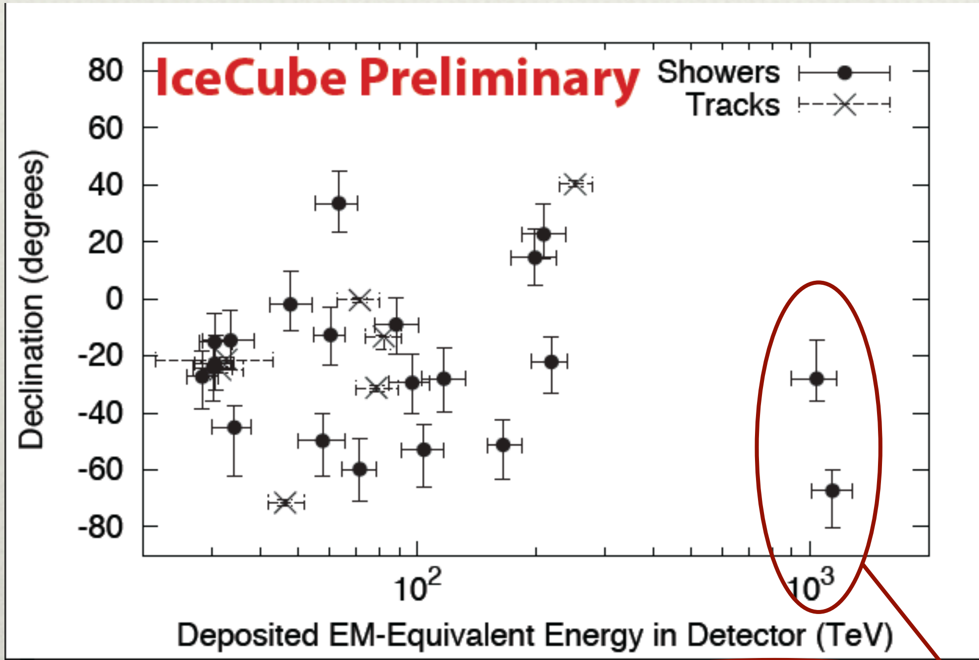


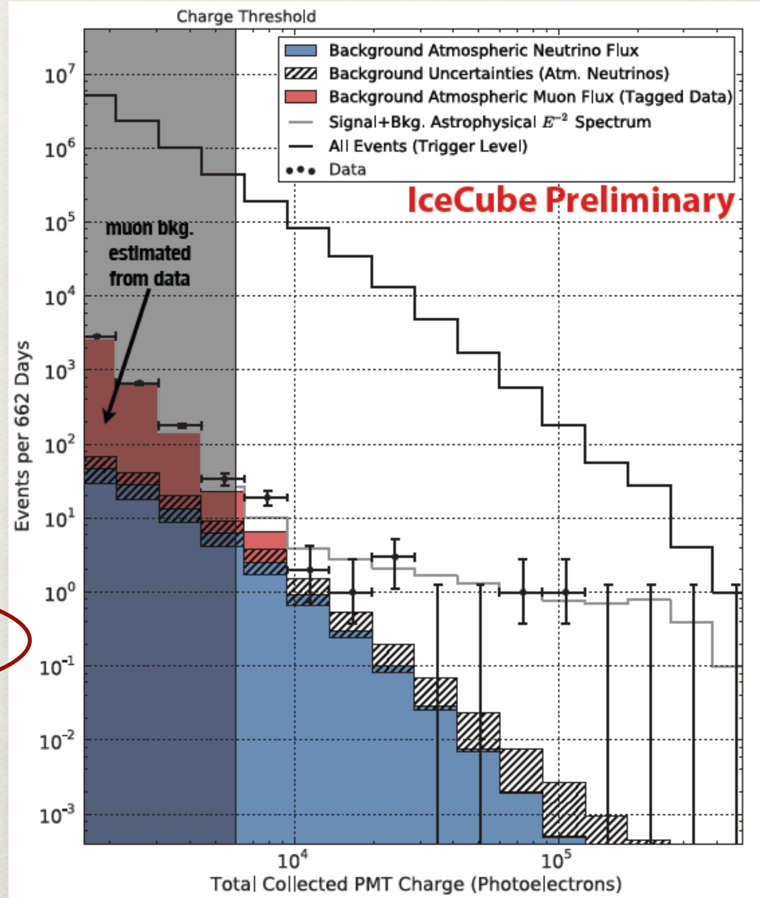
Looking for more events

- Look for events for which the neutrino interaction happens within the detector fiducial volume (400 Mton)
- Use atmospheric muon veto
- Sensitive to all flavors above 60 TeV
- Three times as sensitive at 1 PeV
- Estimate muon background from data: 6 ± 3.4 muon events per 2 years
- Atmospheric ν background decreasing with energy: $4.6^{+3.7}_{-1.2}$ events per 2 years (downward-going often produced with μ → vetoed)



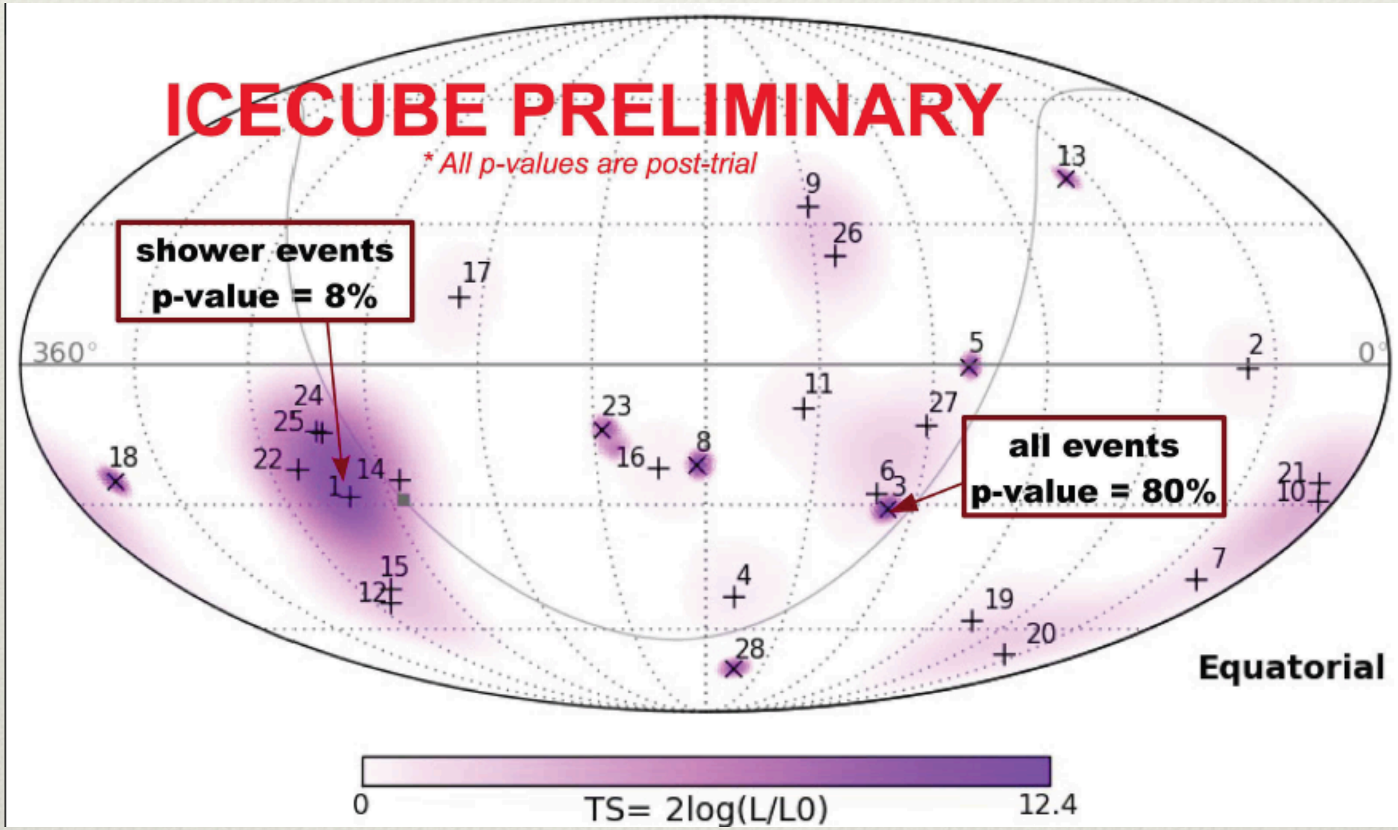
26 more events found





- 28 events observe (including Bert and Ernie); Expected background: $10.6^{+5.0}_{-3.6}$ events; Significance ~4σ
- Good agreement at low energy + high energy tail; maybe cutoff at few PeV

Where do events come from?



- No significant clustering observed
- Distribution of declination (North-South) is compatible with isotropic flux (Northern events absorbed in Earth; minor, not significant excess from South)

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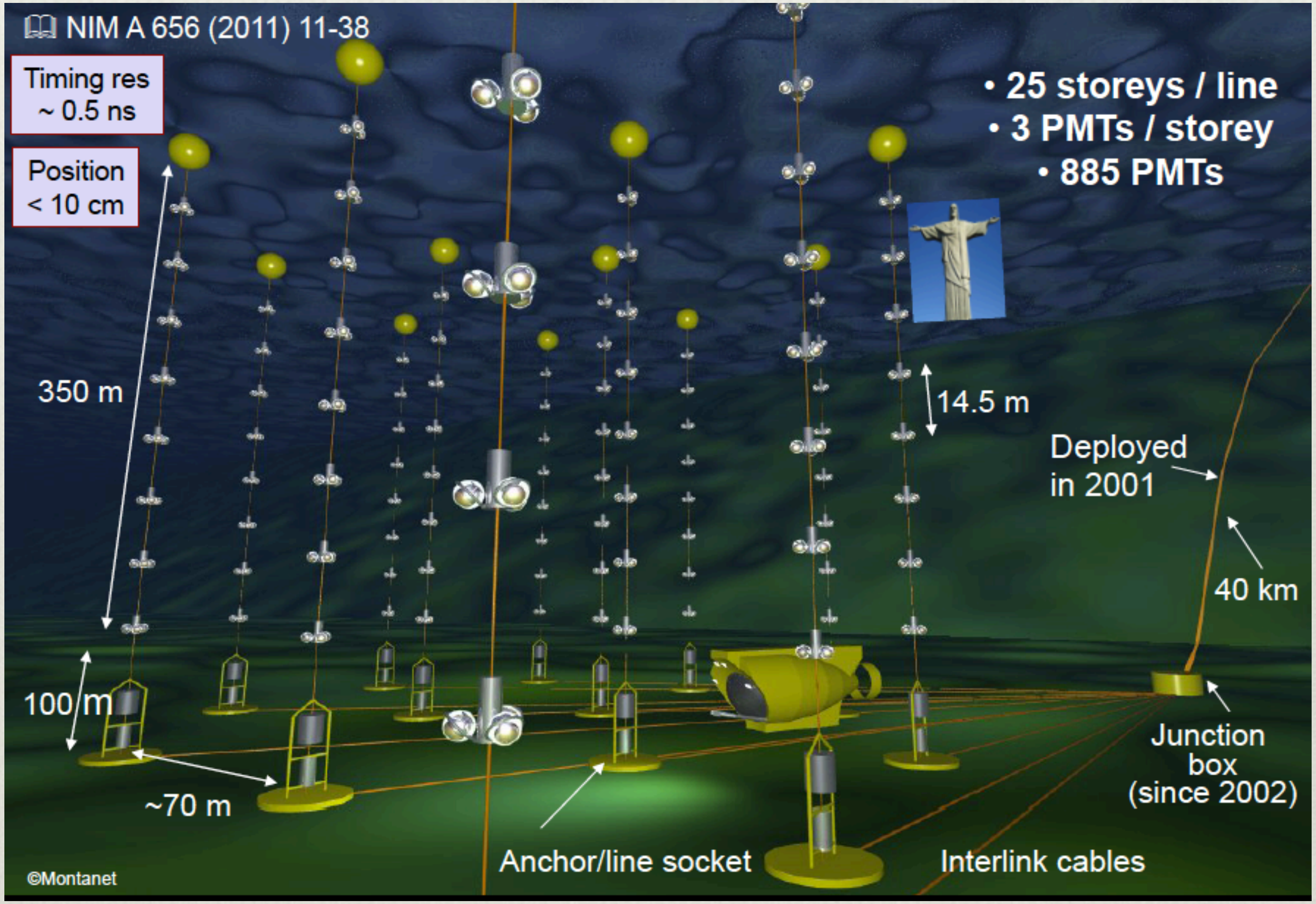


- Similar detection technique as Icecube but in Mediterranean sea (close to Marseille 43° N), 2500 m depth
- Does also very interesting Earth and Sea science

KM3NeT

A research facility in the Mediterranean Sea

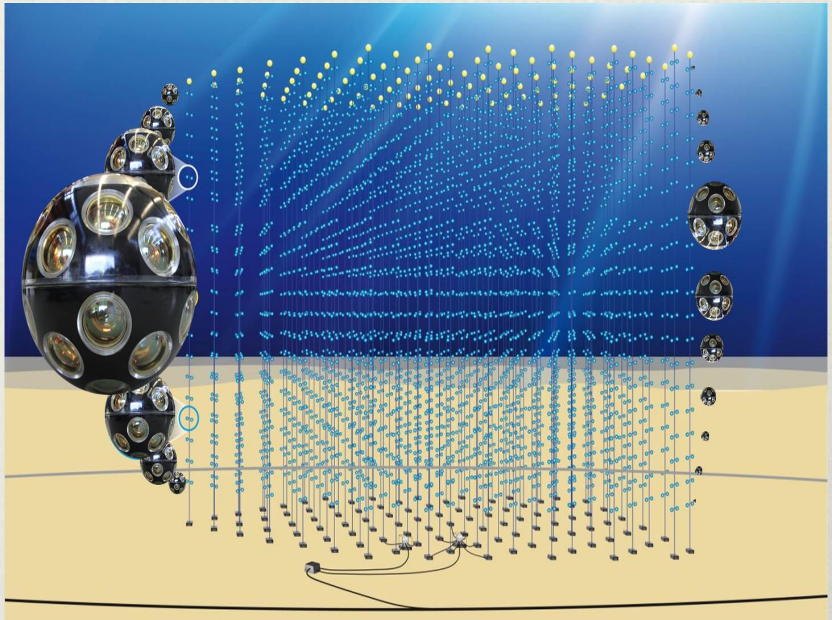
- A next generation neutrino telescope
- Cabled observatory for Earth and Marine sciences

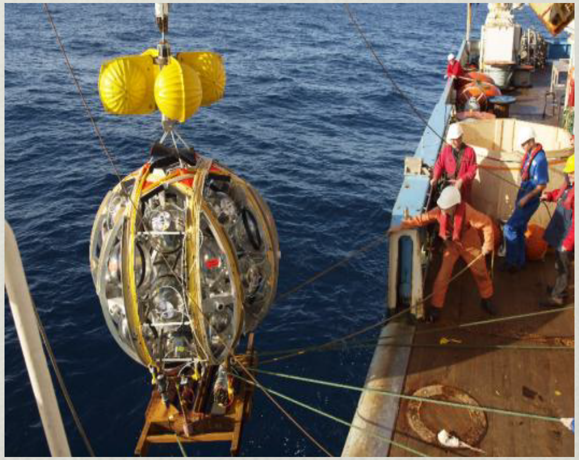
ANTARES + ΝΕΣΤΩΡ + NEMO Neutrino Mediterranean Observatory +...

40 institutes from 10 European countries

What is KM3NeT ?

- Future cubic-kilometre scale neutrino telescope in the Mediterranean Sea
- Exceeds Northern-hemisphere telescopes by factor ~50 in sensitivity → new look into Galactic Center region
- Exceeds IceCube sensitivity by substantial factor
- Focus of scientific interest: Neutrino astronomy in the energy range 1 to 100 TeV
- Provides node for earth and marine sciences





Other detection techniques

- Radio:
  - Coherent radio emission from excess negative charge in an EM shower (similar to Cherenkov effect)
  - e- upscattered into shower, e+ annihilated 20% -ve asymmetry
  - "Shower" is actually a thin disk of HE particles
  - Produced in dielectric medium: eg, ice, Moon regolith
- Acoustic:
  - A pressure wave is generated instantaneous following a sudden deposition of energy in the medium
  - Thermo-acoustic process
    - Increase of temperature,
    - Volume Expansion
  - Neutrino Interaction (strong Earth absorption: look upward)

Epilogue: an alternative definition

- **Astroparticle Physics** is a new and fascinating research field in blooming expansion, that tries to understand the most extreme, violent and energetic phenomena in the Universe, using detectors and telescopes of enormous dimensions using cutting-edge technologies and placed in the most extreme and remote (and interesting) places on Earth.

Manel Martínez (IFAE)