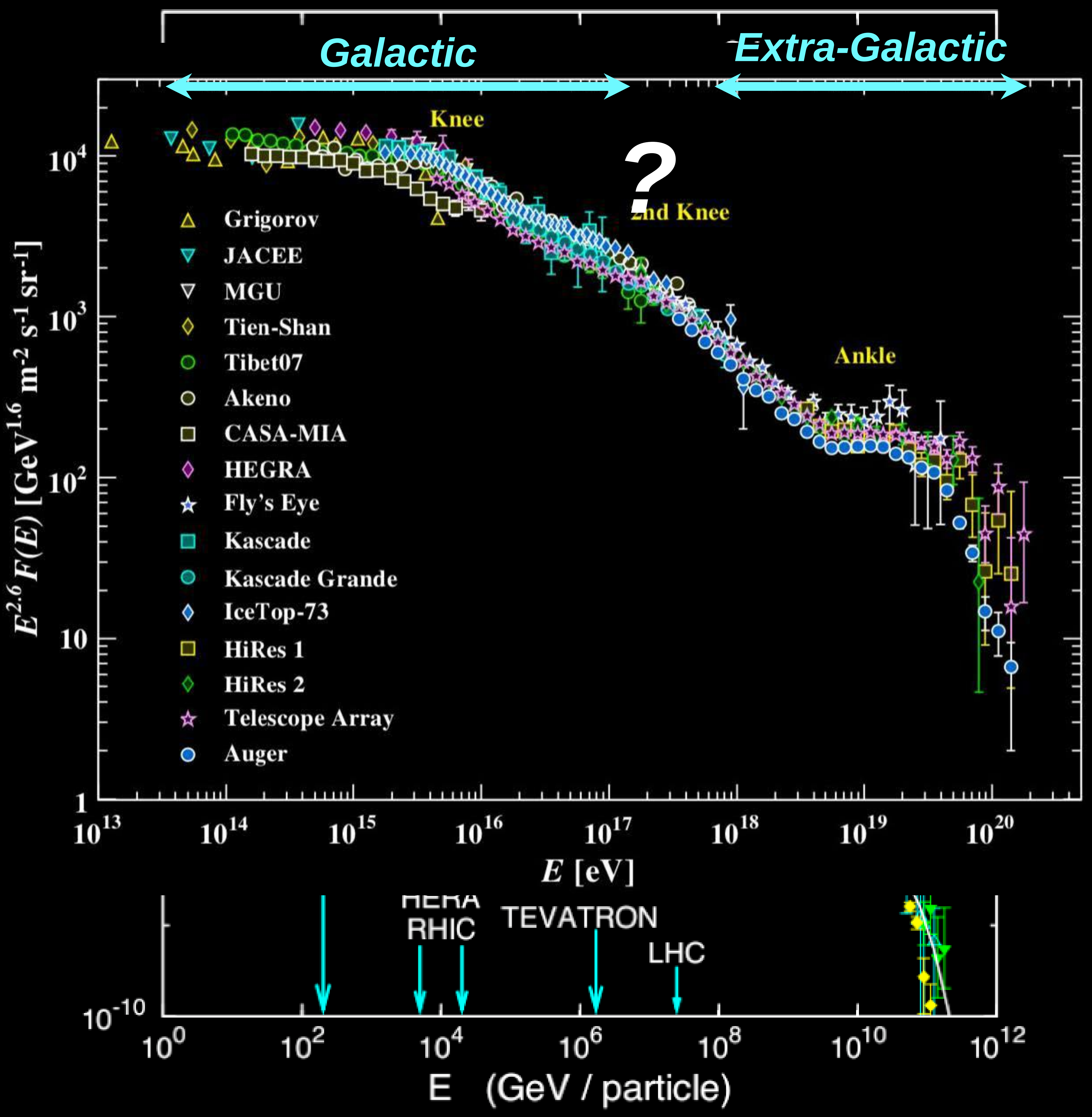
CTA & future astroparticle experiments

D. della Volpe

LHC days 2018,

Split 17-22 September 2018

The cosmic rays - what we know



- The all particle spectrum $\phi_{CR} \sim E^{-2.6}$
  - span over 20 order of magnitude with an exponential decrease of about 10^{30}

$$E_{max} \approx 10^{18}\ eV \times Z \times \left(\frac{R}{kpc}\right) \times \left(\frac{B}{\mu G}\right)$$

  - They propagate through the
    - ISM -InterStellar Matter (ISM)
    - IGM - InterGalactic Magnetic (IGM)
    - CMB (Cosmic Microwave Background)
    - EBL Extragalactic Background Light
  - Acceleration and propagation folded!
  - Below ‘knee’ are galactic, above extragalactic

The main driving force for VHE γ-ray astronomy was initially the search for the sources of the charged cosmic
Now, after the discovery of many sources, the interests have shifted to general astrophysics questions.

γ-rays can be produced in both leptonic and hadronic processes
neutrinos are produced only in hadronic processes and are weakly interacting

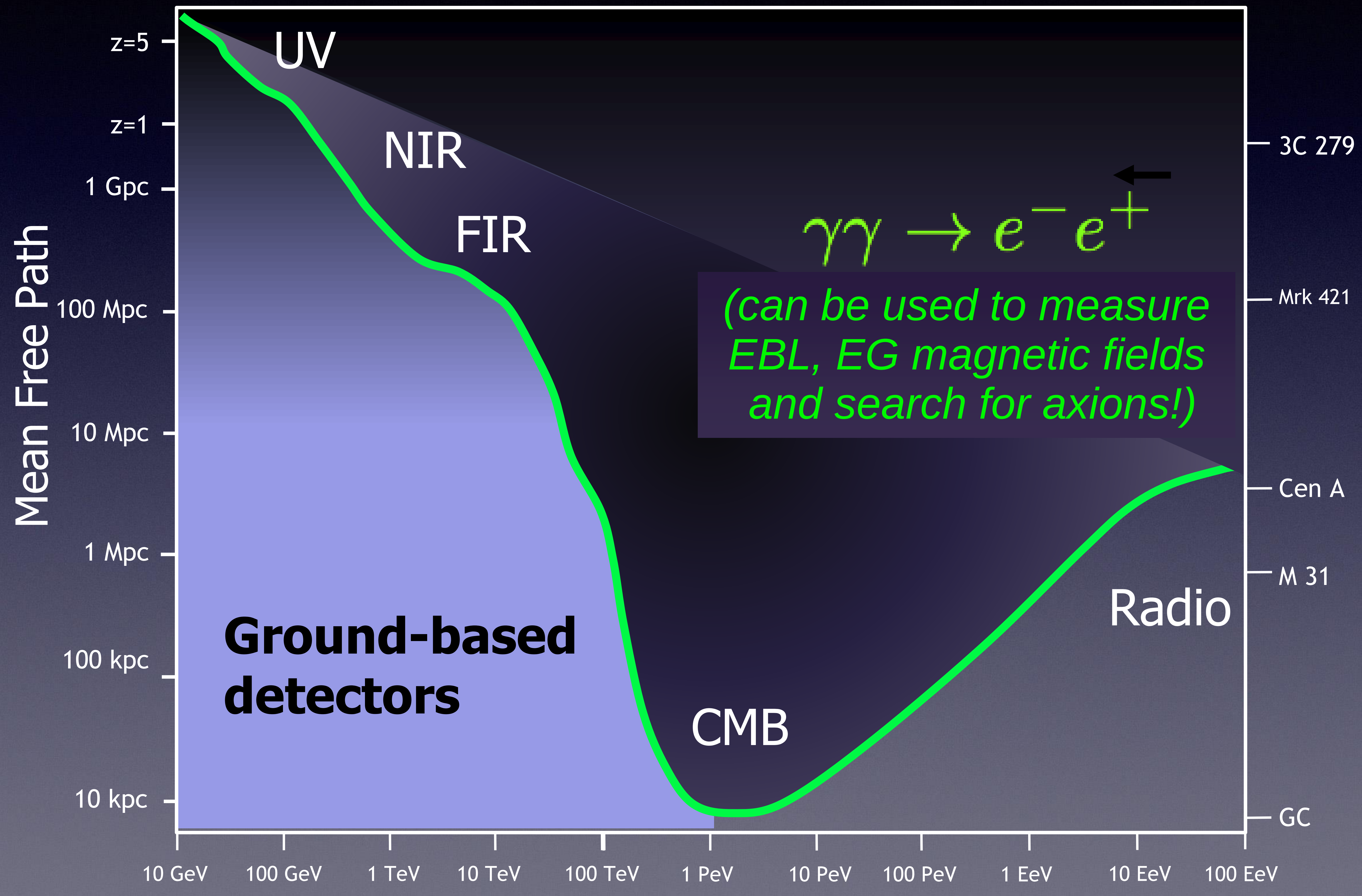
The cosmic rays - what we don't know

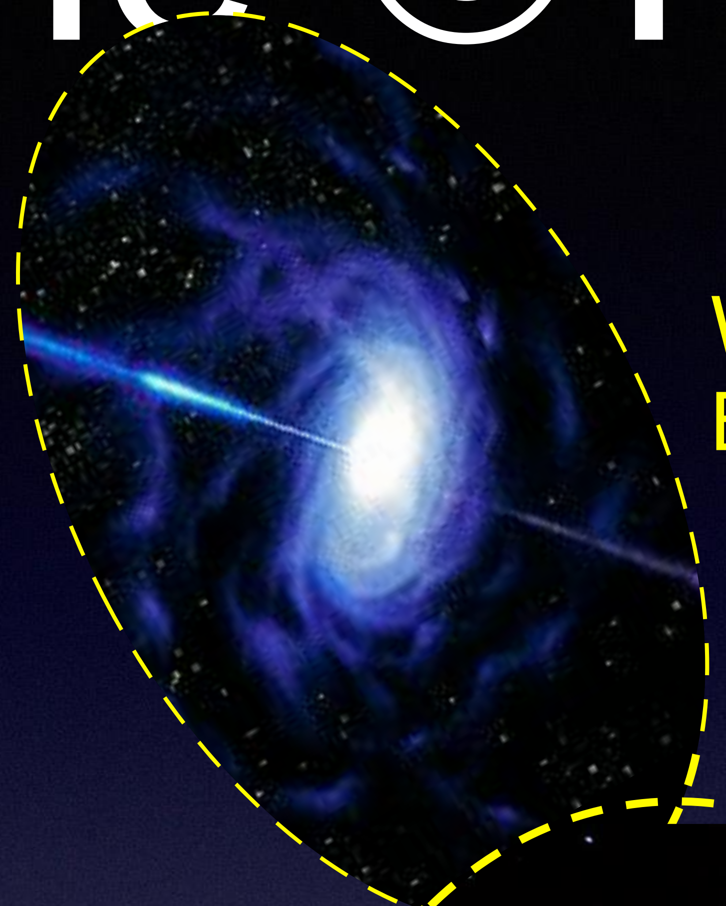
- Who accelerates to PeV (Pevatrons)? SNR, AGNs, PWNe?
- How particle are accelerated?
  - hadronic process or ($\boldsymbol{\gamma}$ - $\boldsymbol{\nu}$ connection)
  - leptonic process?
- What is the origin of the 'knee' ?
  - locally detected nonthermal/relativistic particles - a "local fog"
  - a more fundamental issue ,
    - in the end CRs are the 4th substance of the visible Universe (after the matter, radiation and magnetic fields) -
- GKZ cut-off for E>10^{20} eV?

What do we need ?

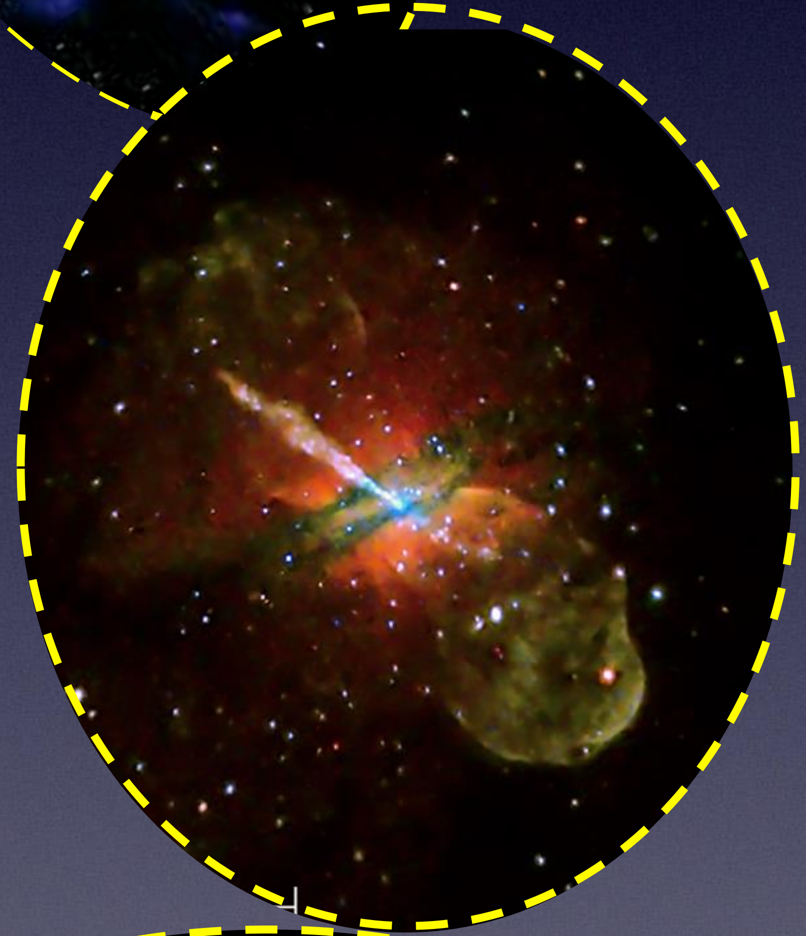
- Survey sky
  - Large FoV/Aperture , high duty cycle
- Find Source
  - Pointing precision, High resolution, high sensitivity , cover a broad energy range
- Study acceleration mechanics
  - Multimessengers, High energy (<10 TeV)
- Understand the Knee - study composition charged cosmic rays (~PeV)
- GZK cut-off 10^{22} eV

How far can we see: the ©Horizon

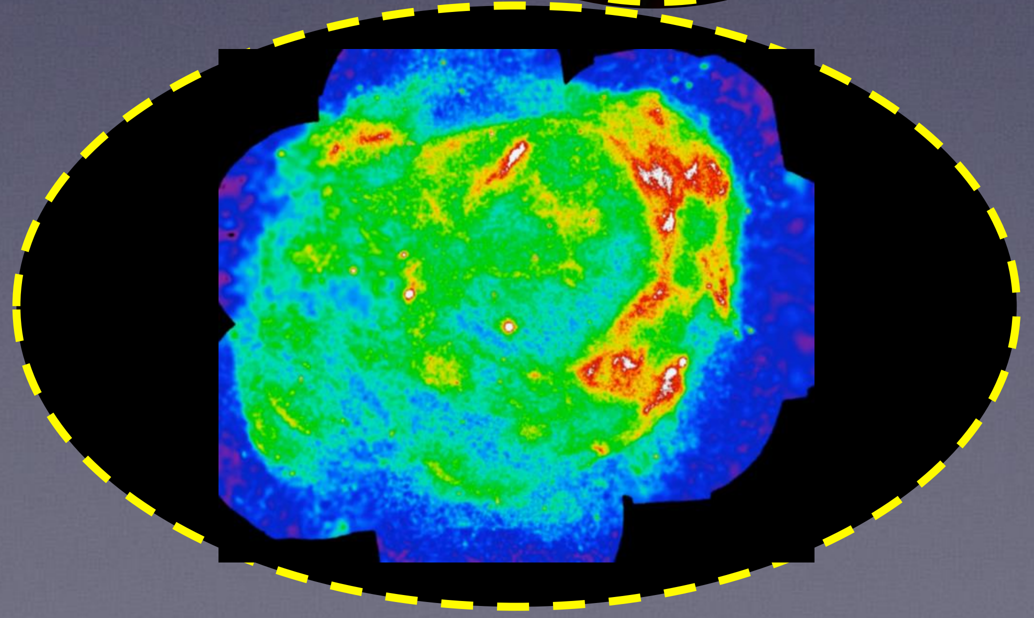




Whole universe visible
Beamed sources, time variability



Precision study of local EG sources, resolved morphology



Precision study of Galactic CR sources, up to the knee

What we can learn from gamma-ray

Gamma ray flux composition (0.1-1000 GeV)

superposition of resolved point and diffuse sources, and of background diffuse emission of galactic/extragalactic origin

E & ang. res, E range and threshold,
n. of telescopes, waveform

Stability of PSF over FoV
Large FoV, Duty Cycle

$$\phi_\gamma(E,\Omega) = \sum_{j\in\{\text{Galactic}\}} \phi_j(E,\Omega_j) + \phi^{\text{Galactic}}_{\text{diffuse}}(E,\Omega)$$

$$+ \sum_{j\in\{\text{Extragalactic}\}} \phi_j(E,\Omega_j) + \phi^{\text{Extragalactic}}_{\text{diffuse}}(E,\Omega)$$

$$\phi^{\text{Extragalactic}}_{\text{diffuse}}(E,\Omega) = \phi^{\text{Extragalactic}}_{\text{unresolved sources}}(E) + \phi^{\text{Extragalactic}}_{\text{diffuse}}(E,\Omega)$$

Extended Air shower

Atmosphere is a calorimeter

1st Interaction:

$z_0 = RT/gM = 8.4\ km$

$X_0 \simeq 37\ g/cm^2$

$\lambda_{pair} = 9/7\ X_0 \simeq 50\ g/cm^2$

$X = X_A\ e^{-z/z_0}$ and $X_A \simeq 10^3\ g/cm^2$

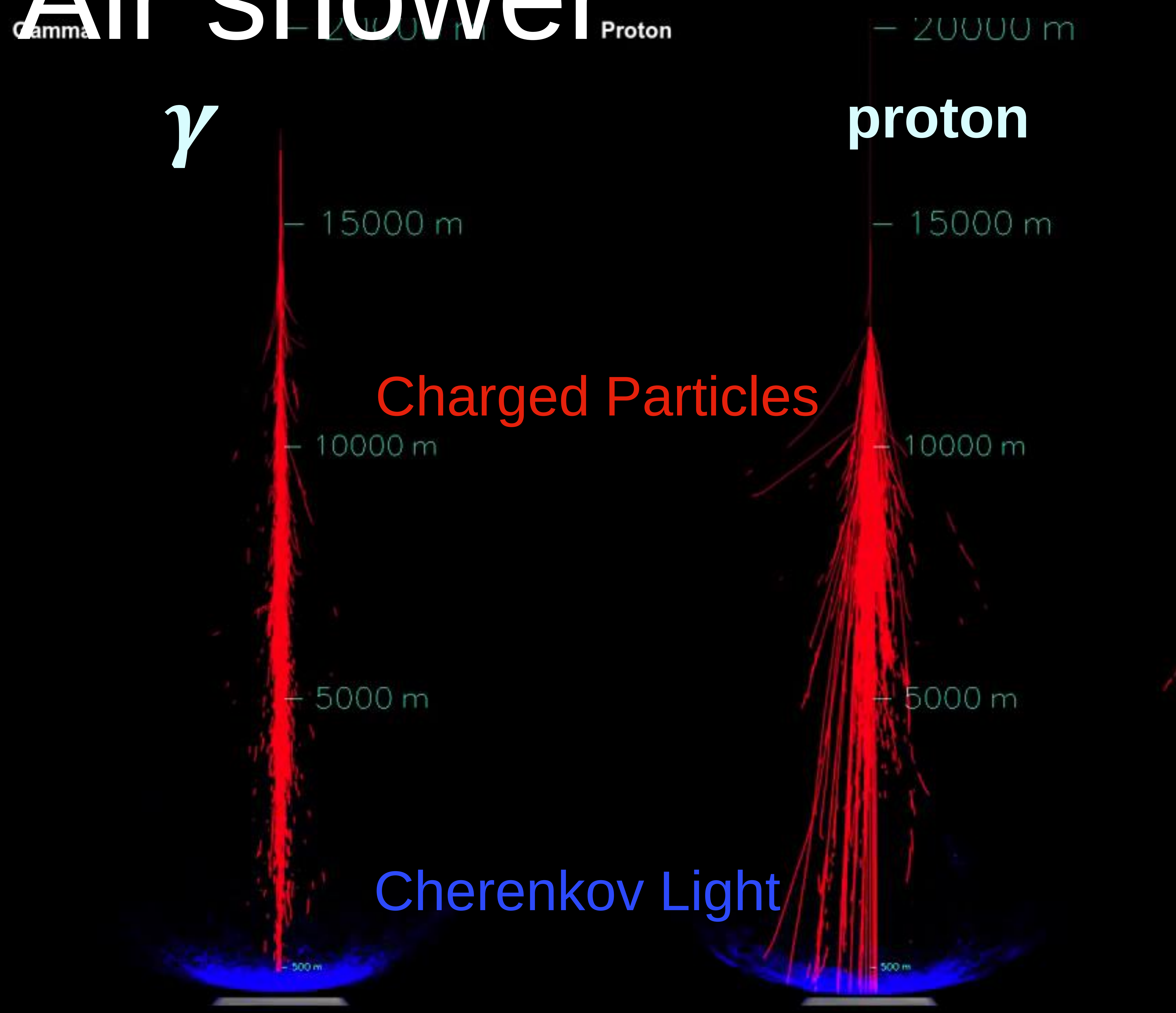
$z_{pair} = z_0 \ln(X_A/\lambda_{pair}) \rightarrow 25\ km$

"Shower Max"

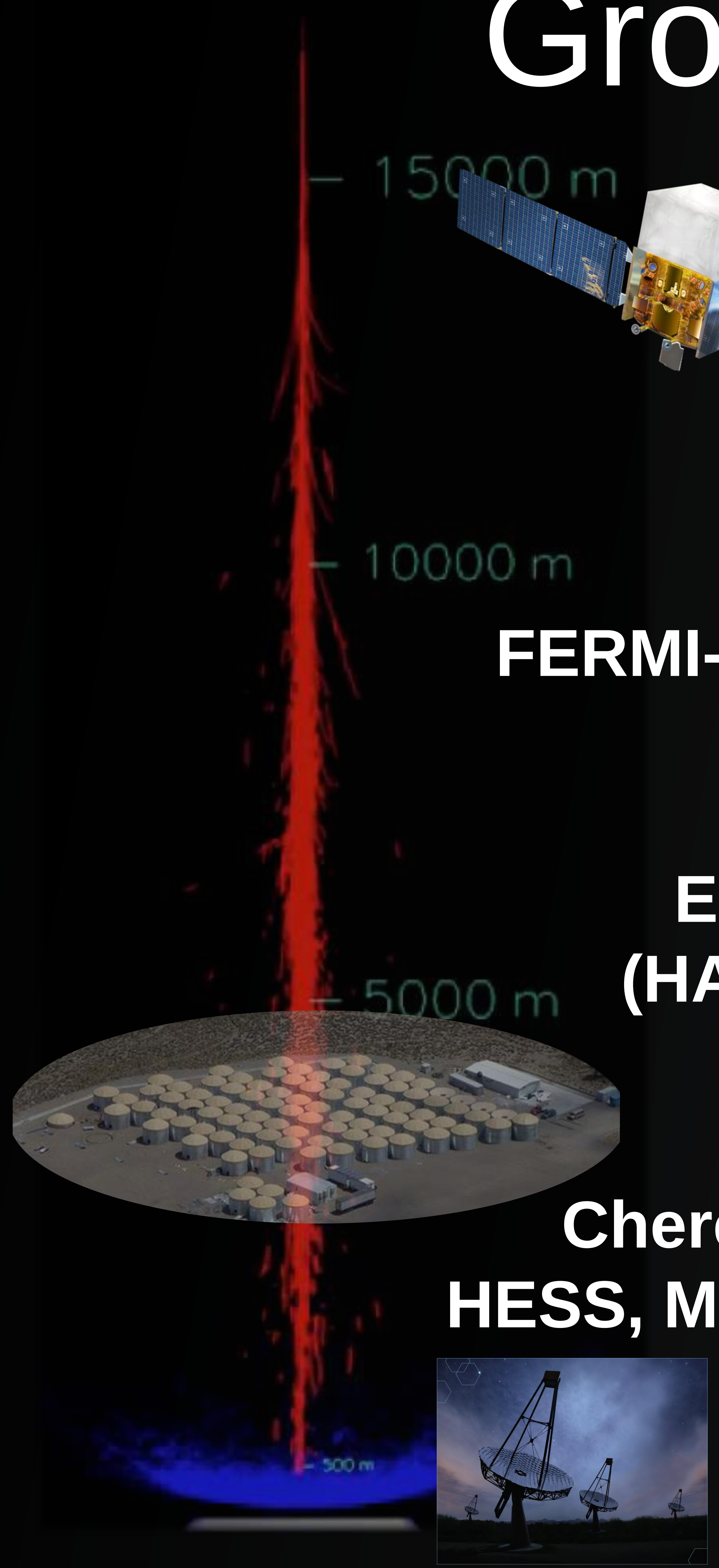
For $E = 1\ TeV$ ($E_C \simeq 80\ MeV$)

$X_{max} \simeq X_0\ \ln(E/E_C) / \ln 2$

$z_{max} = z_0 \ln(X_A/X_{max}) \rightarrow 5\ km$



Ground Base γ-ray Astronomy



Satellite
FERMI-LAT, AMS, DAMPE

EAS Detectors
(HAWC, LHAASO)

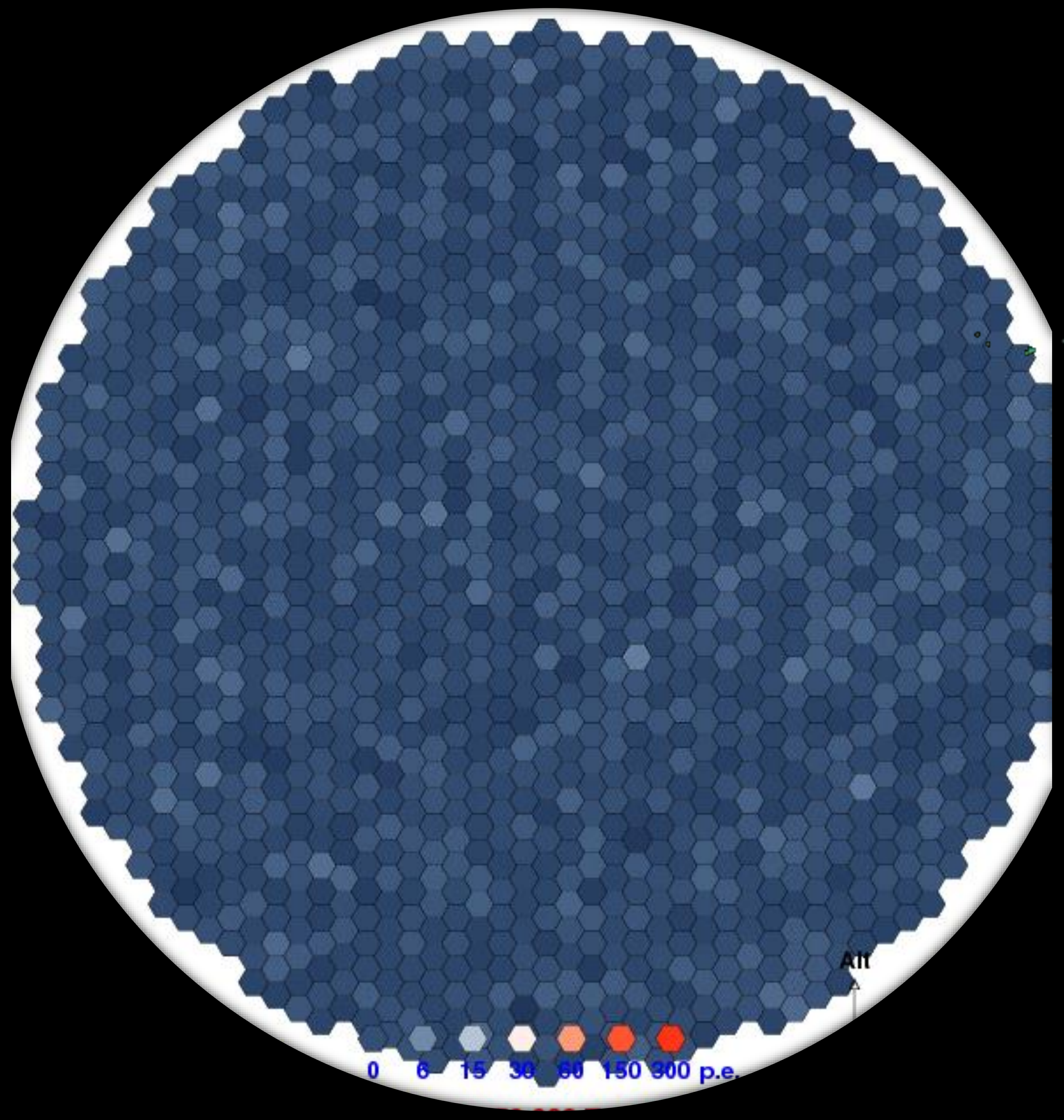
Cherenkov Telescope
HESS, MAGIC,VERITAS, CTA

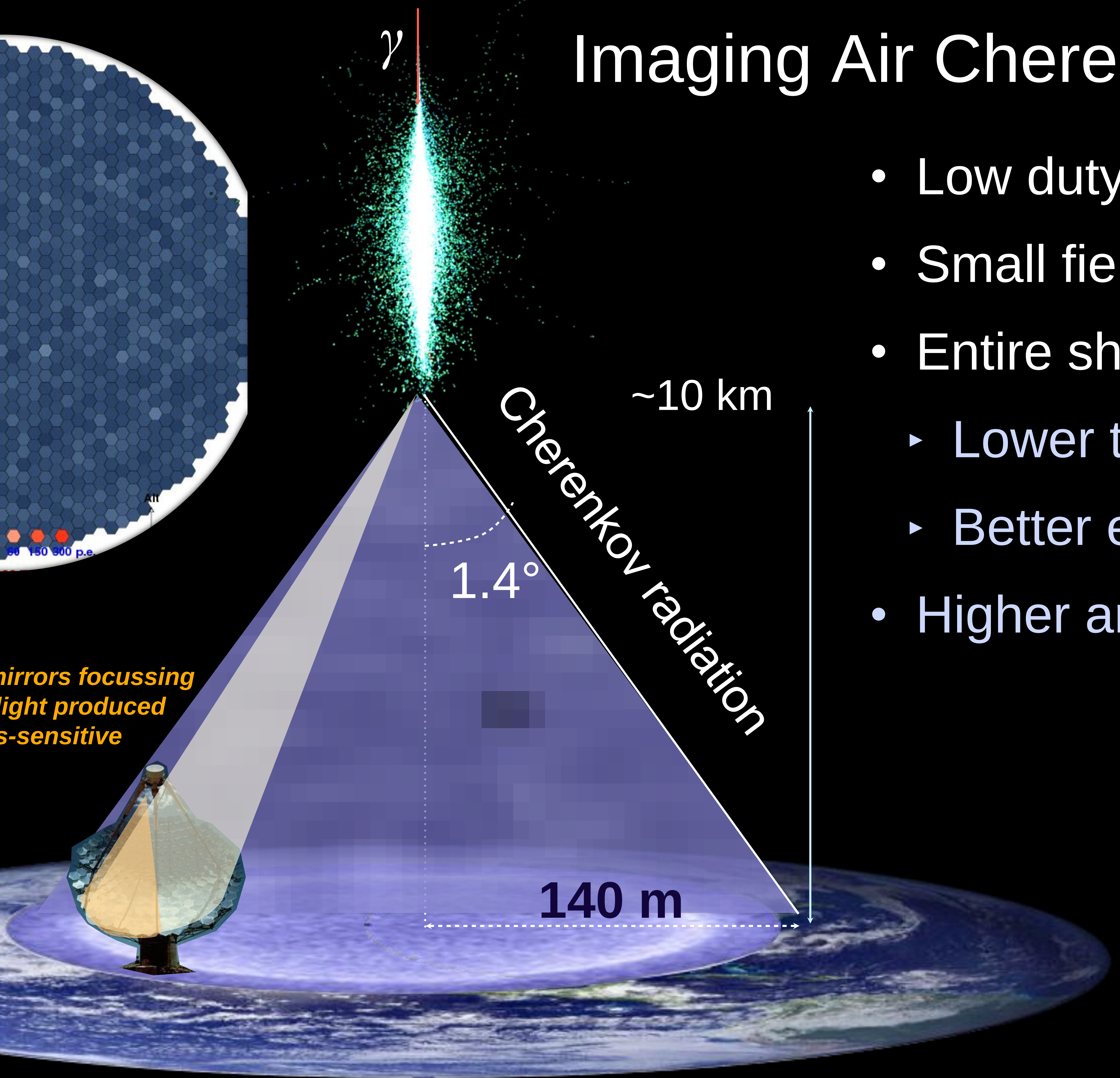
	EAS-D	IACT
Duty-Cycle	High (≈100%)	Low (≈10-15%)
Field-of-View	Large (2 sr)	Small (4-5 deg)
Sensitivity	Good Sensitivity (5-10% Crab flux)	High Sensitivity (< mCrab flux)
Maximum Energy	~ PeV	<100 TeV
Energy Resolution	Modest (~30-40%)	Very Good (~15%)
Energy Threshold	High (~TeV)	Very Low (~10 GeV)
Angular resolution	Good (0.2-0.8 deg)	Excellent (≈0.05 deg)
Effective Area	decrease with zenith	increase with zenith
Background rejection	Good (~80%)	Excellent (>99%)
Zenith dependence	Very Strong ($[\cos\vartheta]^7$)	Weak ($[\cos\vartheta]^{2.7}$)


VERITAS
Arizona
MAGIC II
Canary Island
LHAASO
Sichuan - China
TIBET-AS
HAWC
Mexico
CTA
North Canary Island
South Paranal -Chile
Auger
Argentina
Auger - Coihueco Fluorescence Telescope
H.E.S.S. Namibia

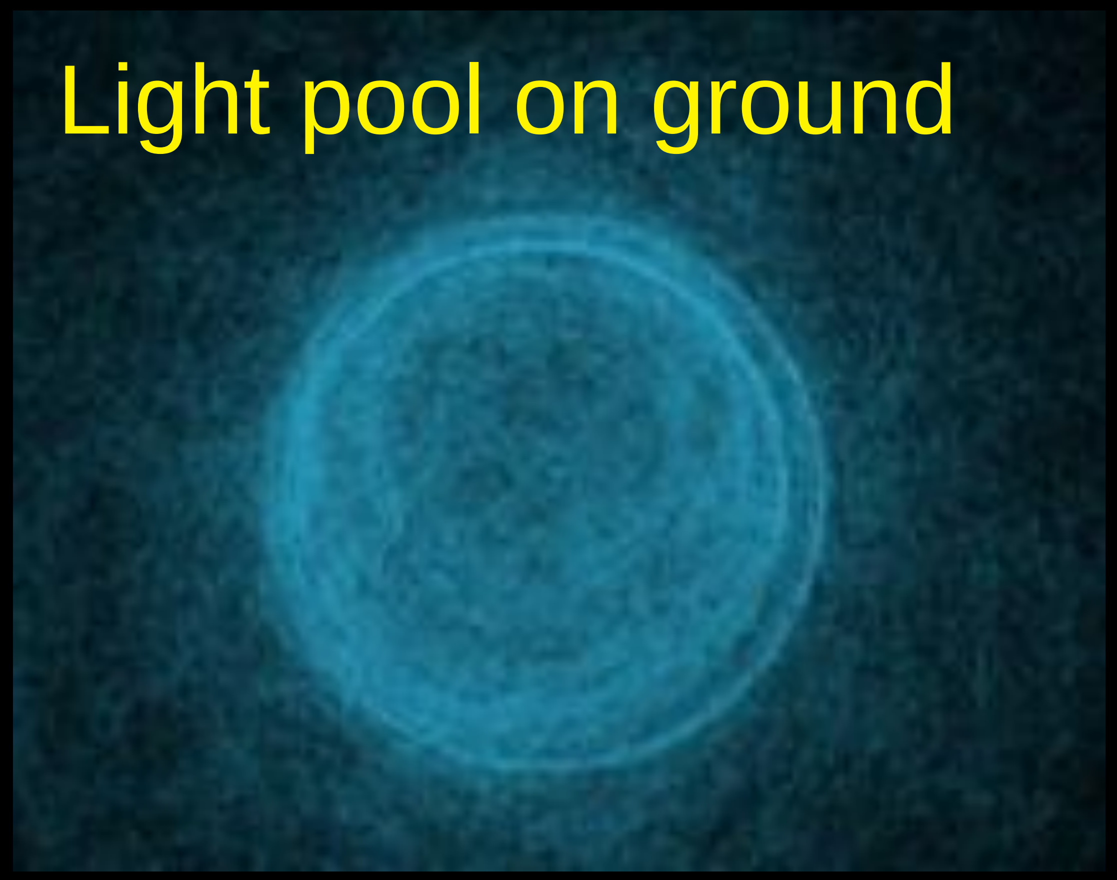
Imaging Air Cherenkov Telescope

- Low duty cycle
- Small field of view (few degrees)
- Entire shower sampling
  - Lower thresholds
  - Better energy determination
- Higher angular accuracy

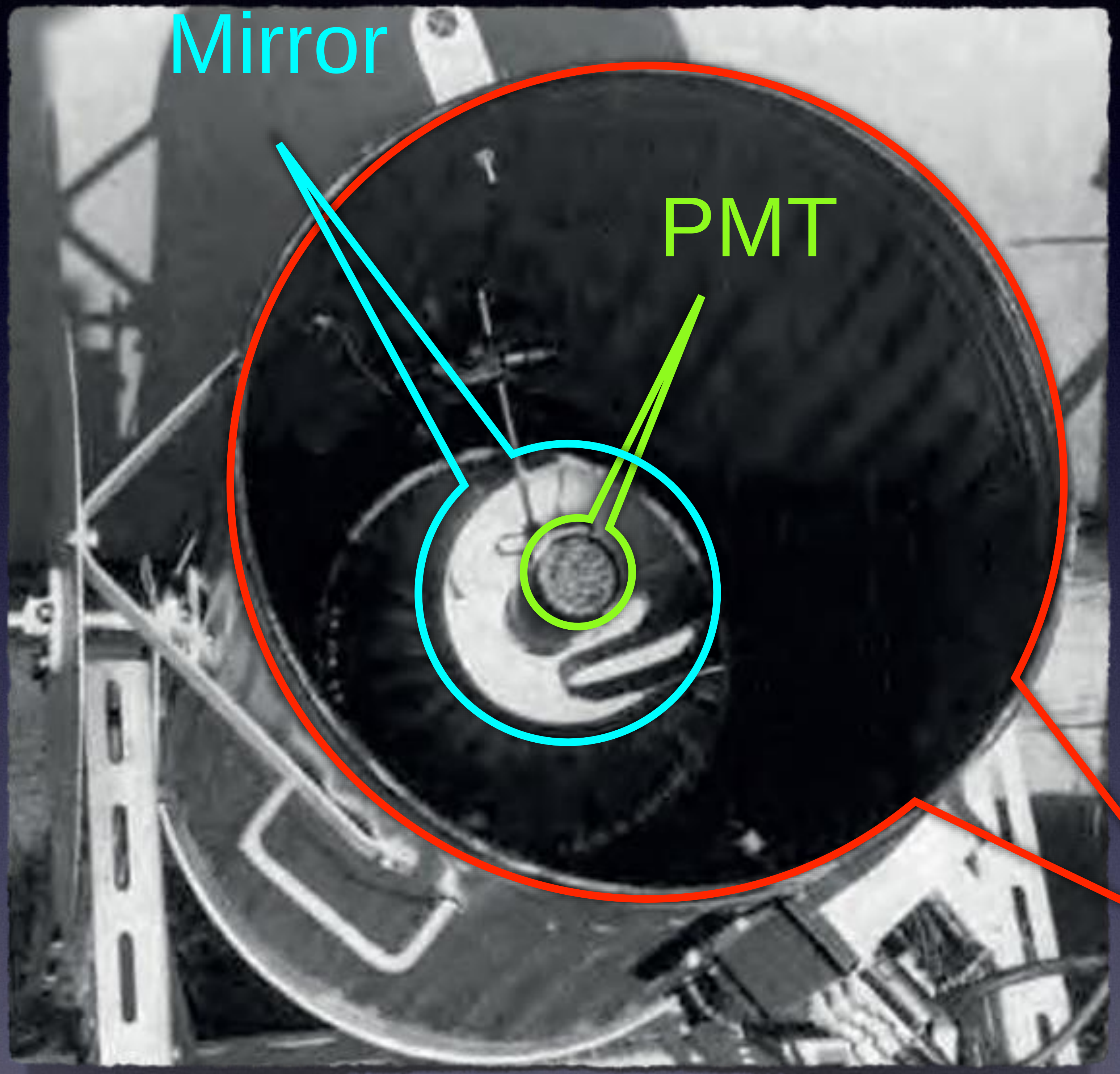


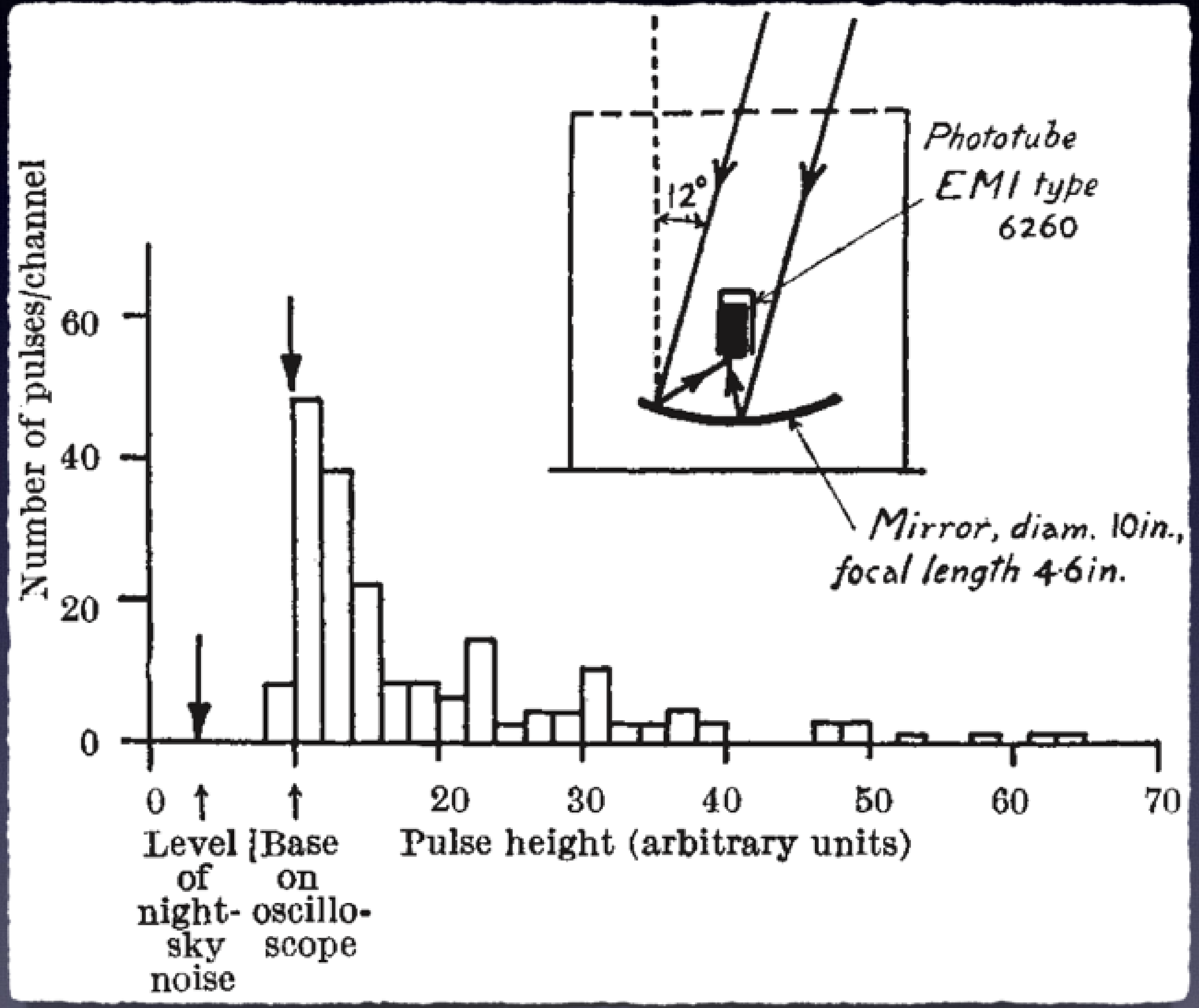


UV-optical reflecting mirrors focussing flashes of Cherenkov light produced by air-showers onto ns-sensitive cameras.



The pioneers





Galbraith, W., Jelley, J.V.. 1953, Nature,171,349
Light Pulses from the Night Sky associated with Cosmic Rays.

with a threshold 4 times higher than the NSB they measured 1 flash every 2-3 minutes

The first array Attempt

Photograph of the Crimean multi-telescope setup (Chudakov et al. 1965).

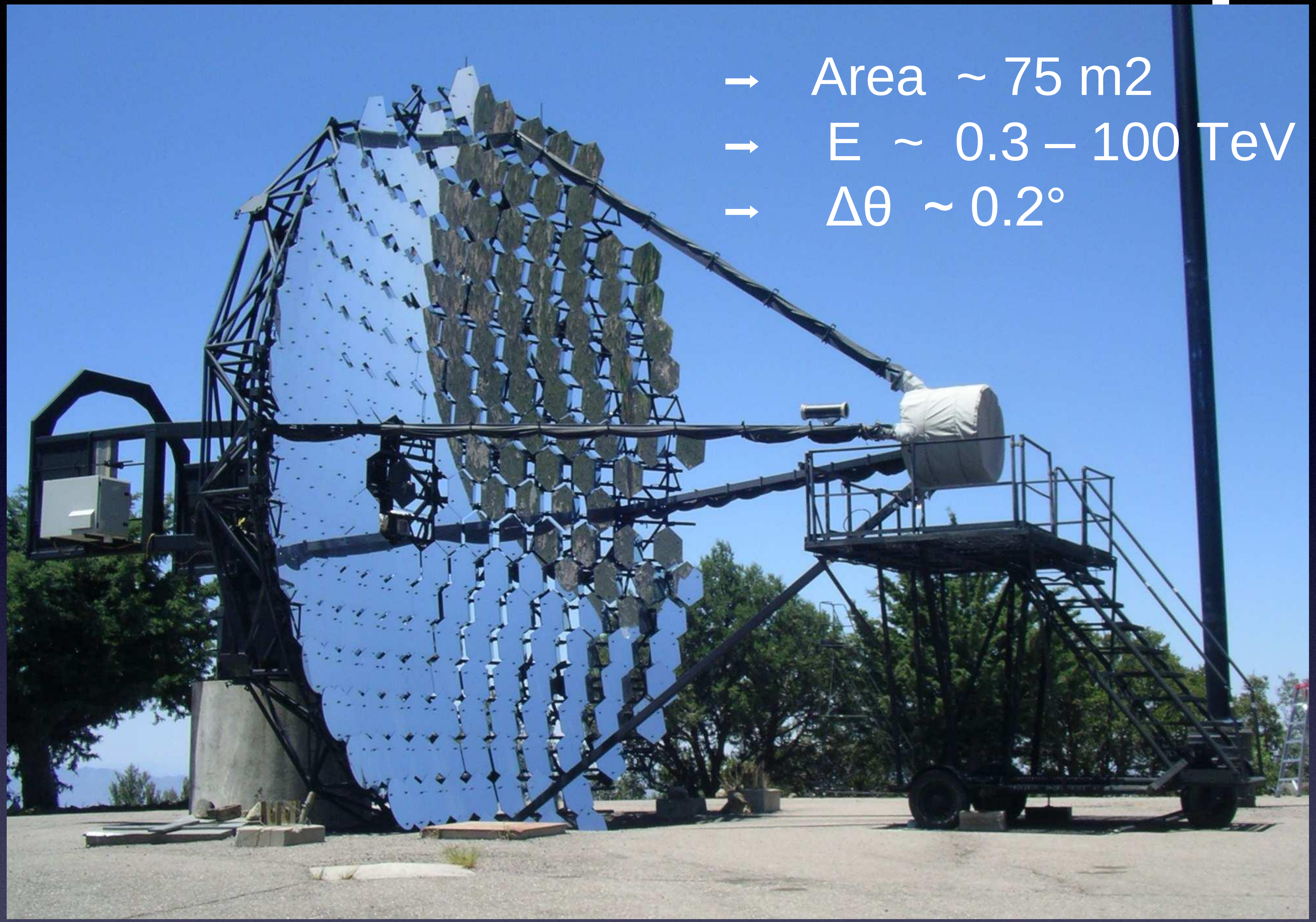
Each of those units can be positioned along a railway system
and view the air showers under slightly different angles.

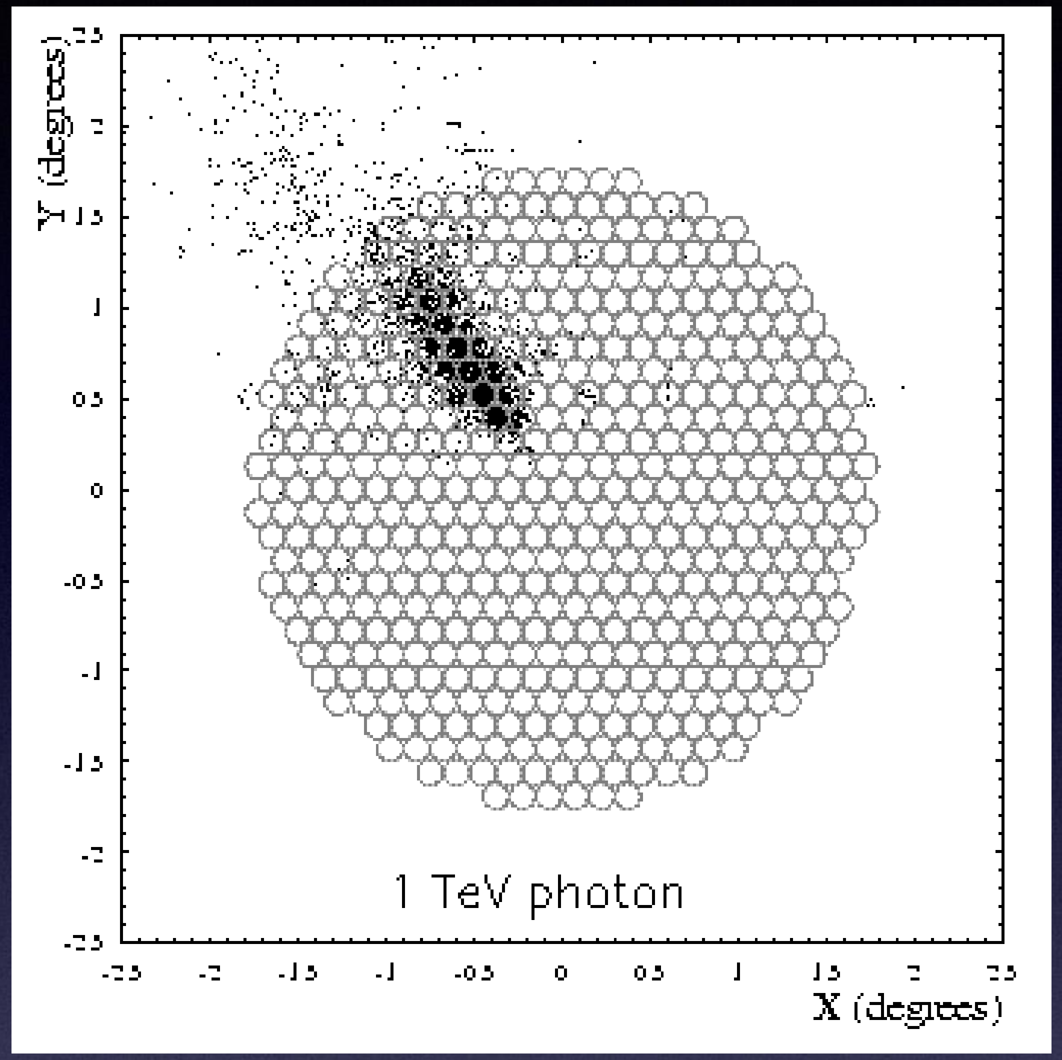
This arrangement allowed both coincidence measurements and simple multi-telescope observations.

The system was used from 1960 until 1963 but unsuccessfully. Why?

High background rate due to hadronic showers (about a factor of 10^3 more than gammas).
Light contamination from NSB, moon, stars.

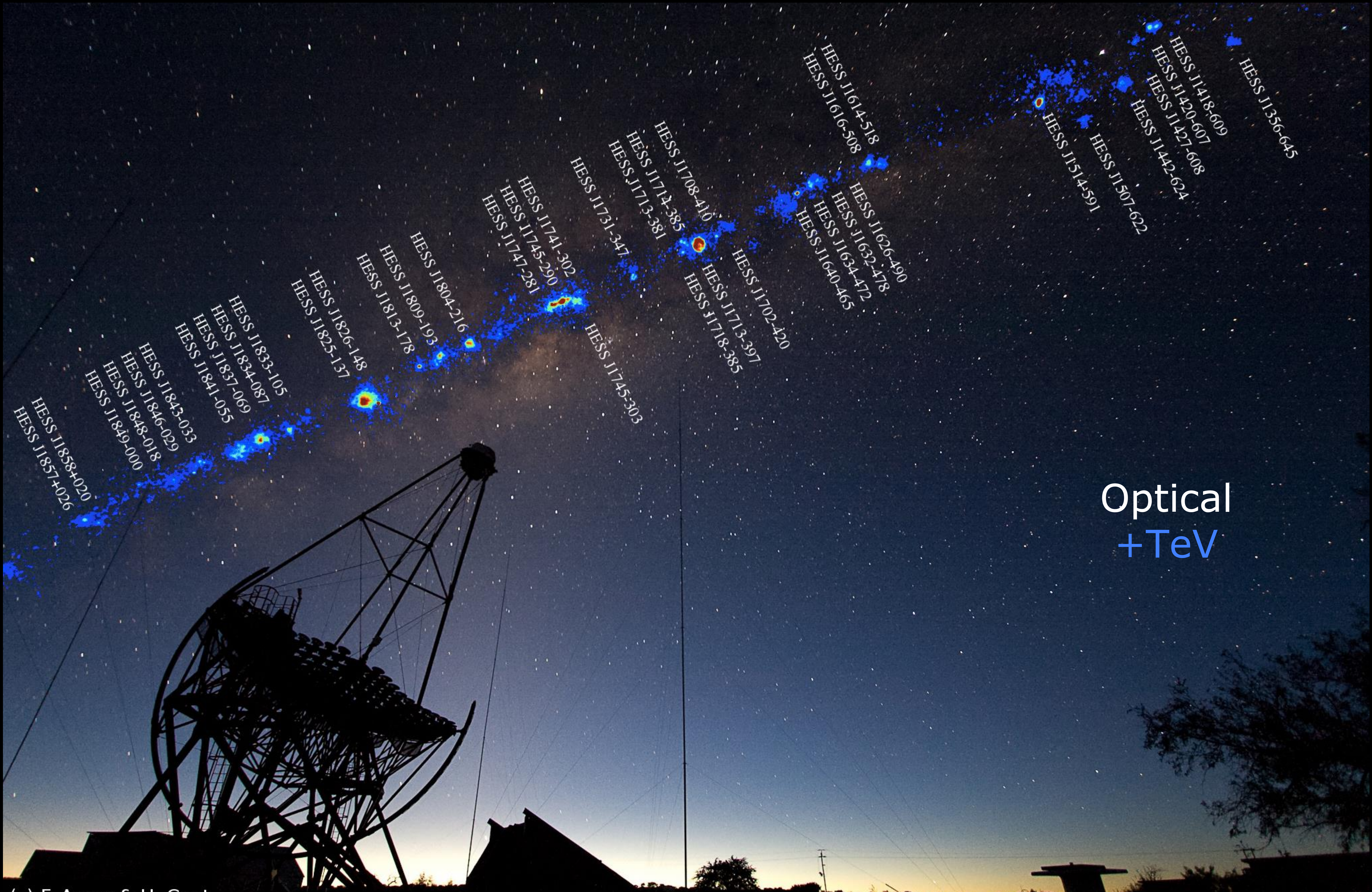
The Whipple telescope





The keys of success

- Large light collection area and imaging camera (37 PMTs) covering a field of view of 3.5 degrees
- A significant of effort to improve the analysis and gamma/hadron discrimination methods, based on image first and second moments 3 commonly known as Hillas parameters
- Focused on Crab Nebula …strongest steady state gamma-ray emitter!!

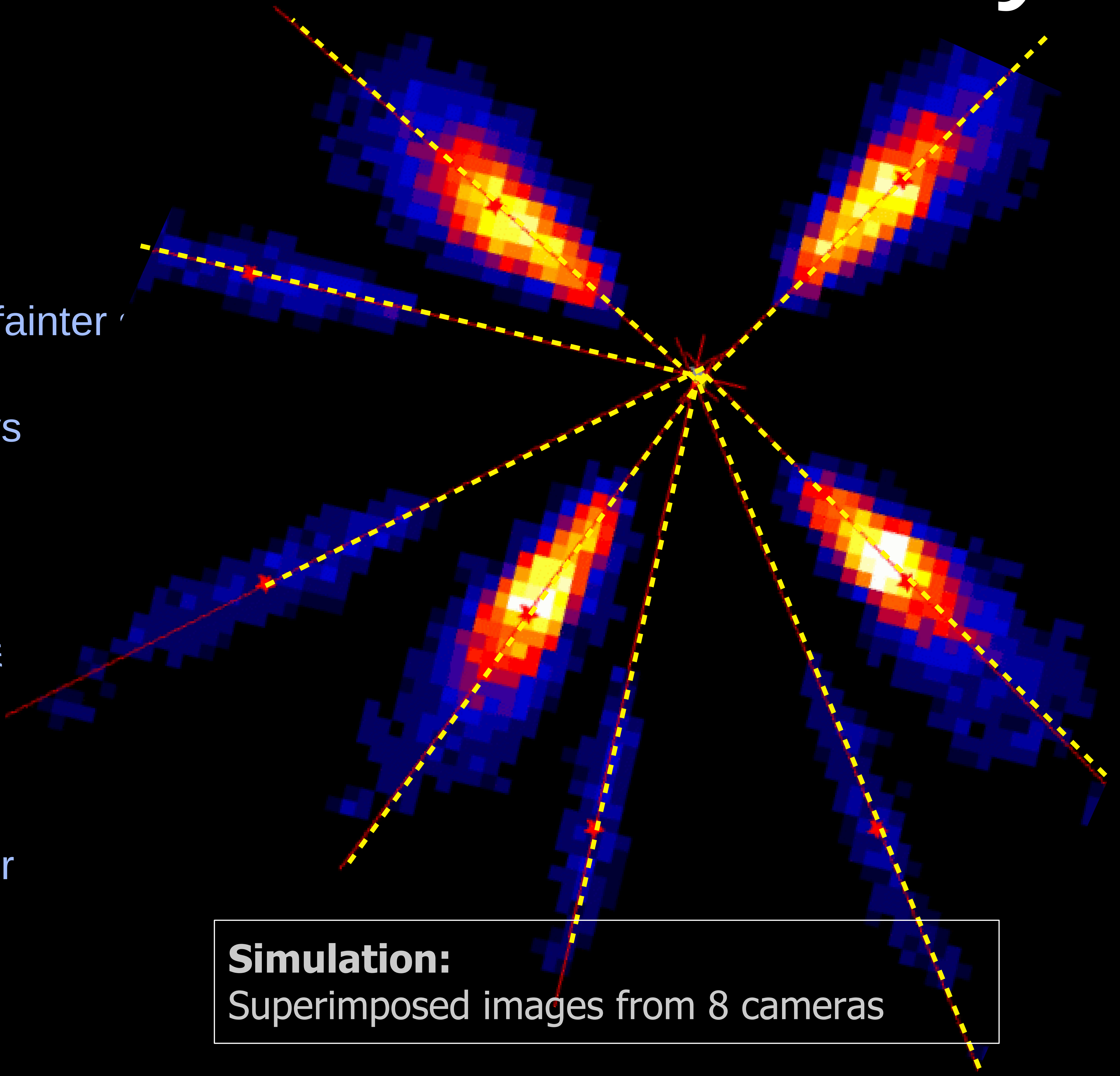


HESS J1858+020
HESS J1857+026
HESS J1843-033
HESS J1846-029
HESS J1848-018
HESS J1849-000
HESS J1833-105
HESS J1834-087
HESS J1837-069
HESS J1841-055
HESS J1826-148
HESS J1825-137
HESS J1804-216
HESS J1809-193
HESS J1813-178
HESS J1741-302
HESS J1745-290
HESS J1747-281
HESS J1745-303
HESS J1731-347
HESS J1708-410
HESS J1714-385
HESS J1713-381
HESS J1702-420
HESS J1713-397
HESS J1718-385
HESS J1614-518
HESS J1616-508
HESS J1626-490
HESS J1632-478
HESS J1634-472
HESS J1640-465
HESS J1514-591
HESS J1507-622
HESS J1418-609
HESS J1420-607
HESS J1427-608
HESS J1442-624
HESS J1356-645
Optical
+TeV

How to do better with IACT arrays?

- More events
  - More photons = better spectra, images, fainter
    - ✓ Larger collection area for gamma-rays
- Better events
  - More precise measurements of atmosphe
    - ✓ Improved angular resolution
    - ✓ Improved background rejection power

→ More telescopes!

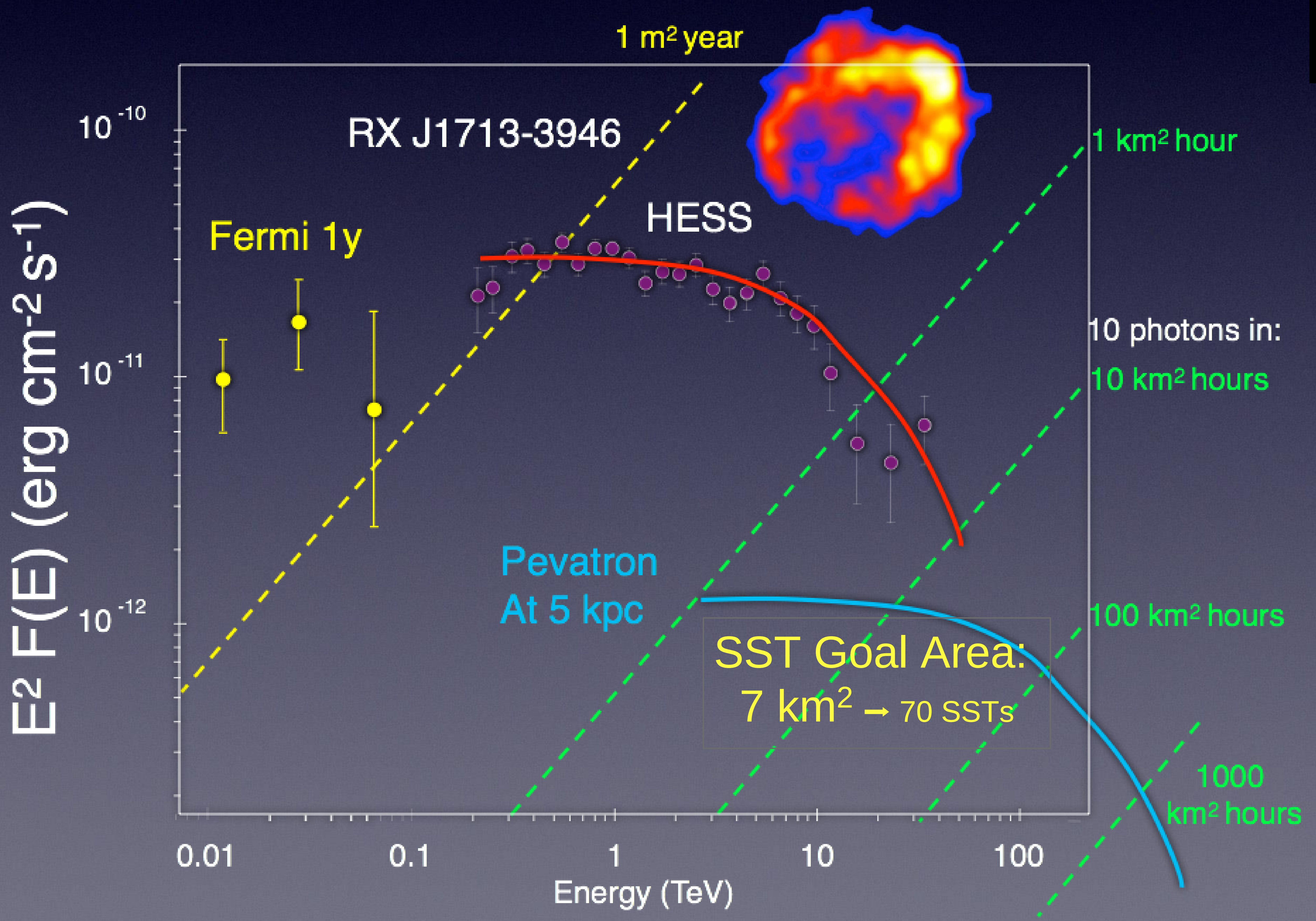


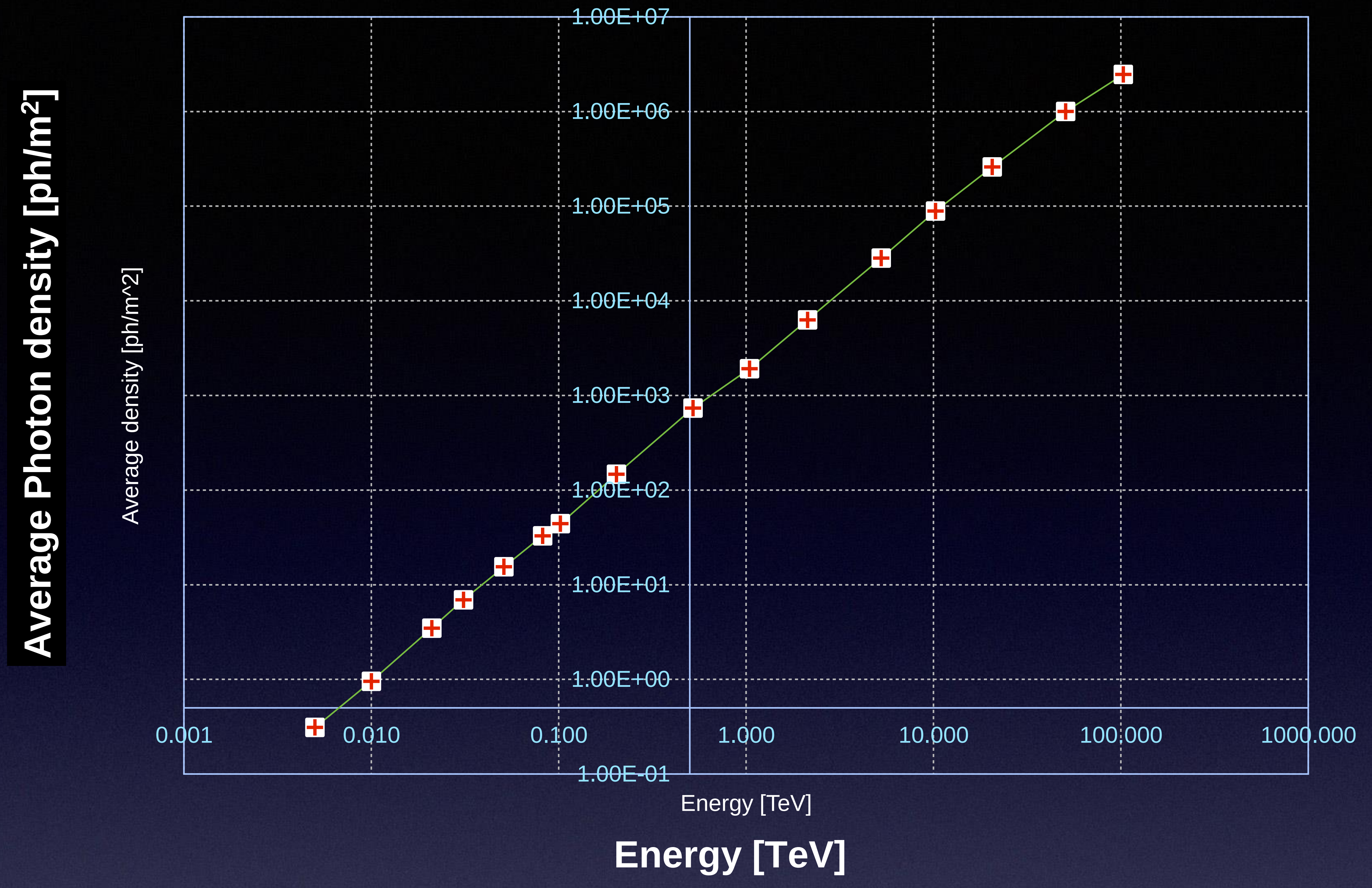
Simulation:
Superimposed images from 8 cameras

Energy threshold depends on collection area of a single telescope

$$N_{pe} = \rho_{ph} \times A \times R \times QE \times f$$

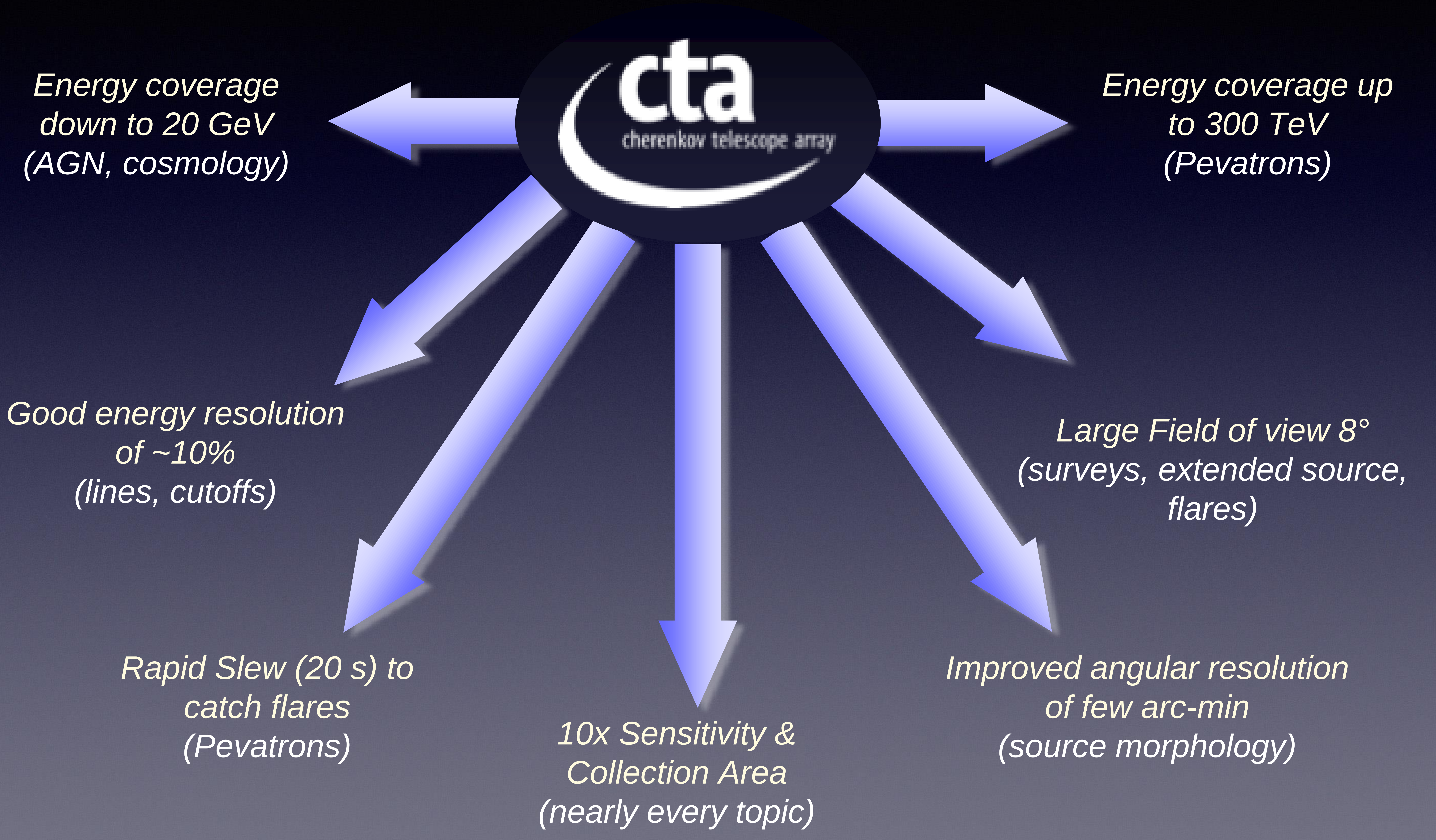
High energy → small mirror area





Collection Area of the array
↓
Photon Statistics at High Energy
↓
Number of Telescopes

Requirement & Drivers



CTA Science

- **Cosmic Particle Acceleration**
  – How and where are particles accelerated? – How do they propagate?
  – What is their impact on the environment?

- **Probing Extreme Environments**
  – Processes close to neutron stars and black holes – Processes in relativistic jets, winds and explosions – Exploring cosmic voids

- **Physics frontiers – beyond the Standard Model**
  – What is the nature of Dark Matter? How is it distributed? – Is the speed of light a constant for high-energy photons? – Do axion-like particles exist?

The Cherenkov Telescope Array

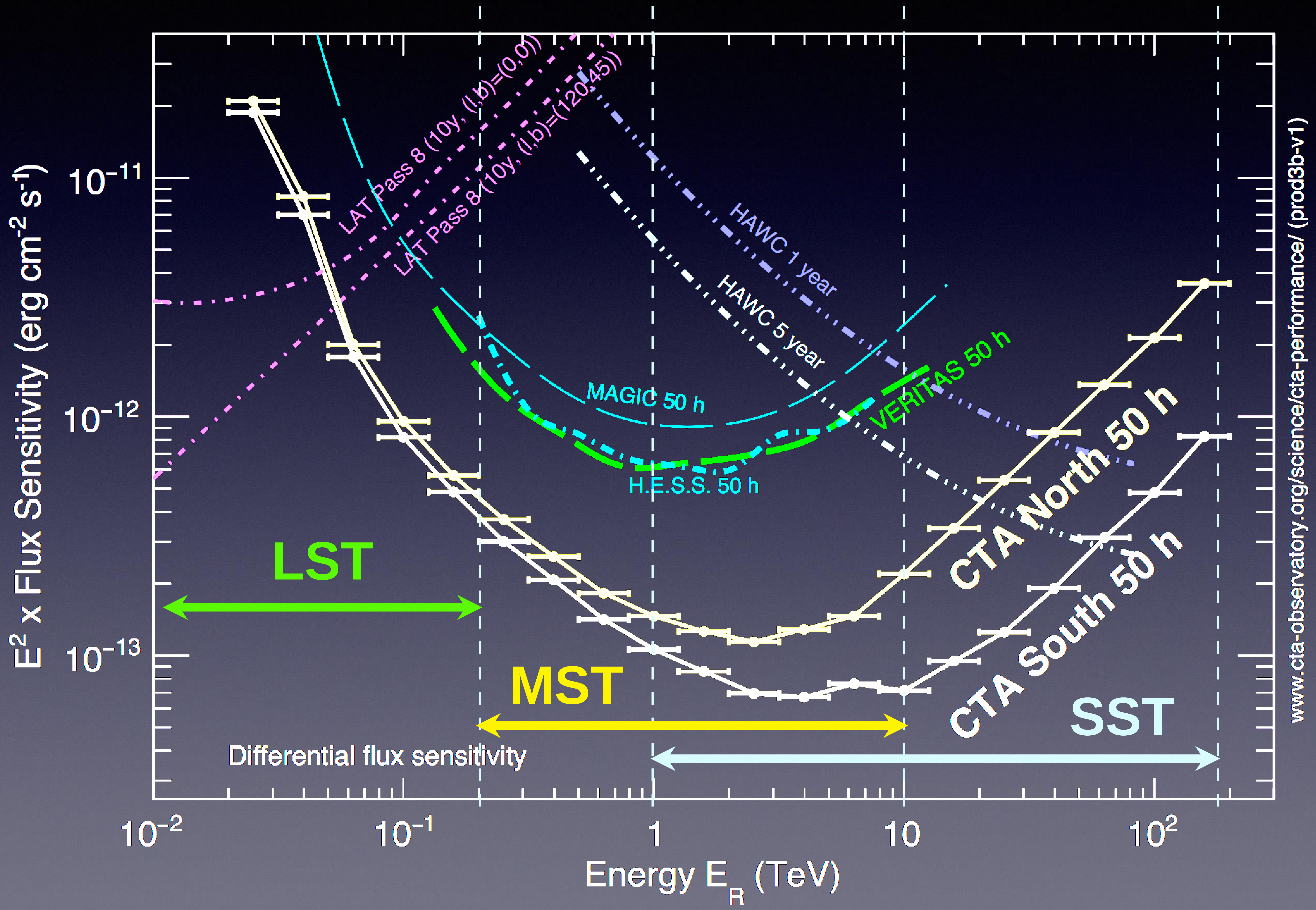
CTA Southern Site:

4 LST, 25 MST, 70 SST (~4 km^2)

CTA Northern Site:

4 LST, 15 MST (~0.6 km^2)

CTA Sensitivity



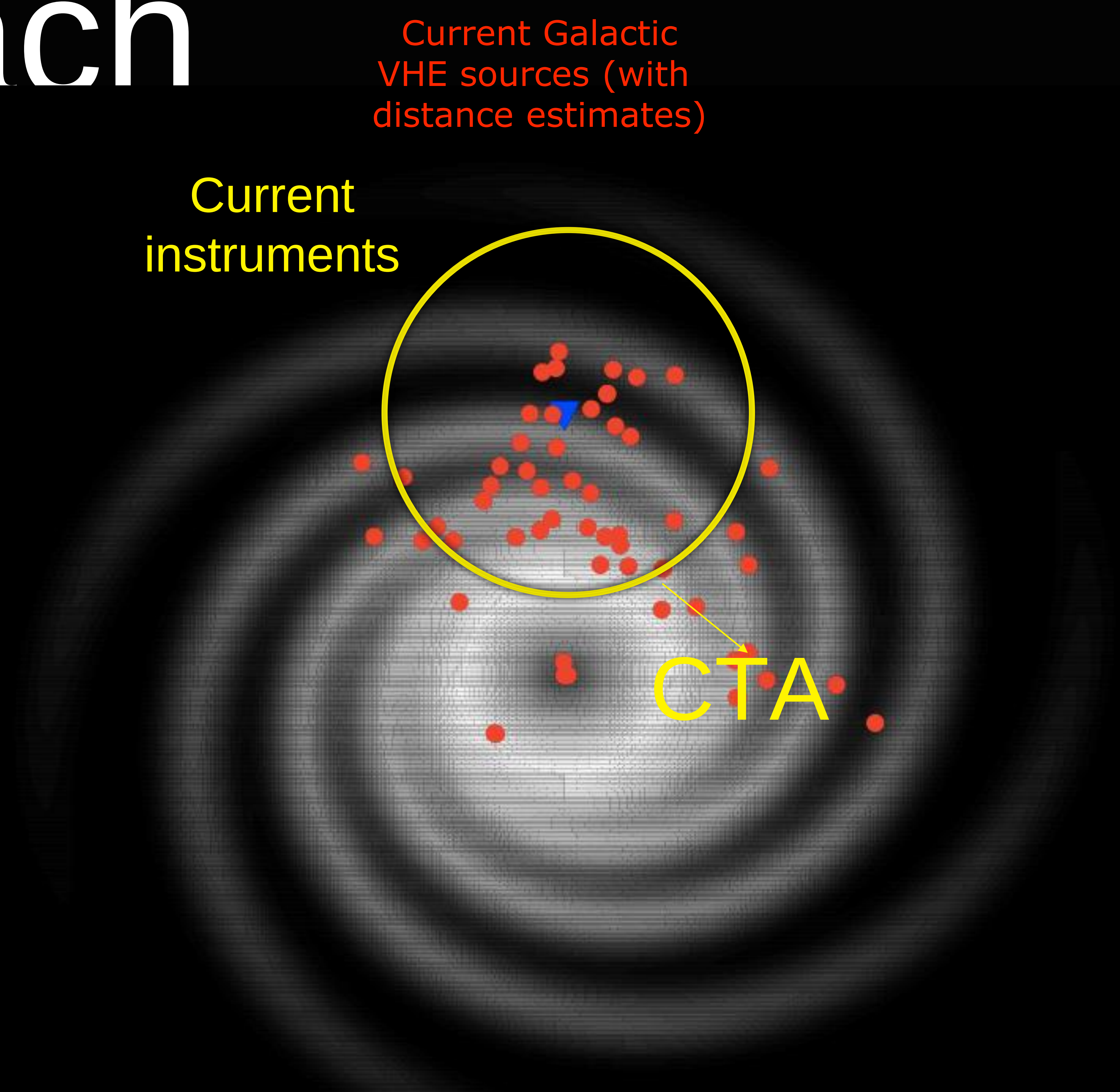
CTA Reach

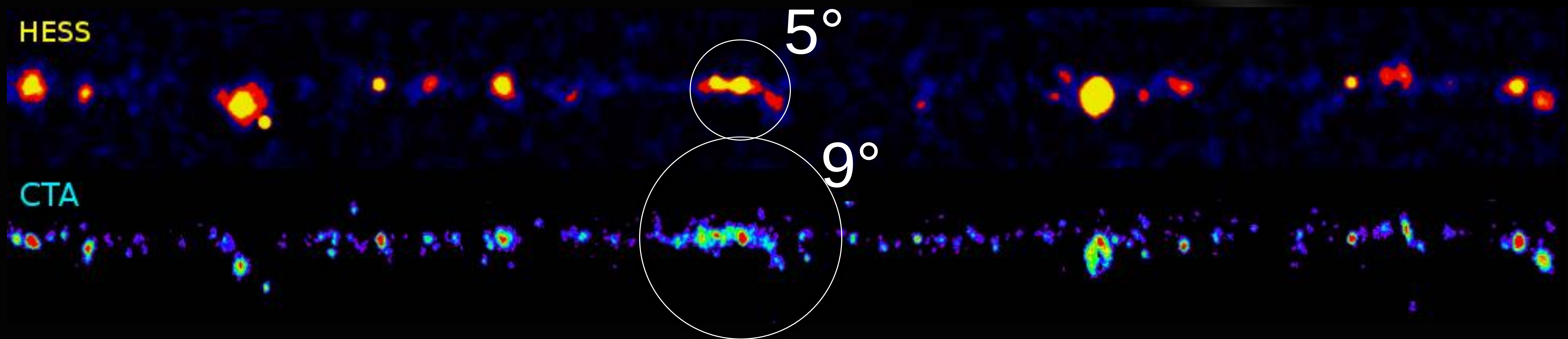
➡ e.g. **Galactic objects**

- Newly born pulsars and the supernova remnants
  - have typical brightness such that HESS etc can see only relatively local (typically at a few kpc) objects
- CTA will see **whole** Galaxy

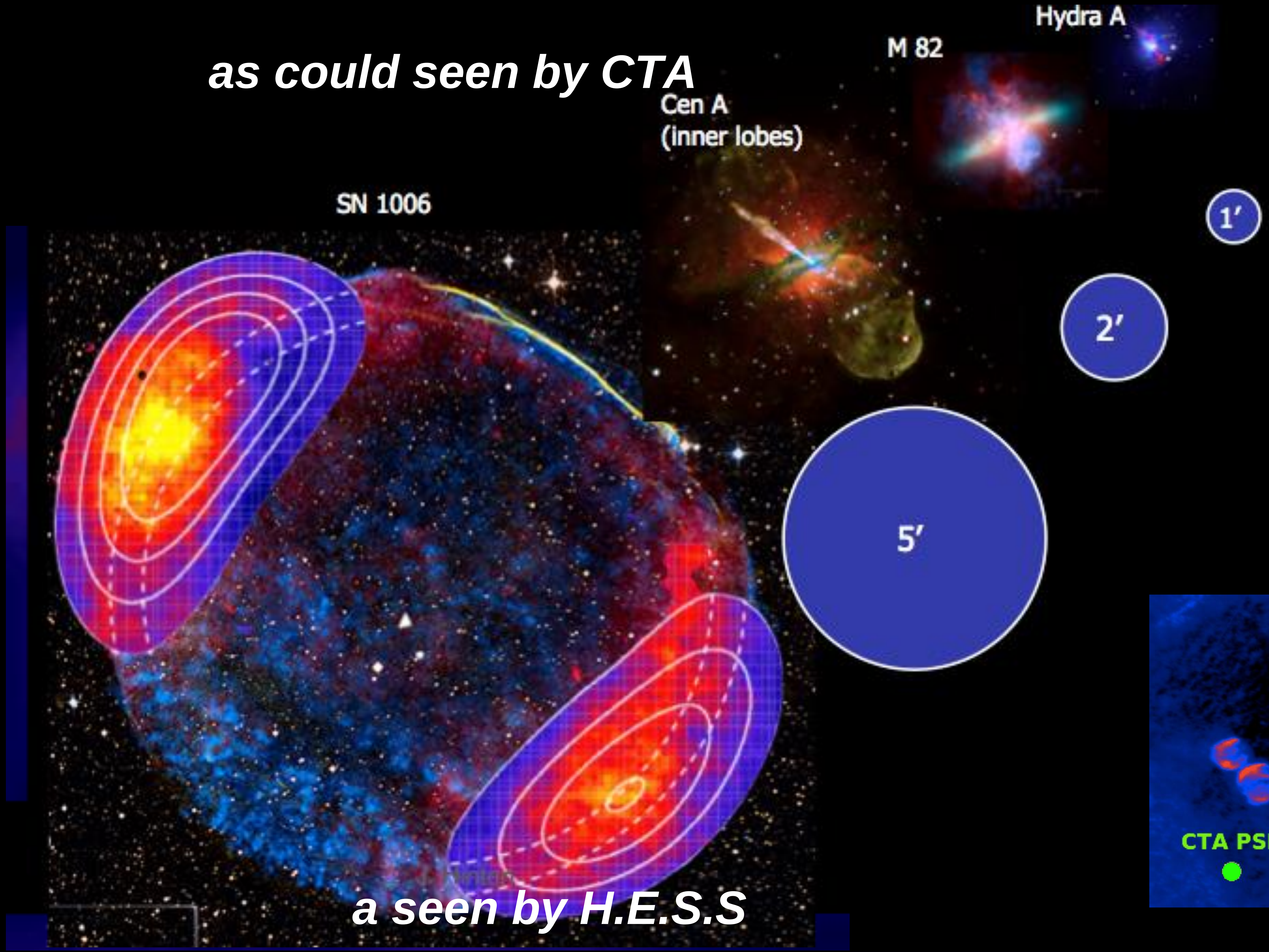
➡ Field of view + sens.

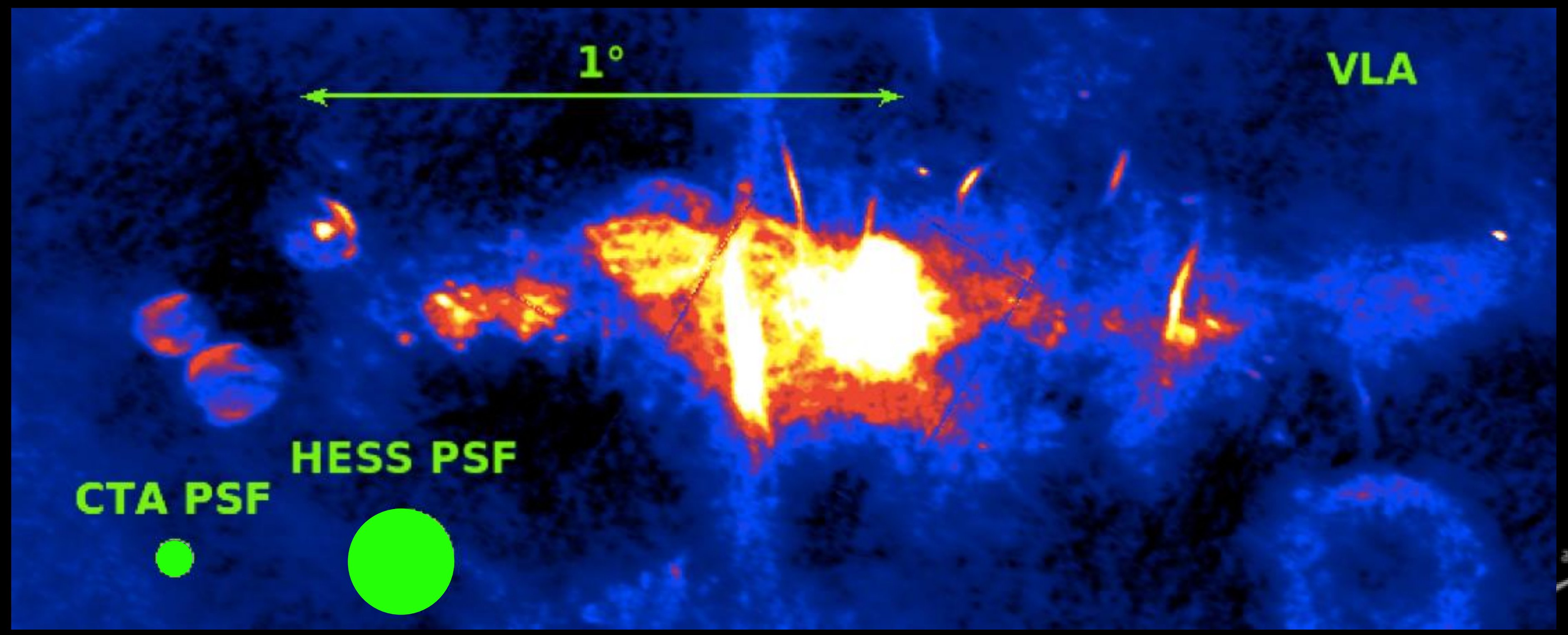
- Survey speed ~300×HESS



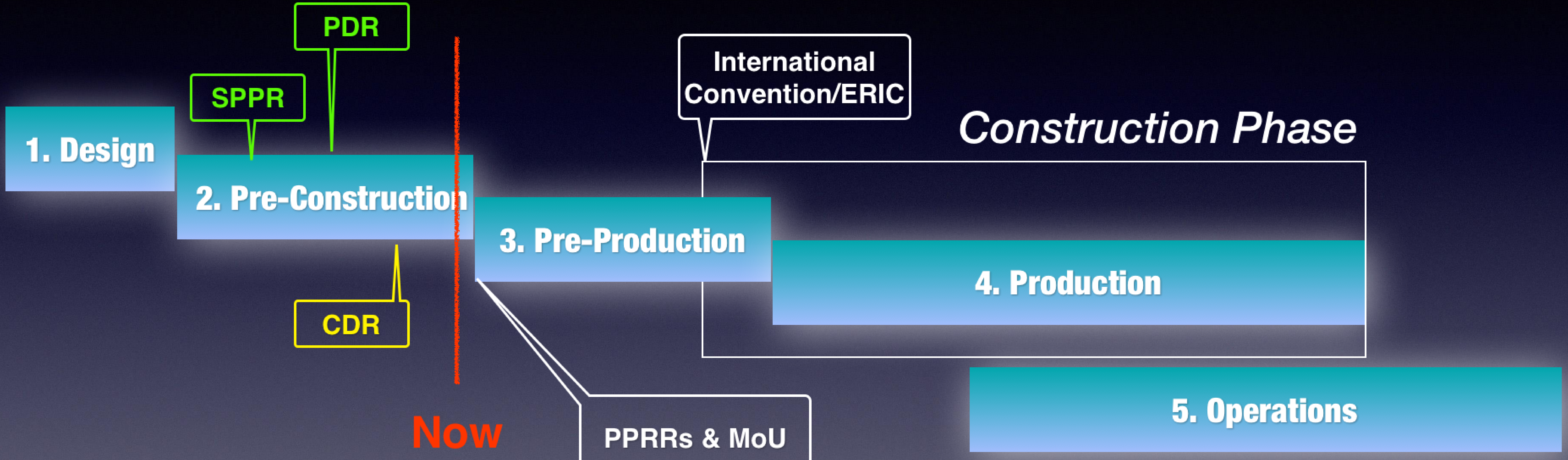


Better Angular Resolution





CTA Timeline



- 2017-8: Hosting agreements, site preparations start
- 2019: Start of construction
- Construction period of ~6 years
- Initial science with partial arrays possible before construction end

Large **H**igh **A**ltitude **A**ir **S**hower **O**bservatory (LHAASO)

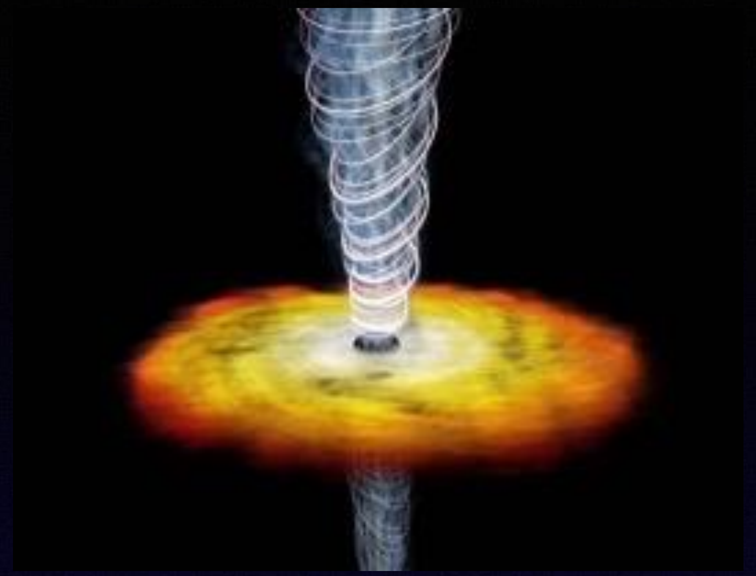
multi-component air shower detector for
- gamma ray astronomy in the energy range ~2×10^{11}-10^{15} eV
- cosmic ray studies at energies ~10^{12}-10^{18} eV.

LHAASO
高海拔宇宙线观测站

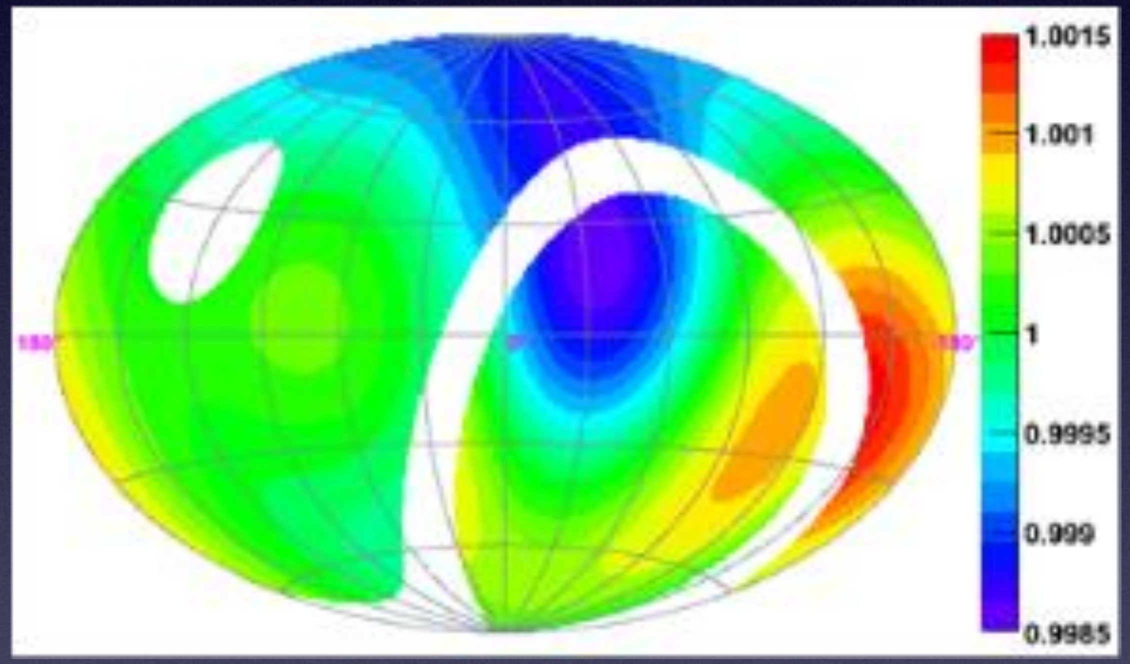
Physics of LHAASO

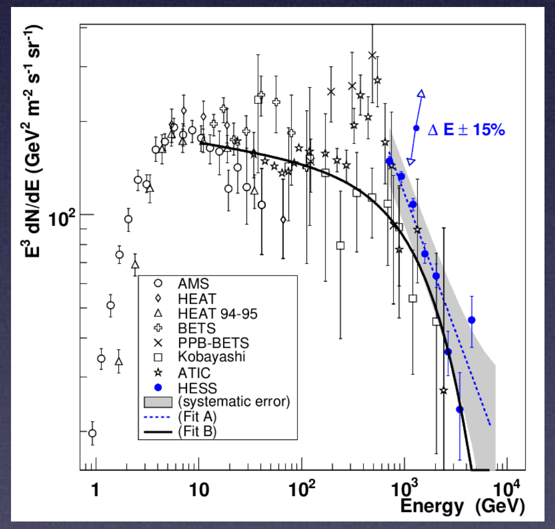
- VHE gamma sky survey (100 GeV-1 PeV):
  - Galactic sources;
  - Extragalactic sources & flares;
  - VHE emission from Gamma Ray Bursts;
  - Diffused Gamma rays.



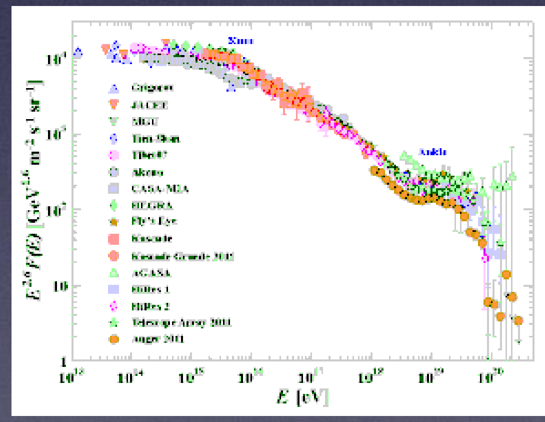
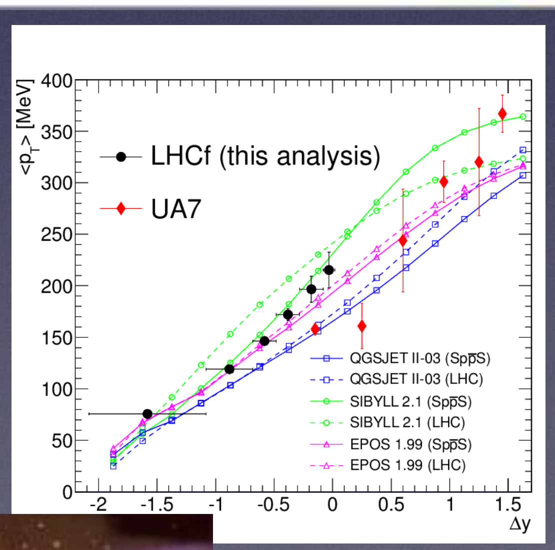



- Spectrum measurement at the high end:
  - Nature of the acceleration: leptonic or hadronic;
  - Origin of cosmic rays – 100 years’ mystery.

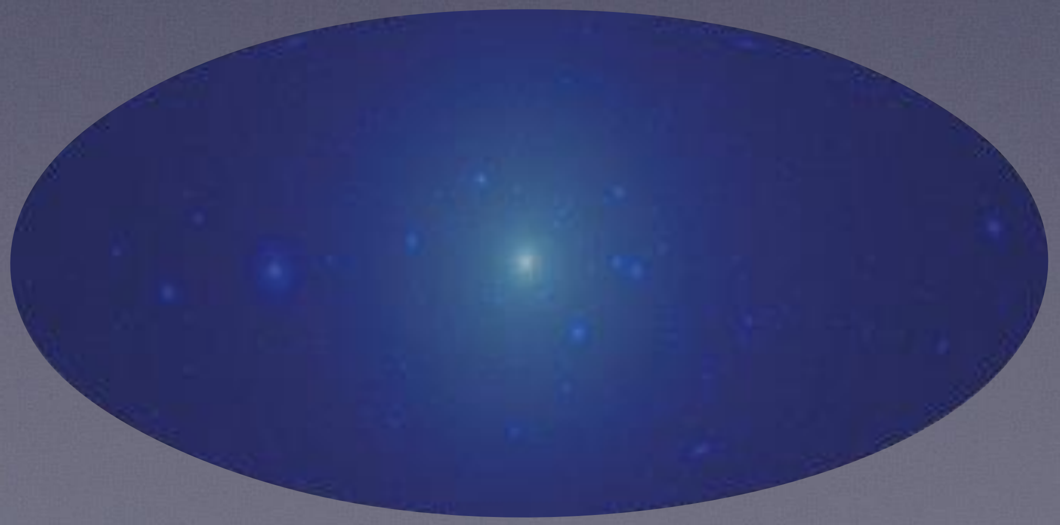
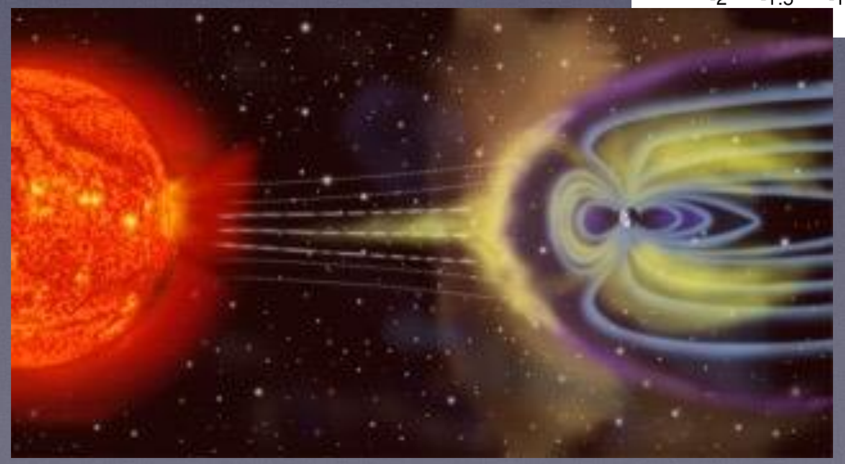




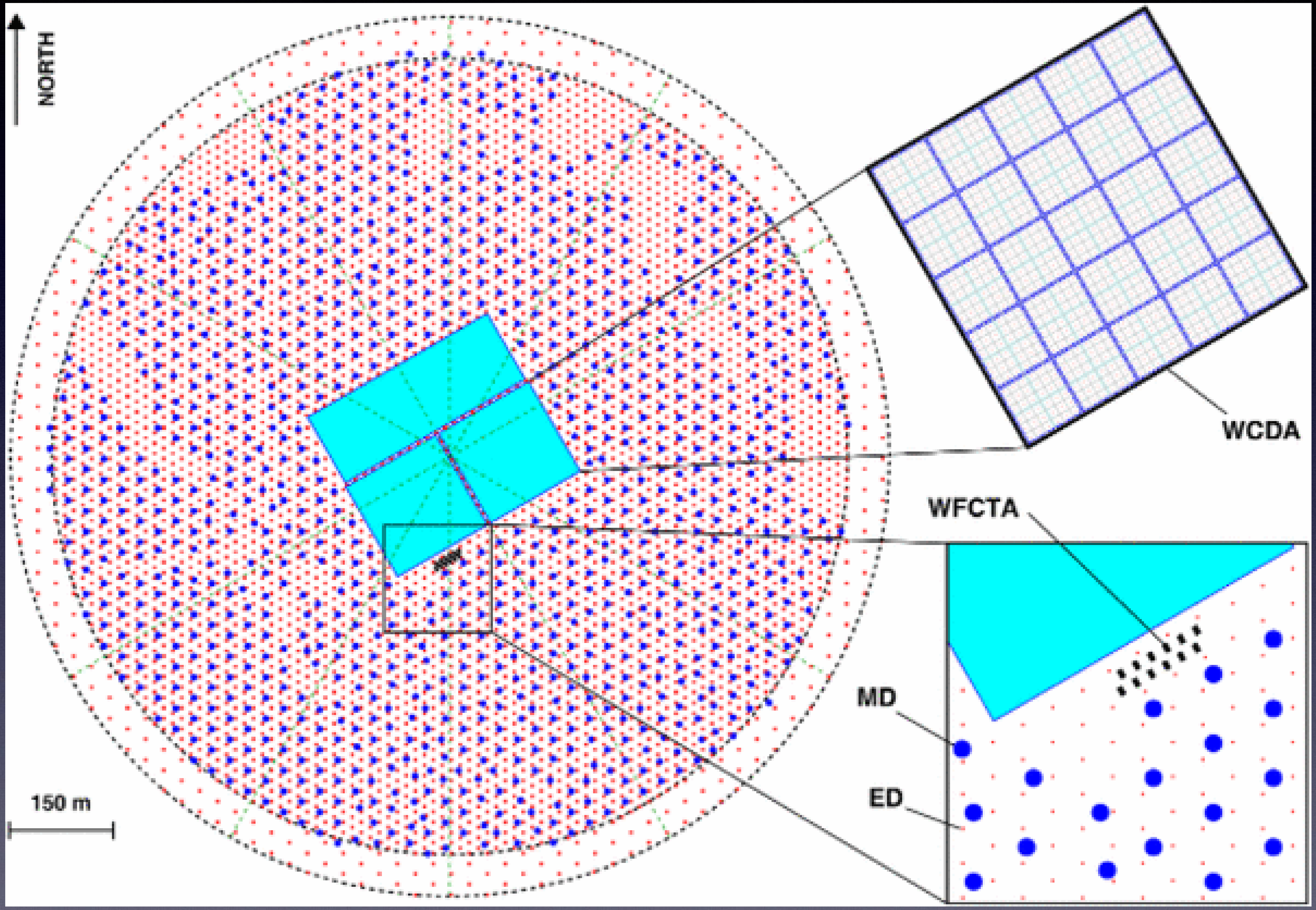
- Cosmic rays
  - Spectra of CR Species;
  - Anisotropy of VHE cosmic rays;
  - Cosmic electrons / positrons;

- Miscellaneous:
  - Gamma rays from dark matter;
  - Sun storm & IMF.

LHAASO Layout



WCDA - Water Cherenkov Detector Array

- Measuring shower direction and location

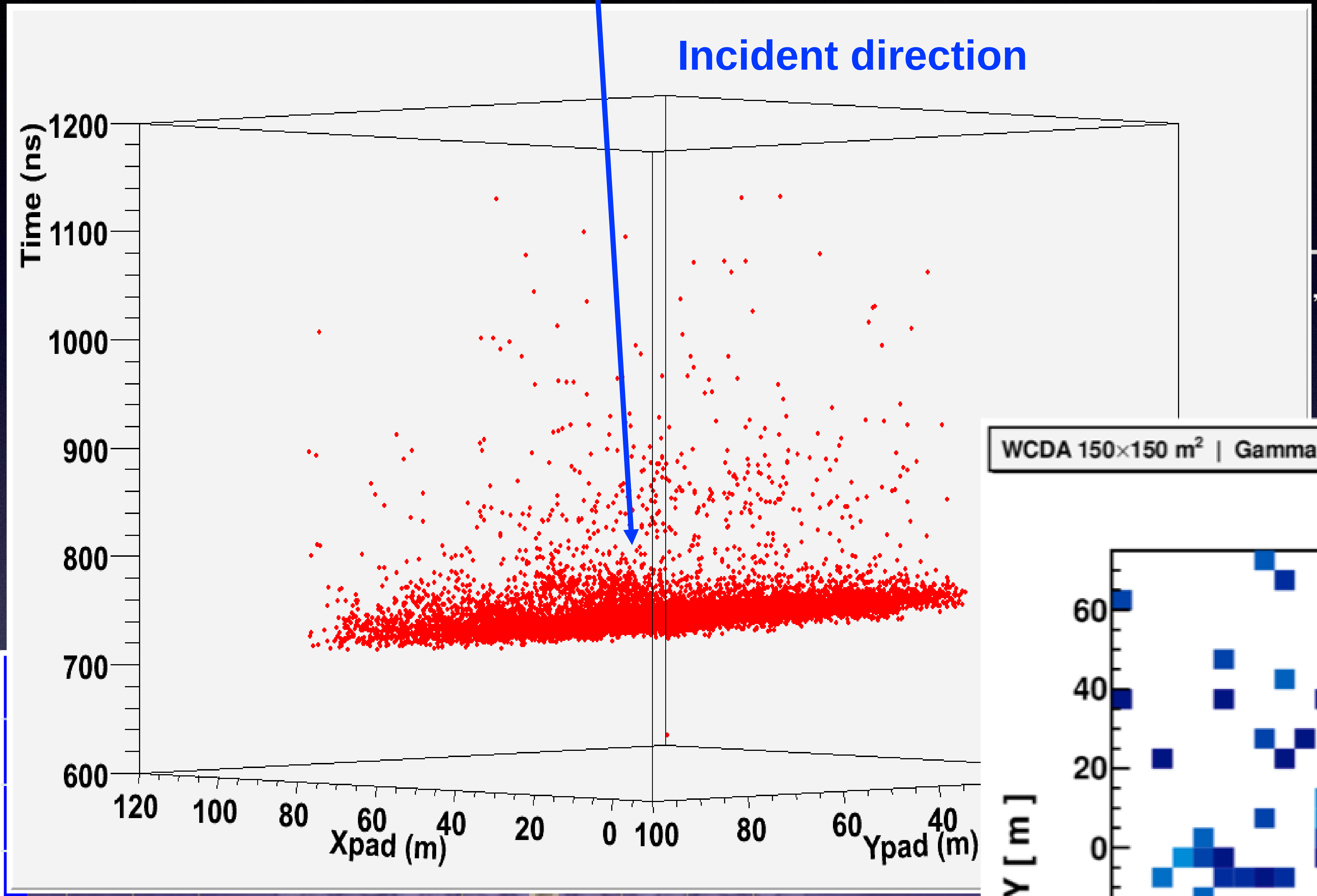
KM2A - Km-square array

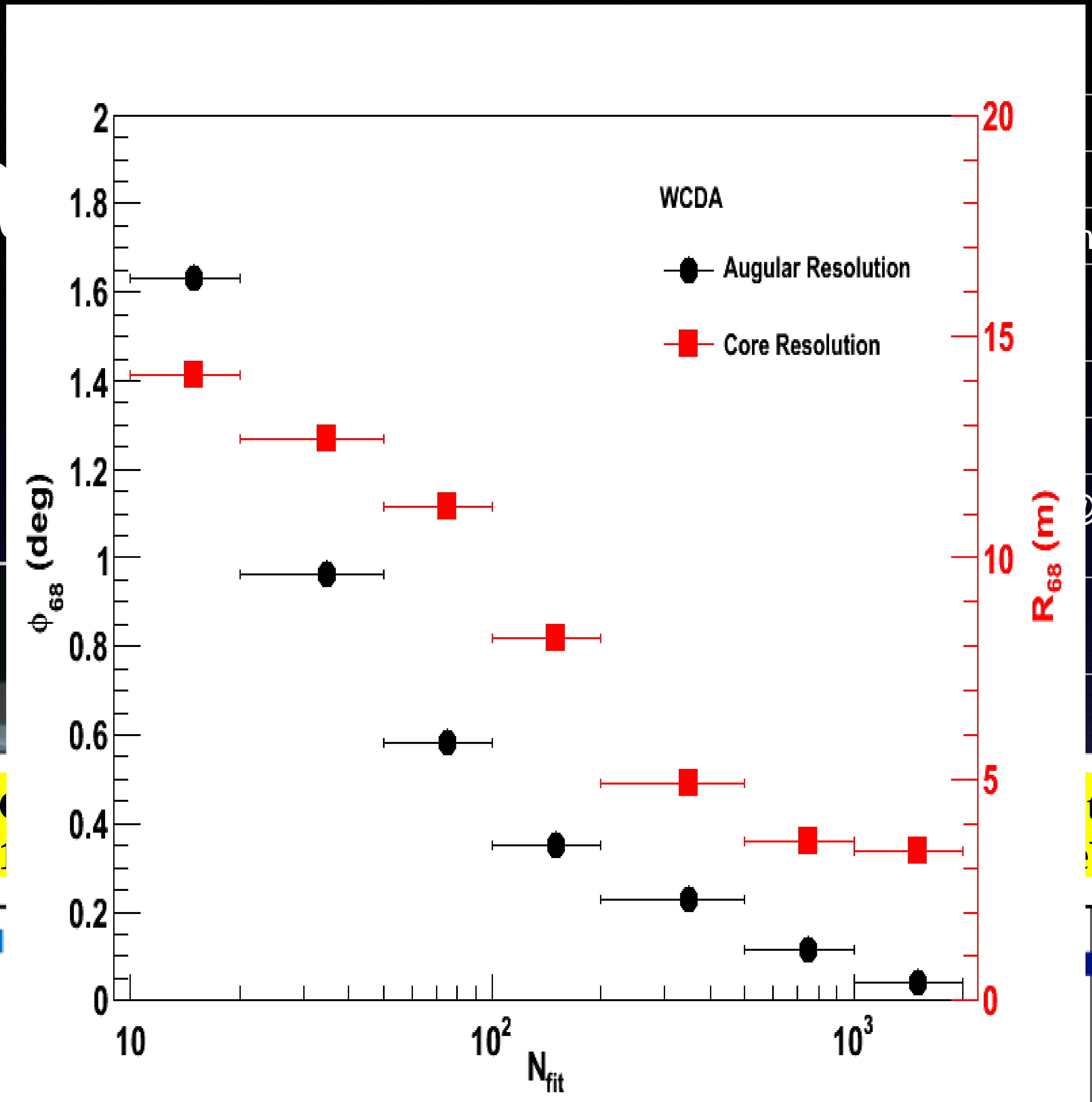
- Measuring shower direction and location
- Measuring μ–content with the largest MD array ever
- Clean γ selection

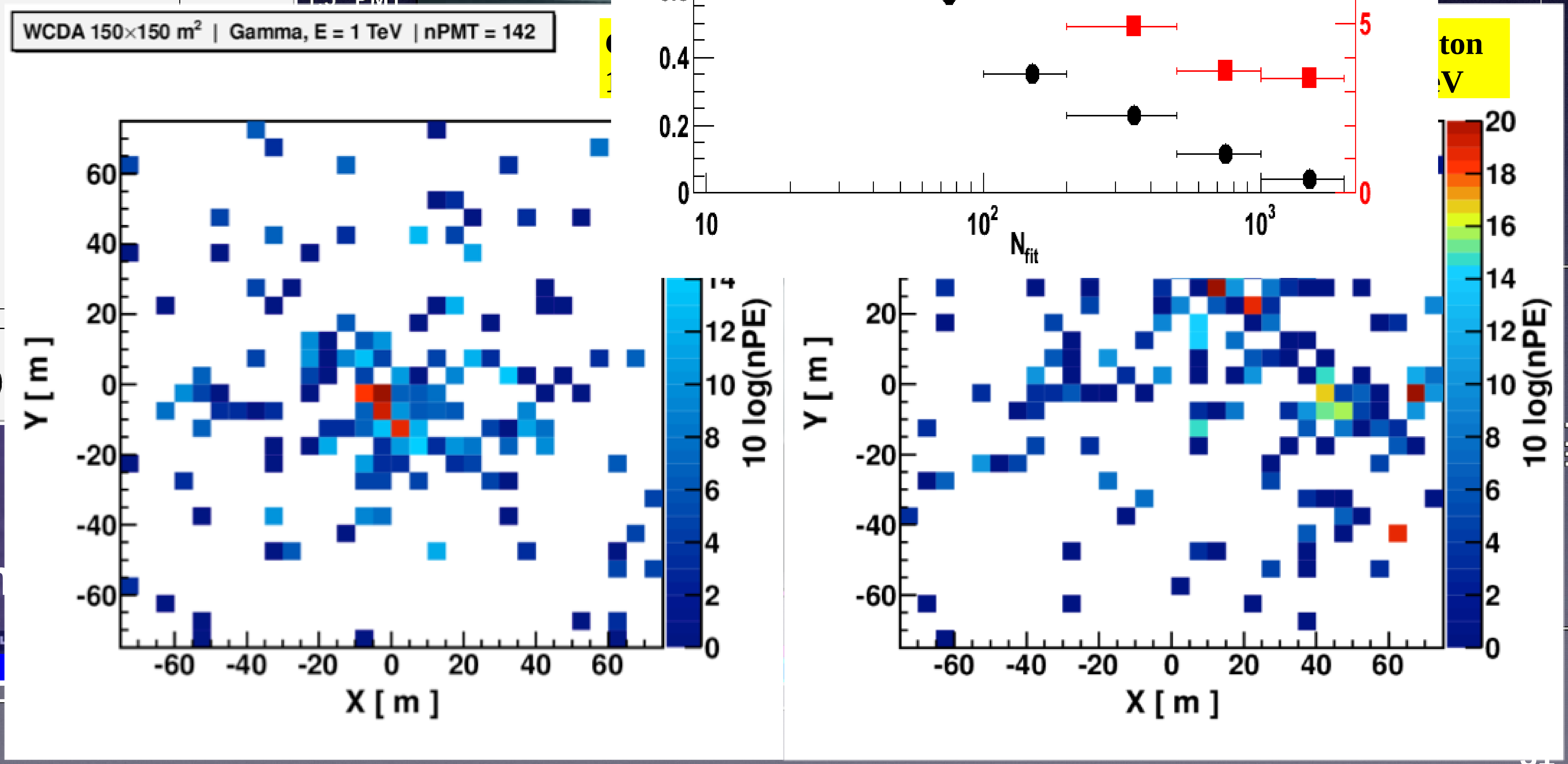
WFCTA - Wide Fielf-of-view Cherenkov array

- Extend energy range
- Measure Shower fluorescent light
- Particle discrimination for composition study at knee

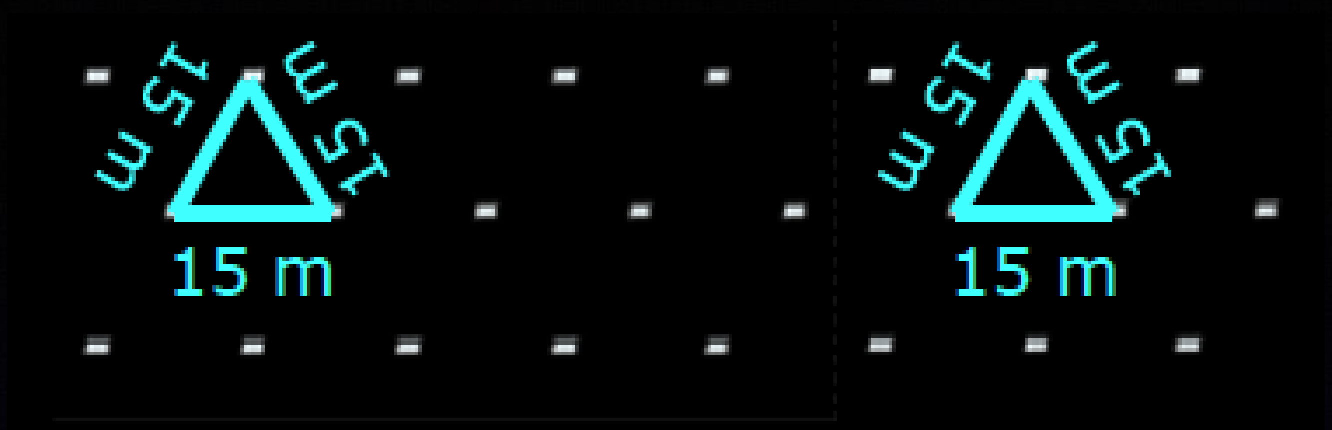
Water Cherenkov Detector Arra

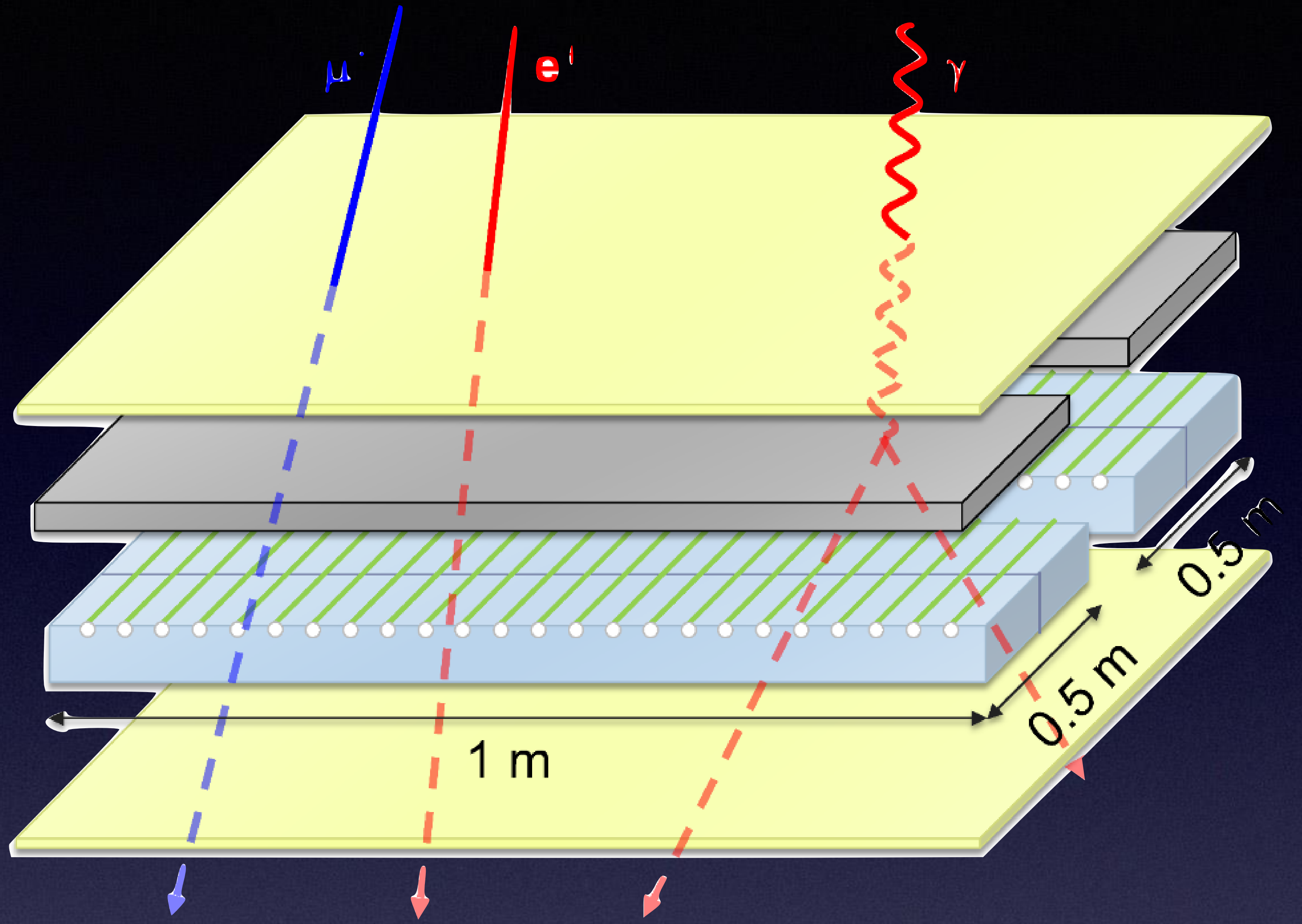


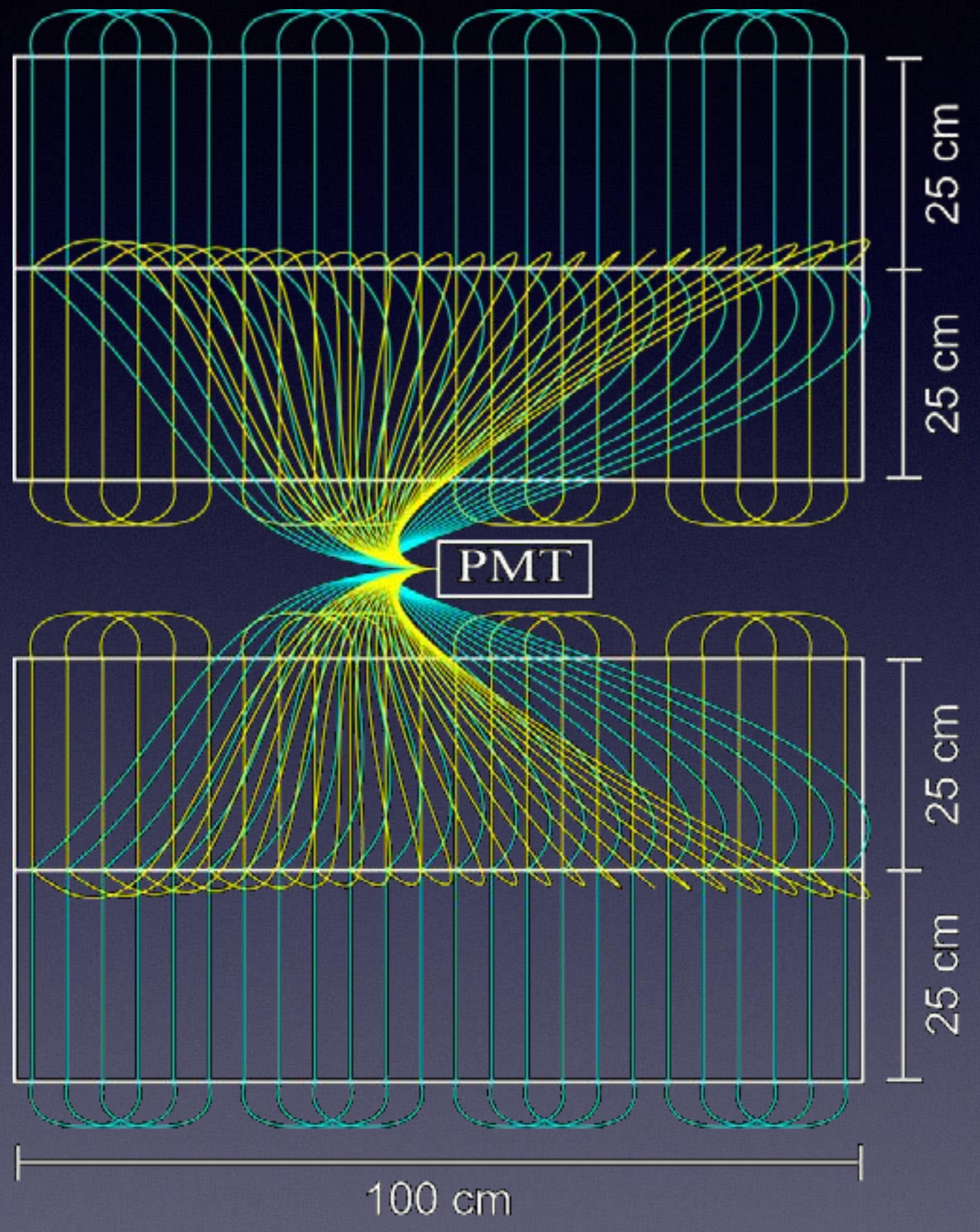




KM2A - Electromagnetic Detector



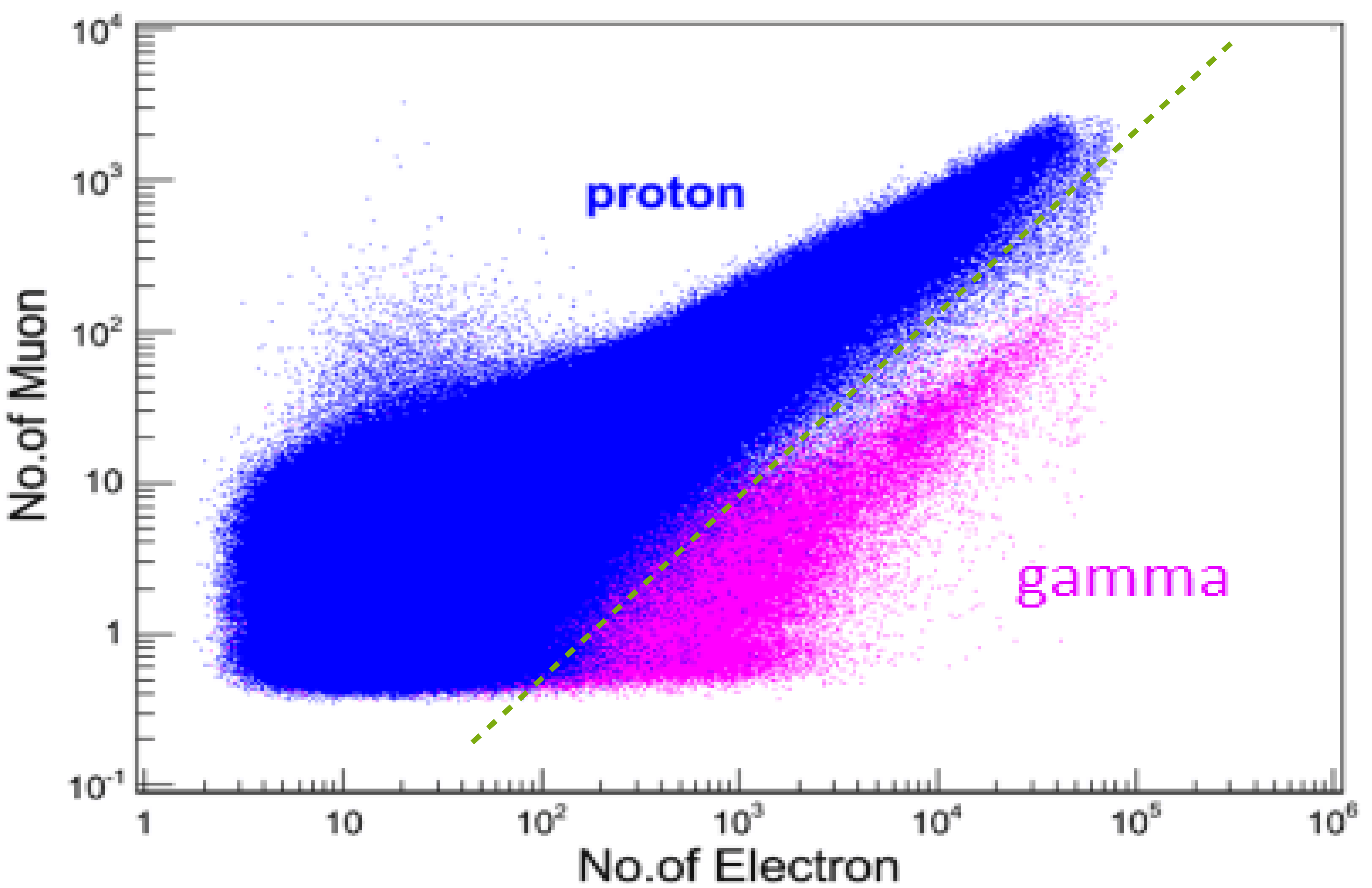


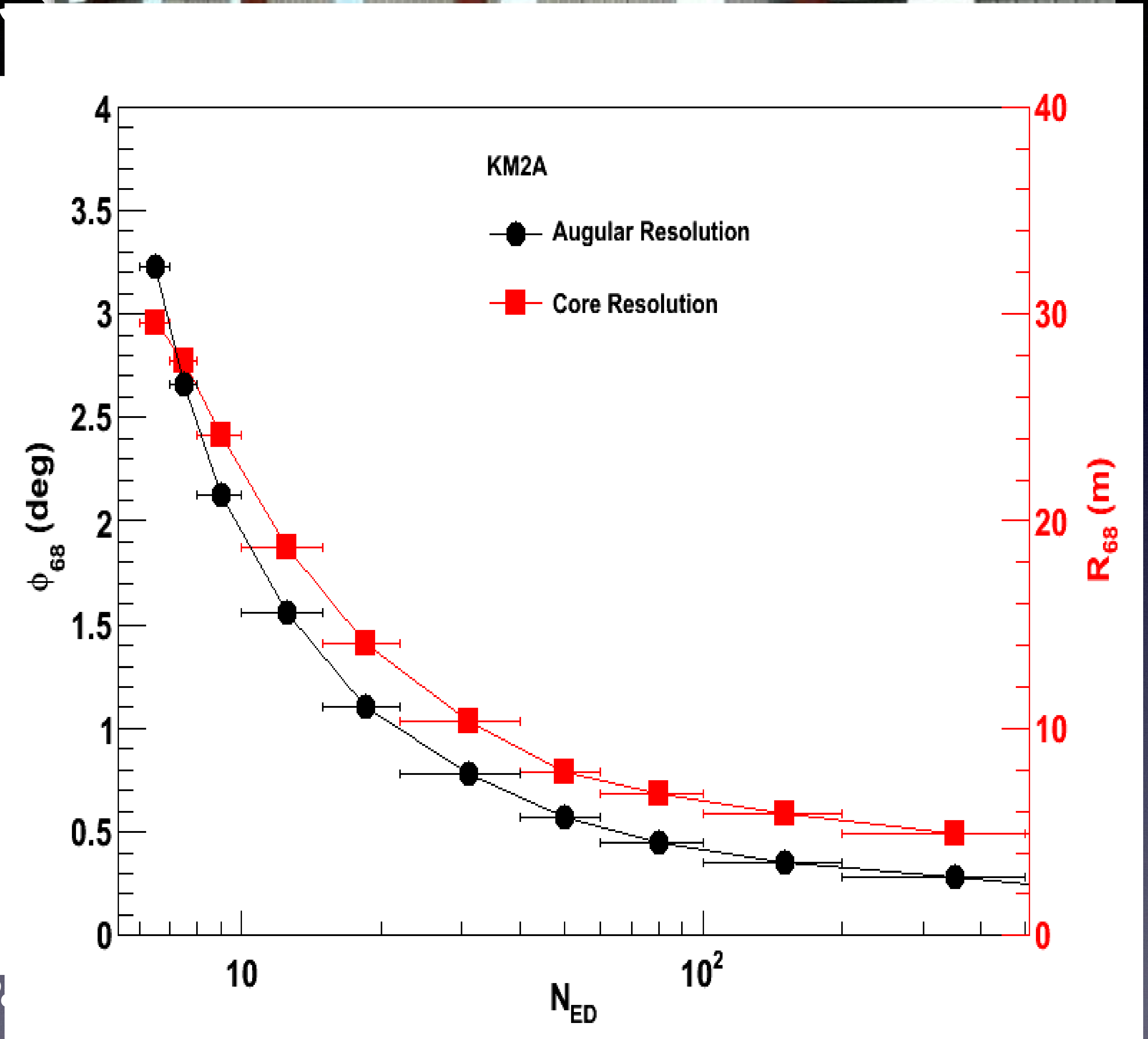


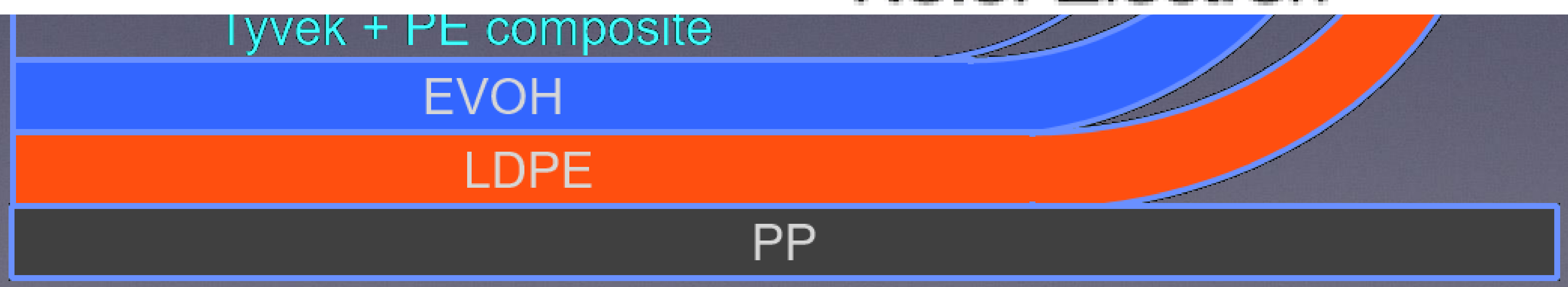
Effective Area	1 m^2
Tiles thickness	1 cm
# WLS fibers	24/tile x f
Detection efficiency	>95%
Dynamic range	1-10’000
Time resolution	<2 ns
Particle counting resolution	25%@1 particle 5% @ 10’000 Particle
Aging	<20% (10 Years)
Spacing	15 m
Total Number of ED	5195

First 33 detectors has been installed on the site in Feb.- 2018

KM2A - Muon Detectors





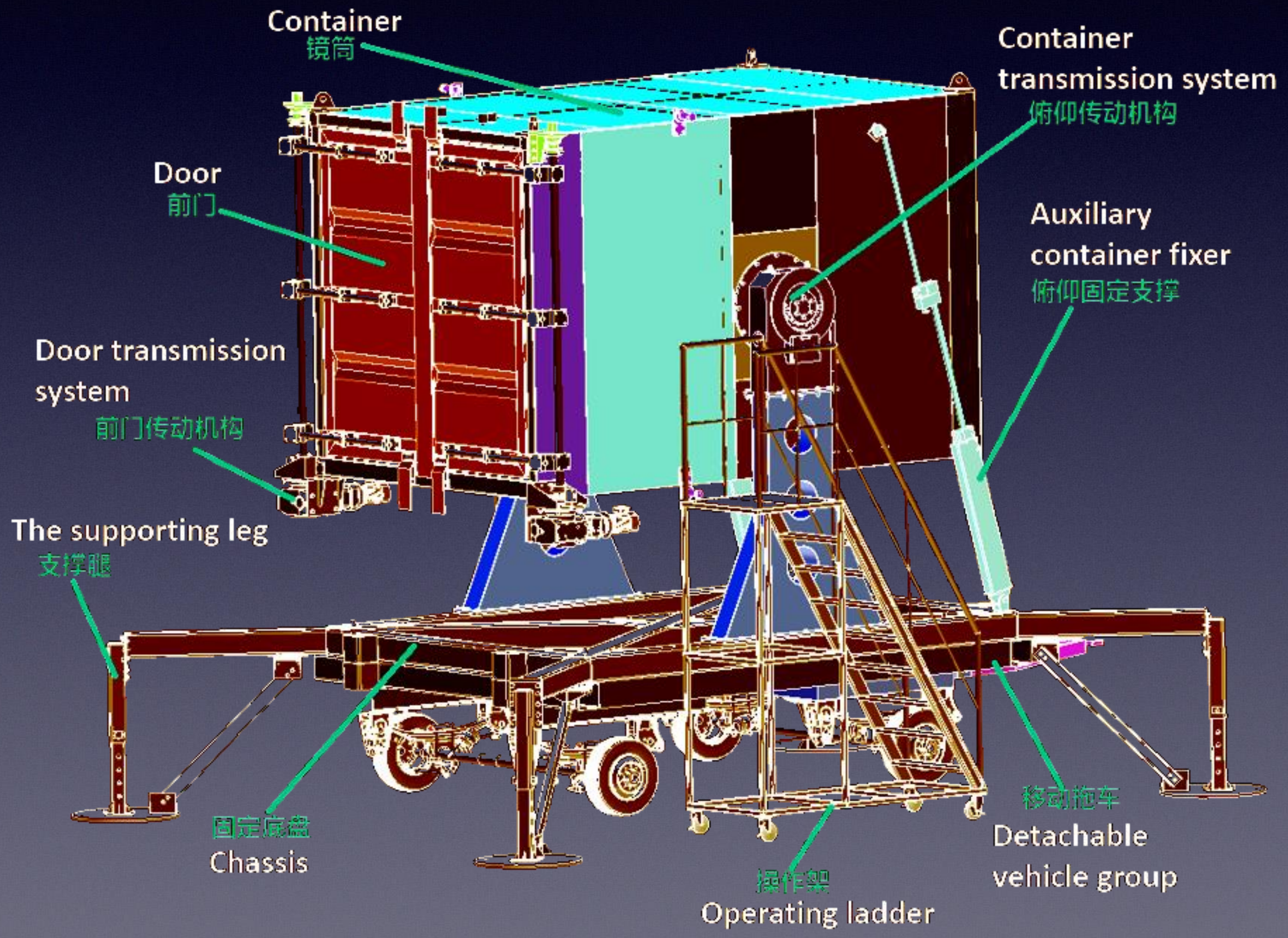


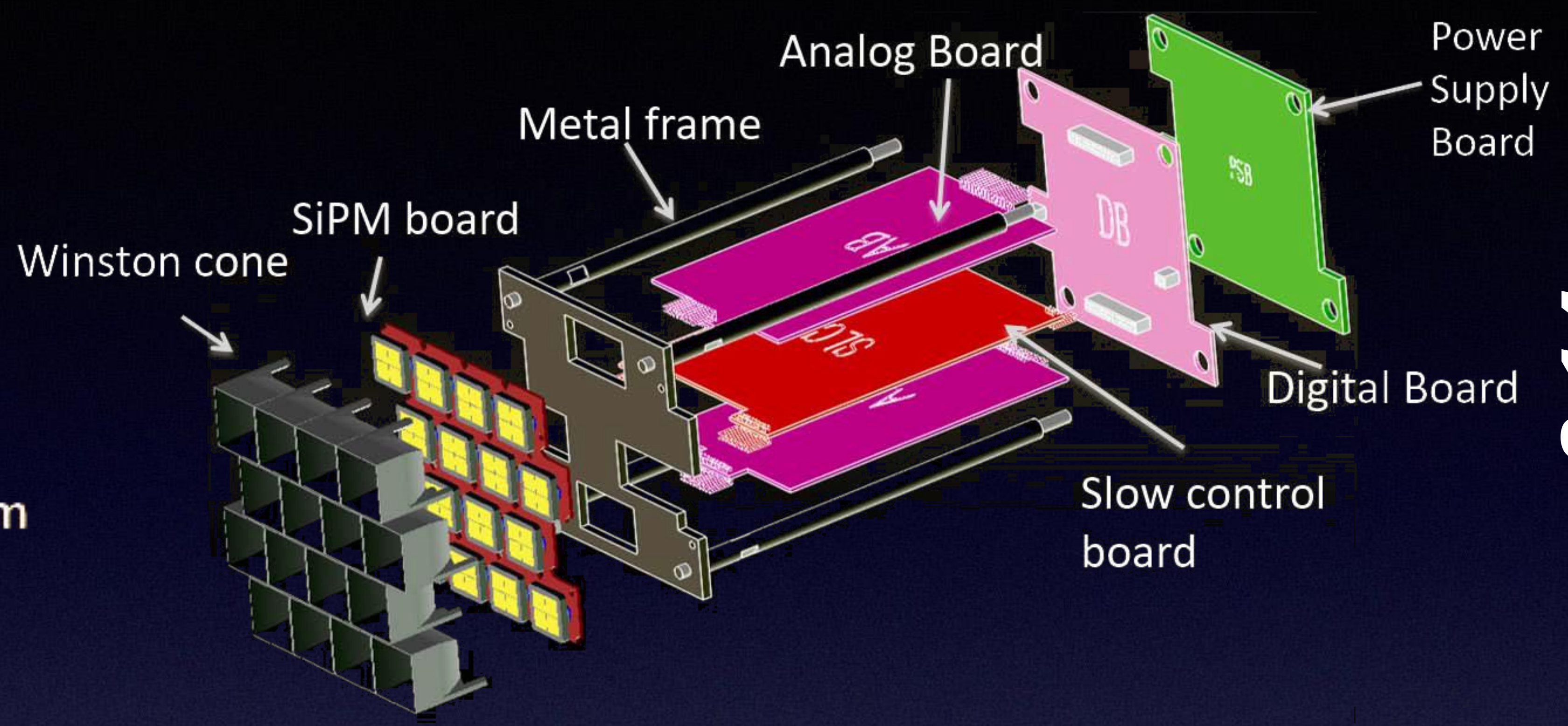
Lifetime	>20 years
Spacing	30 m
Total Number of ED	1171

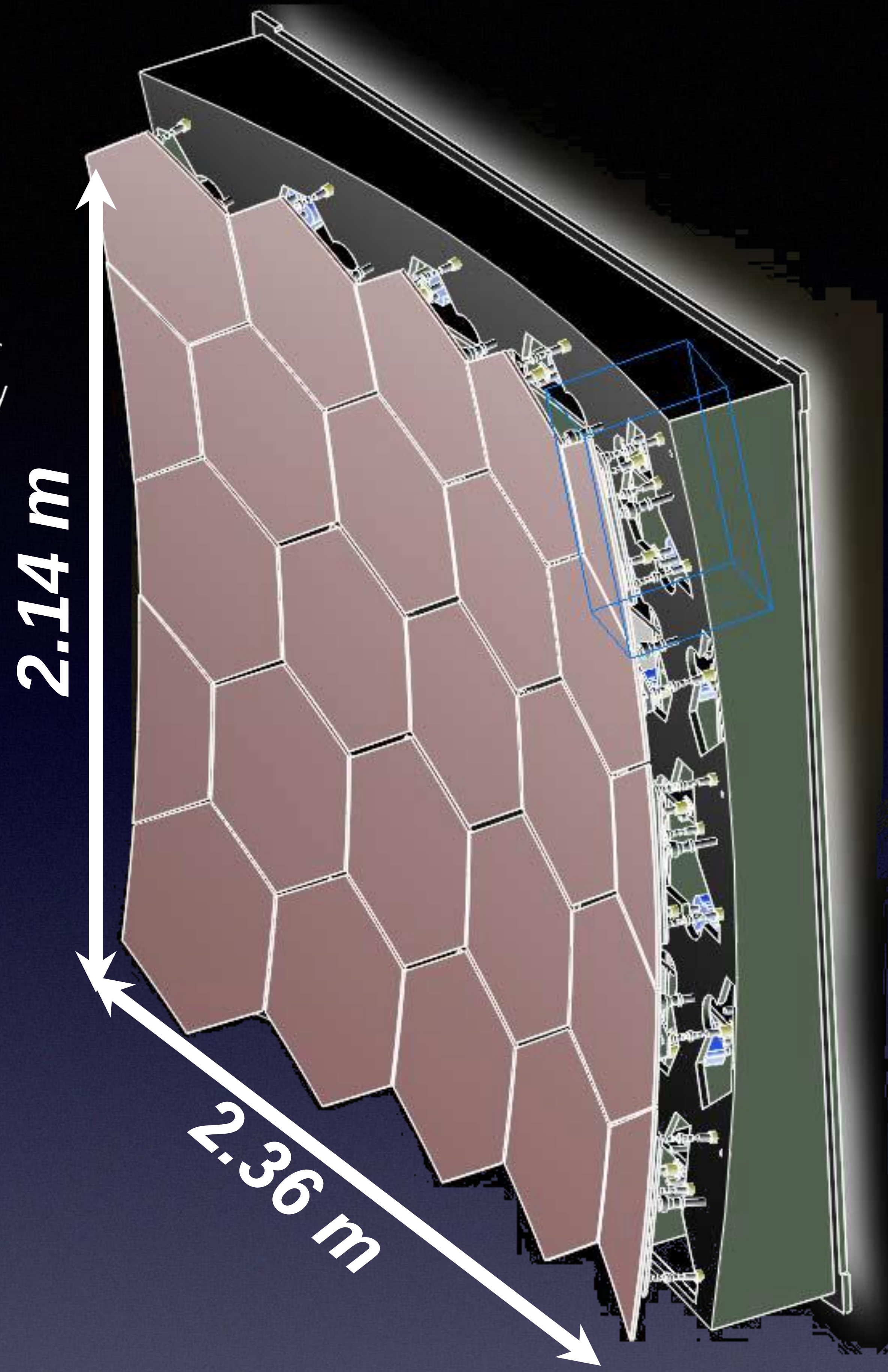
Angular res.

Core res.

Wide Field Cherenkov Telescope Array



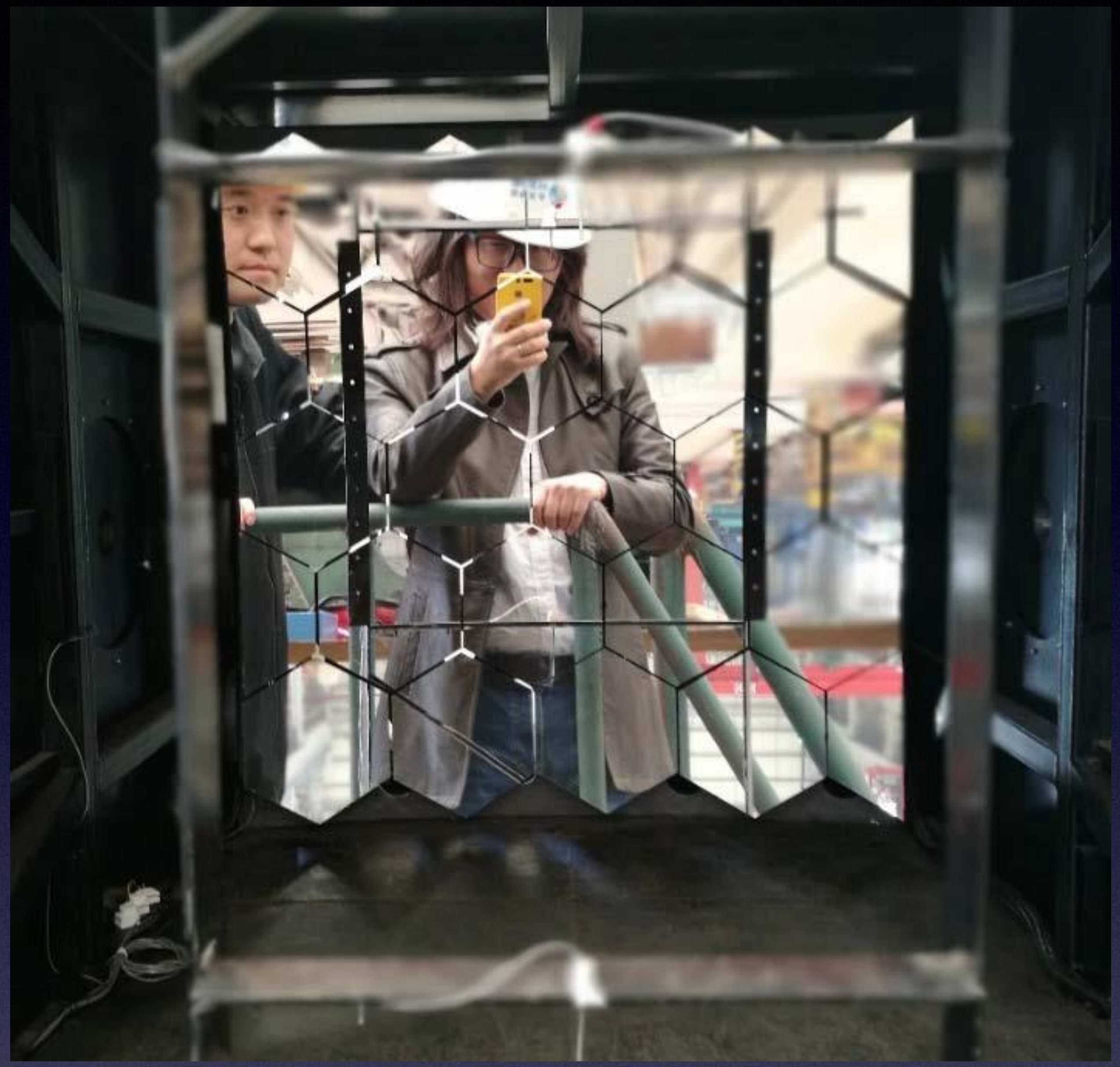
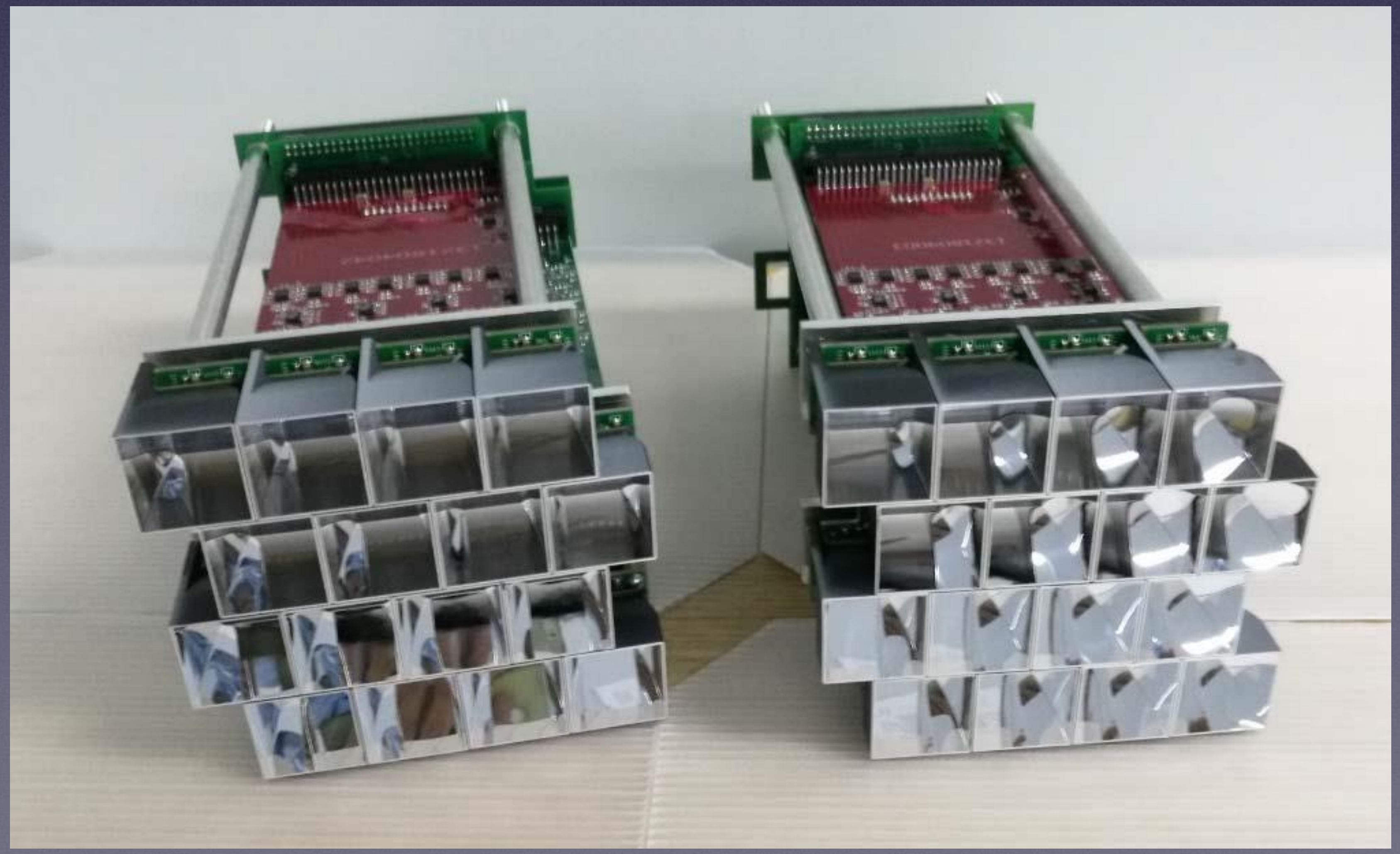




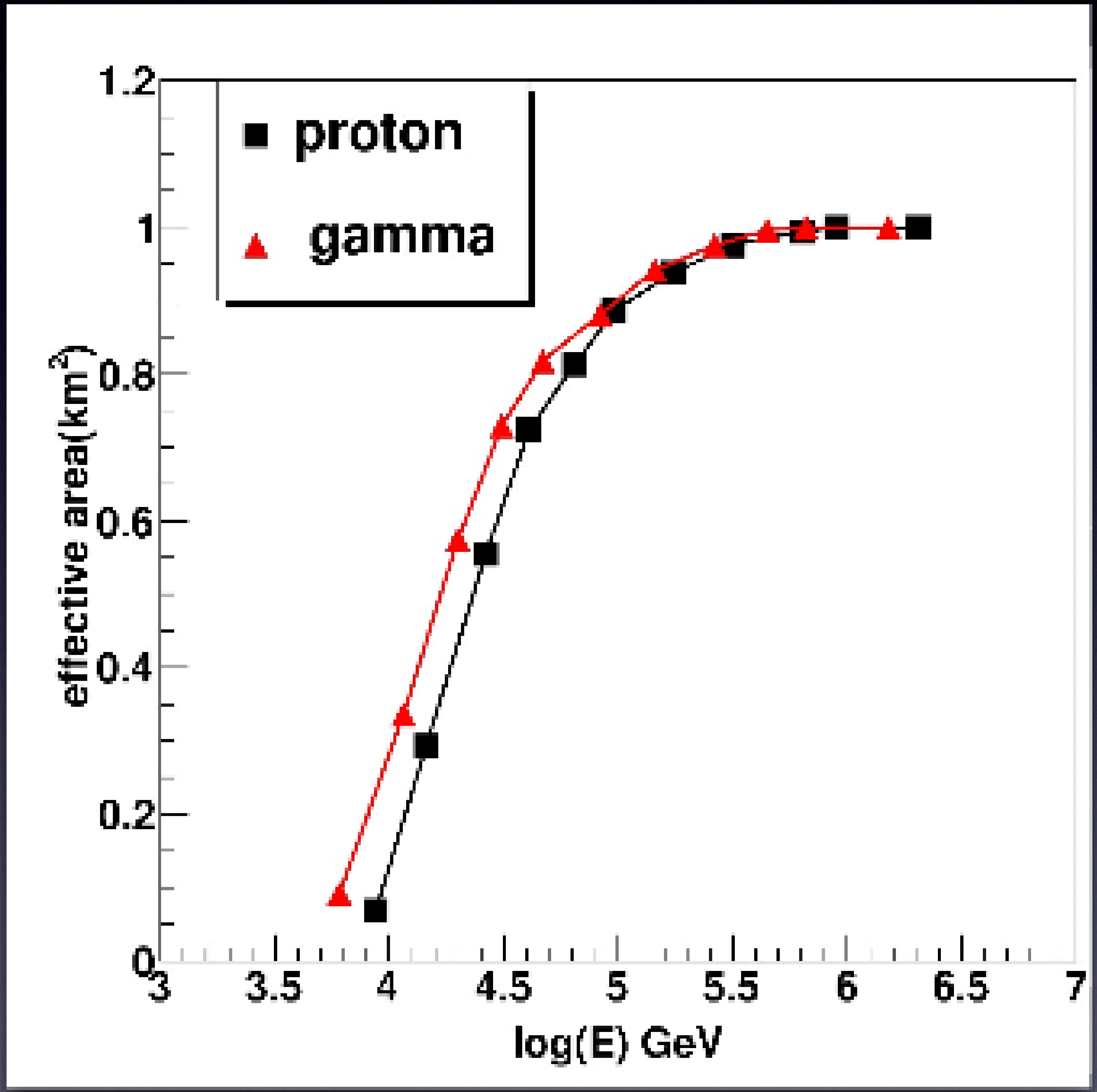
Mirror Size	5 m^2
Pixel Size	0.5°
# Pixels	1024
FoV	14”x16”
Dynamic range	1-32’000 PE/pixels (<10% nonlinearity)
Time resolution	<2 ns
PDE	>28%@400nm >22%@350nm >17%@310 nm
Time resolution	< 10 ns
Charge resolution	<50%@10 PE <5 %@1000PE
Pointing Accuracy	<0.1%
# of telescopes	16(18)

Wide Field Cherenkov Telescope Array

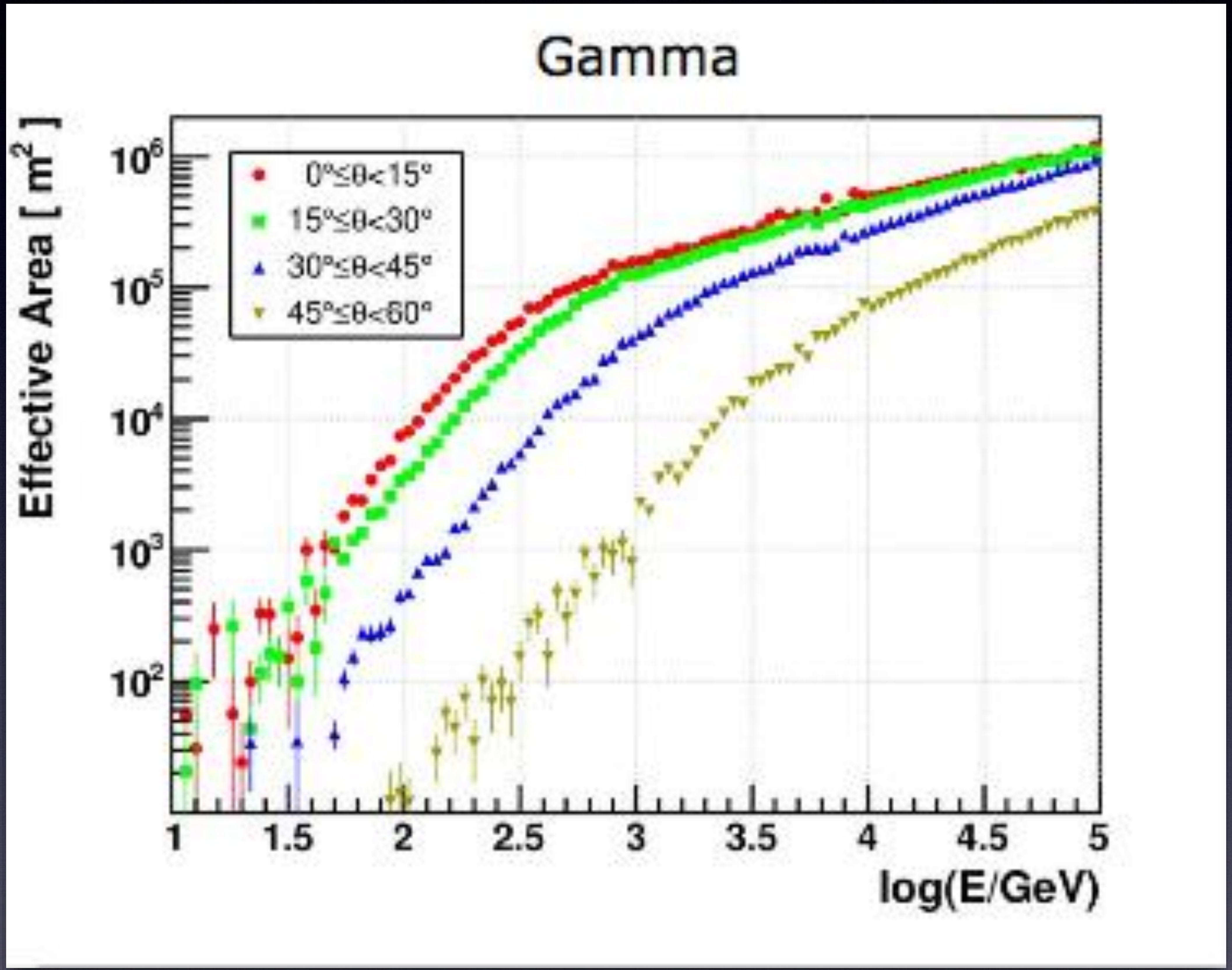



LHAASO Effective Area

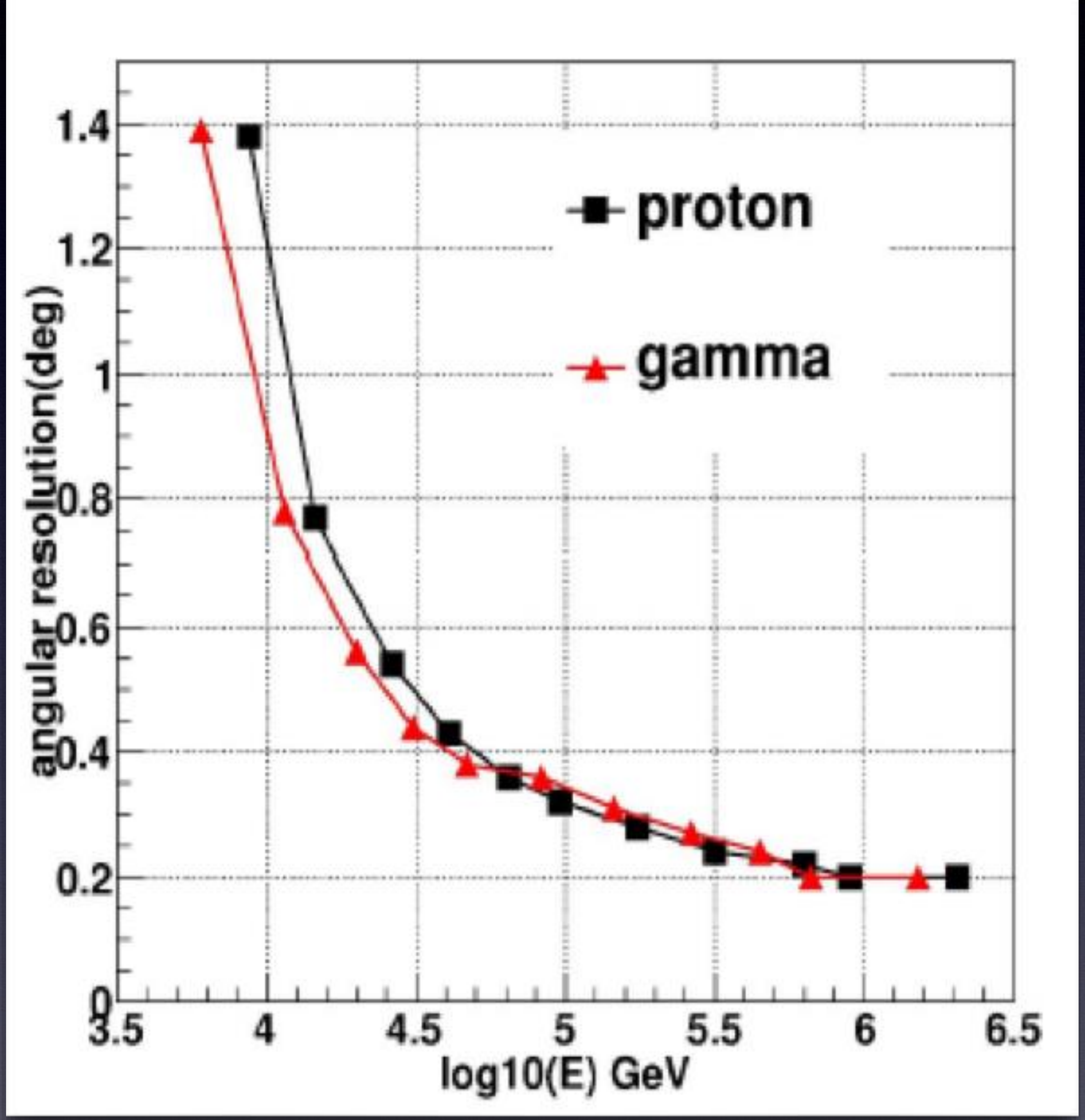


KM2A

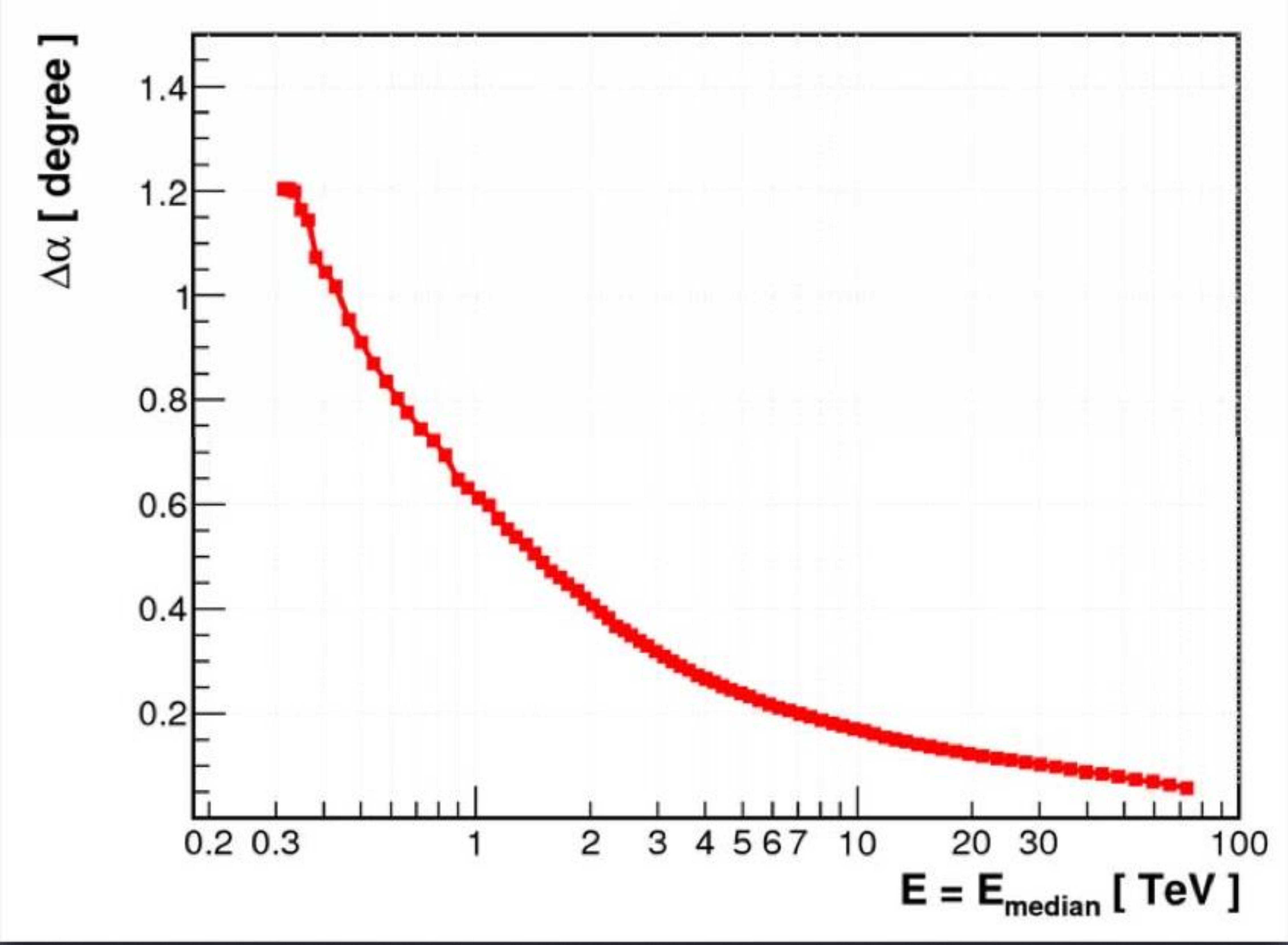


WCDA

LHAASO Angular resolution

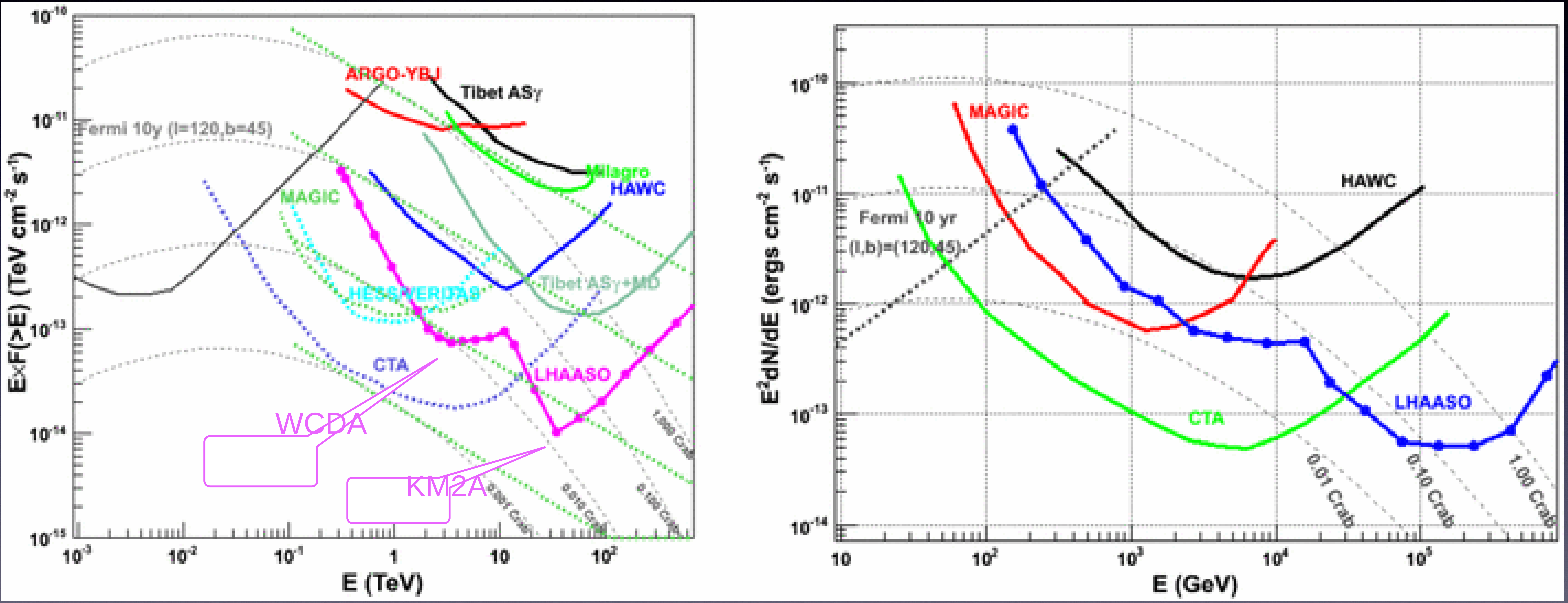


KM2A



WCDA

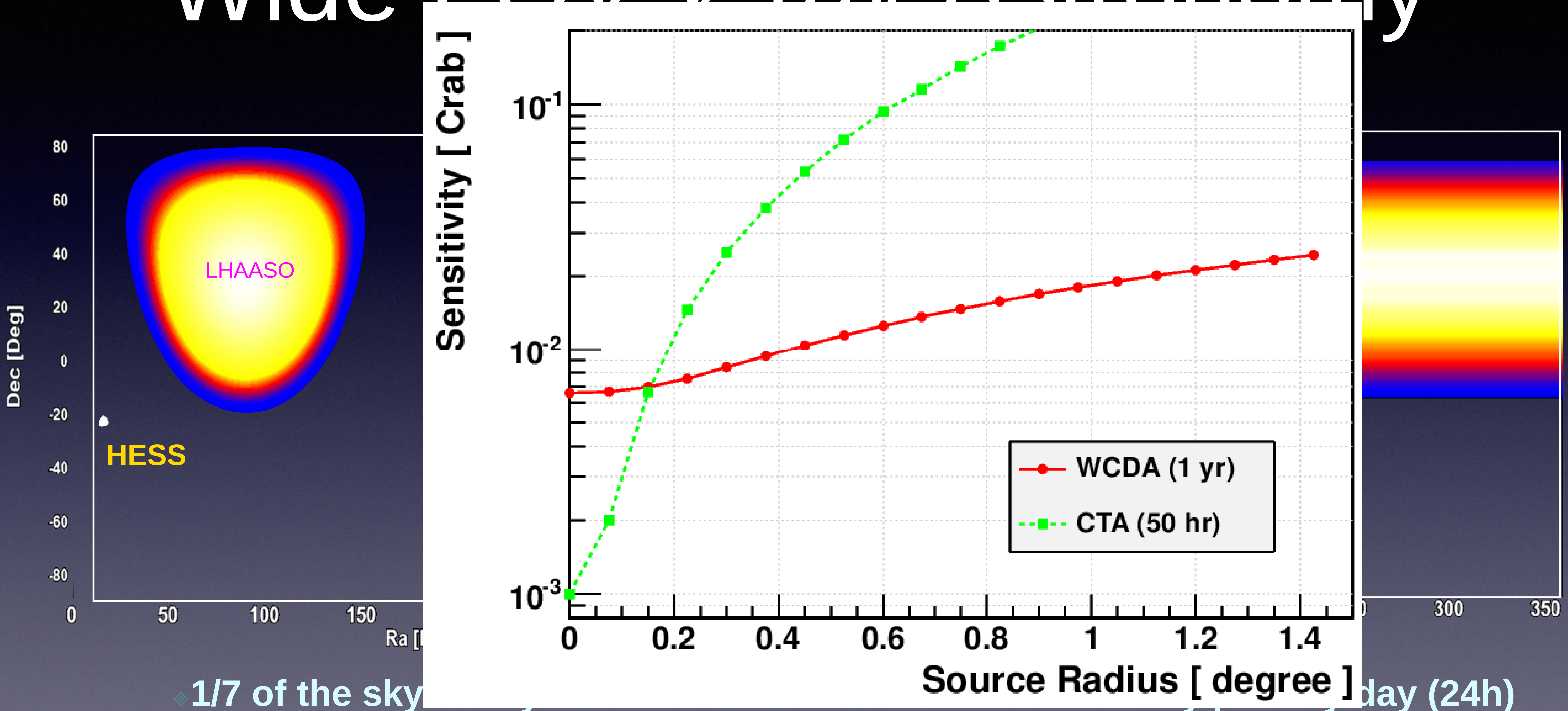
LHAASO Integral Sensitivity



Integral

Differential

Wide FOV γ-ray Astronomy



1/7 of the sky … day (24h)

LHAASO Timeline

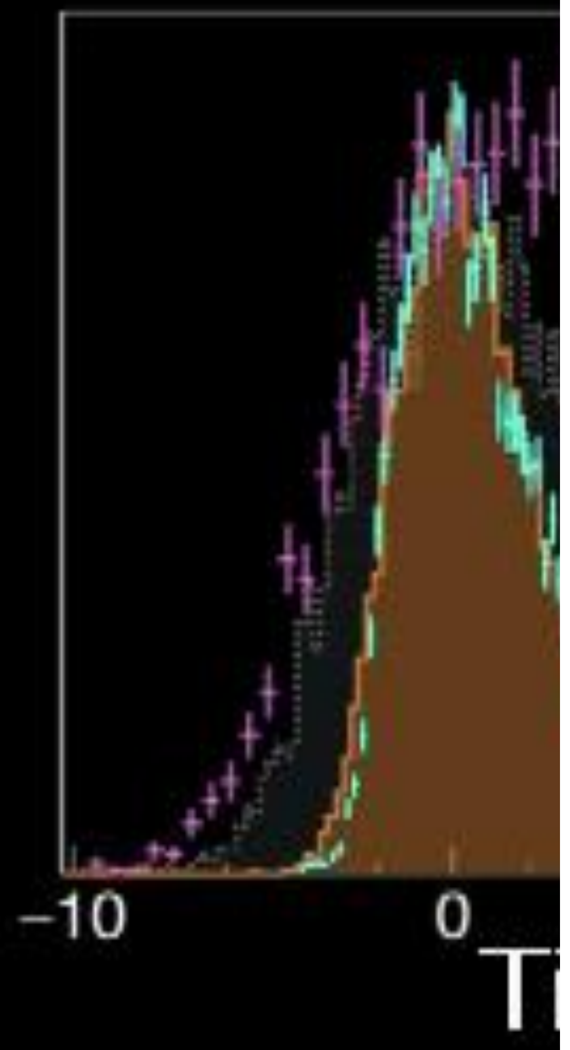
- 2015 TDR
- 2016 approval & release of funds
- 2017 Start of construction
- 2018-2020 construction
- 2021 start or operation

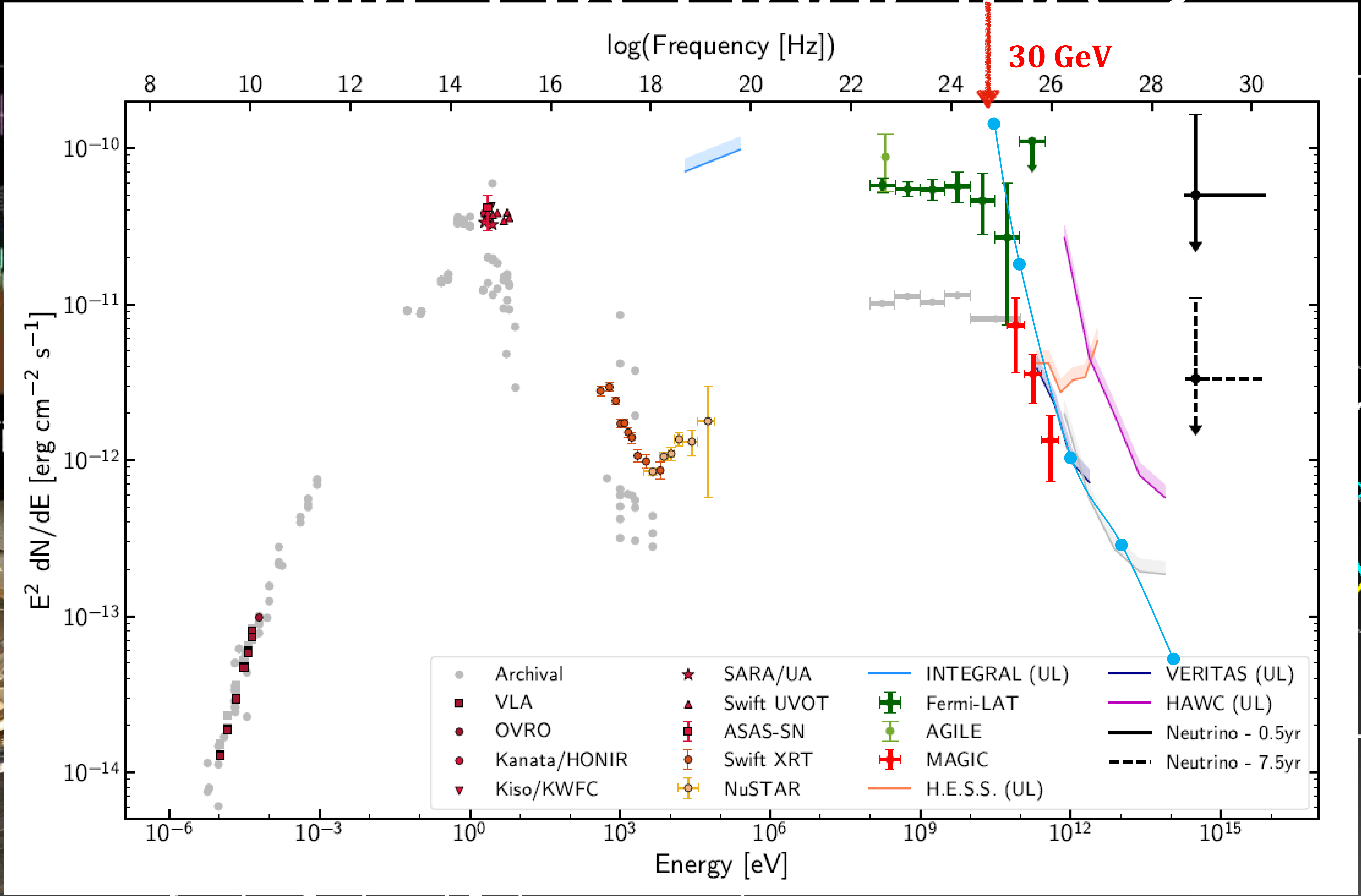
February 2019 25% ready

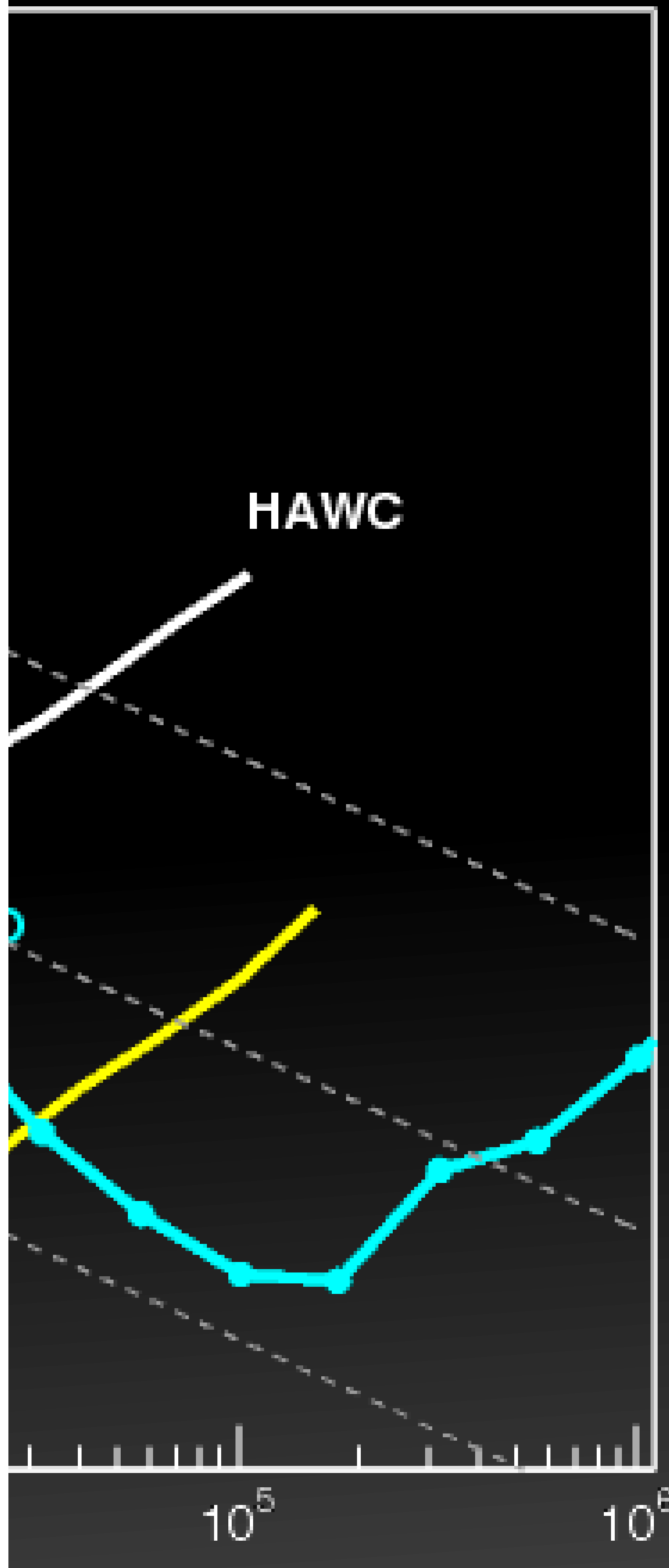
	2018					2019			2020			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
KM2A ED				1383 Units				1800 Units				2008 Units
KM2A MD				300 Units				415 Units				456 Units
WCDA				1st pool May / 2nd pool Sept.								3rd pool July 2020
WFCTA				4 Telescopes		10 telescopes				18 telescopes		

WCDA - Status

WCDA Upgrade 2

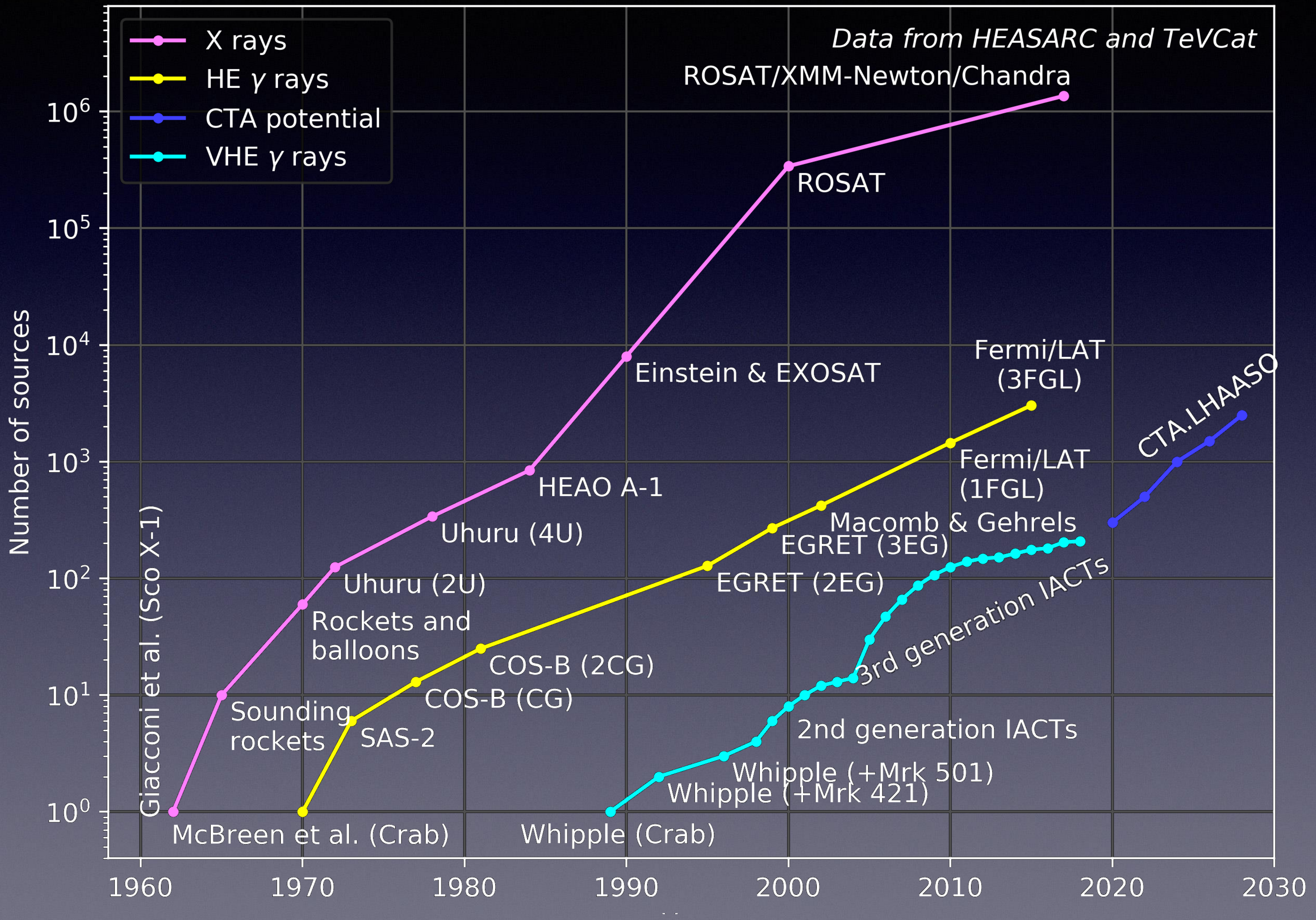






for the 2nd and 3rd water pond.

Conclusion



3FGL 3034 sources > 100 MeV
95% extragalactic!
21% BL Lacs
16% FSRQ
19% unclassified blazars +
22% unassociated high lat
Still lots of association work to come!
(CTA, HAWC, LHAASO, SPACE??…)

My personal Kifune Plot
based on Fegan macro