Ground-base Astrophyics
Experimental methods

Cracow School of Theoretical Physics,
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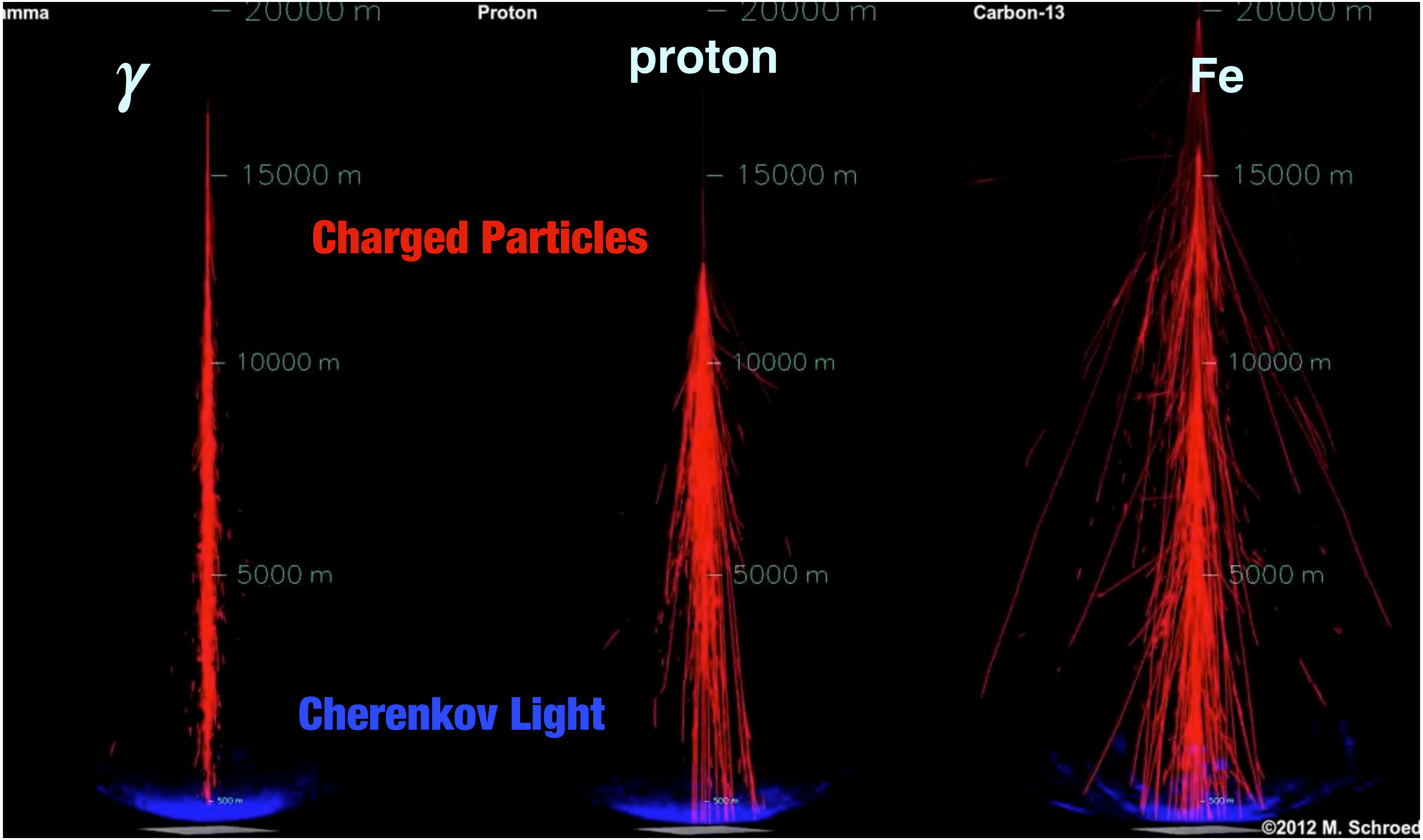
FACULTÉ DES S

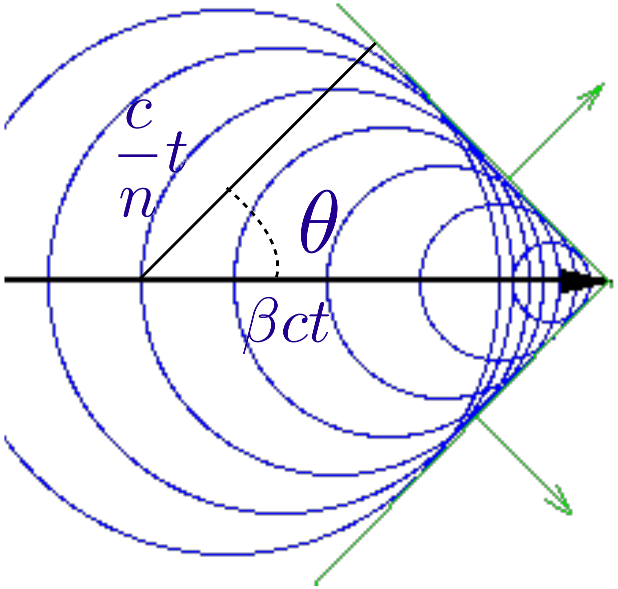


mma
Proton
Carbon-13
20000 m
20000 m
20000 m
γ
proton
Fe
15000 m
15000 m
15000 m
Charged Particles
10000 m
10000 m
10000 m
5000 m
5000 m
5000 m
Cherenkov Light
©2012 M. Schroed

for water $\theta_c^{max} = 42°$
for neon at 1 atm $\theta_c^{max} = 11\ mrad$

renkov Radiation

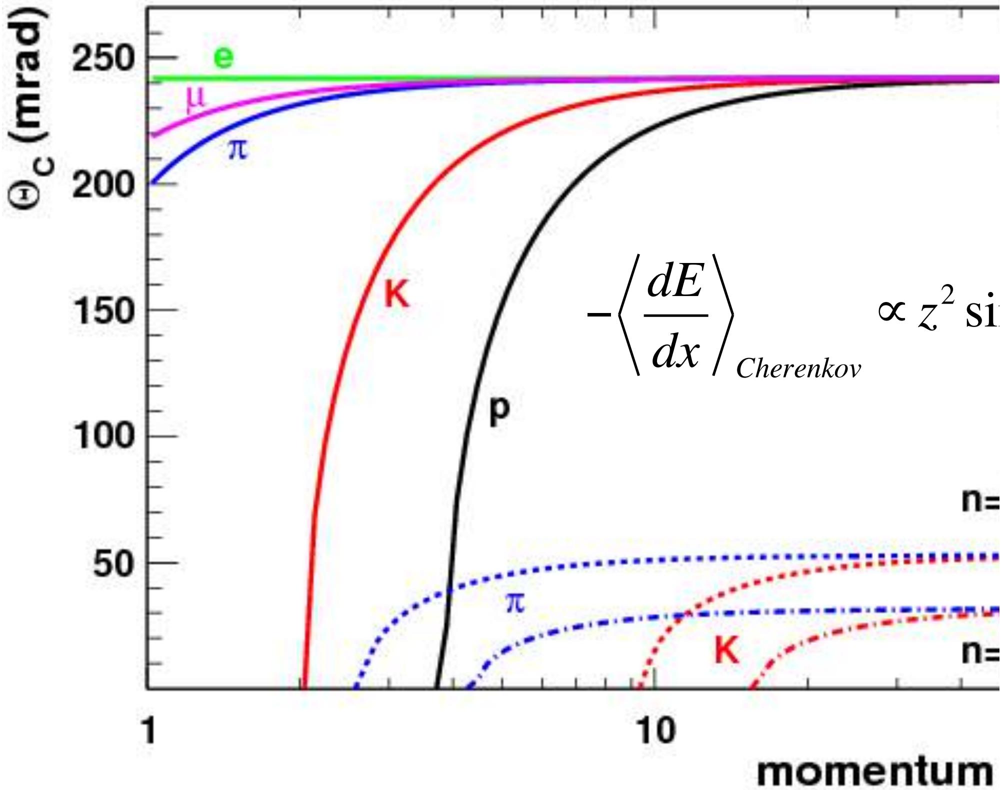
ion…. The material is the radiator not the particle!



$$cos(\theta_c) = \frac{1}{\beta n}$$

$$\Downarrow$$

$$\beta_{th} > \frac{1}{n}$$



$$\frac{N_{ph}}{dx d\lambda} = 2\pi\alpha Z^2 \frac{sin^2\vartheta_c}{\lambda^2}$$ **NR. OF γ PRODUCED**

Energy loss by Cherenkov radiation very small w.r.t. ionization (< 1%)

$$\frac{N_{ph}}{dX d\lambda} = 2\pi\alpha Z^2 \frac{sin^2\vartheta_c}{\lambda^2}\frac{z_0}{X} \Leftarrow dX = \frac{X}{z_0}dz \Leftarrow$$

$\rho(z) = \rho_0 e^{-z/z_0}$ $z_0 = RT/gM=8.4$

HYDROSTATIC ISOTHERMAL ATMOSP

·enkov light

$$\frac{{}^2 N_{ph}}{lX d\lambda} = 2\pi\alpha Z^2 \frac{sin^2\vartheta_c}{\lambda^2}\frac{z_0}{X}$$

$$T = X_0 \sum_{\mu=0}^{t_{\max-1}} 2^\mu + t_0 \cdot N_{\max} \cdot X_0$$

with t_0: range of electron [given in units of X_0]

$$= X_0 \cdot (2^{t_{\max}} - 1) + t_0 \cdot \frac{E_0}{E_c} X_0$$

$$= X_0 \cdot (2^{\log_2 E_0/E_c} - 1) + t_0 \cdot \frac{E_0}{E_c} X_0 \approx (1 + t_0) \cdot \frac{E_0}{E_c} X_0 \quad \text{c}$$

E
tc

KOV LIGHT A CALORIMETRIC ME/

As only electrons contribute ...

$$T = \frac{E_0}{E_c} \cdot X_0 \cdot F \qquad [\text{ with } F < 1]$$

$$\cdot = \int_{\lambda_1}^{\lambda_2} 2\pi\alpha Z^2 \frac{\sin^2\vartheta_c}{\lambda^2} = 2\pi\alpha Z^2 \sin^2\vartheta_c \left[\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right] \approx 390 Z^2 sin^2\vartheta_c \text{ photons}/cm \quad [350\ nm; 500\ nm]$$

$$\approx 780 Z^2 (n-1) \text{ photons}/cm$$

$1)_{air} = 0.00028$

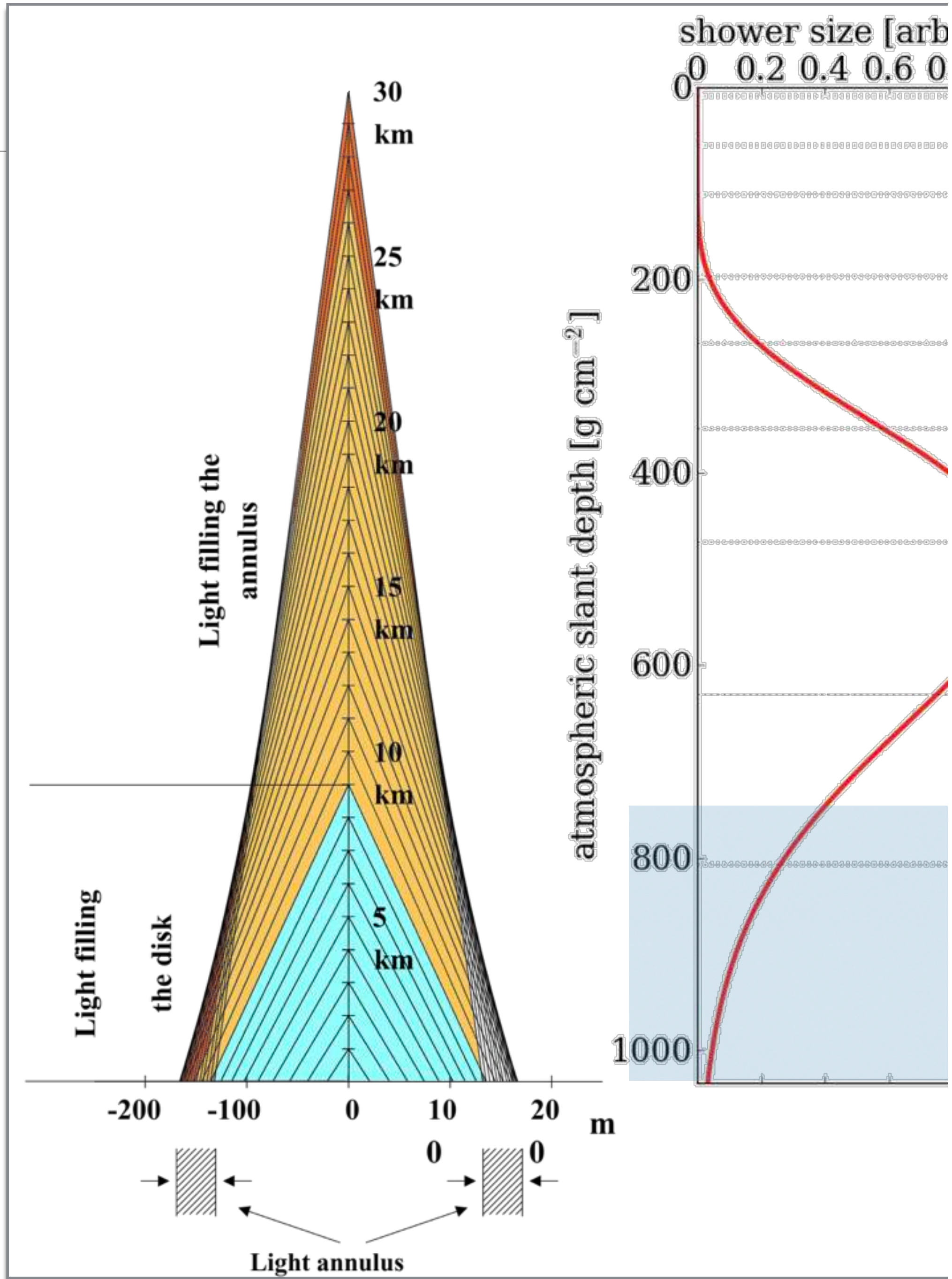
2-3 photons!

But we need to integrate along track lengths and also we have many partial in the s

$$\frac{N_{ph}}{d\lambda} = \int dX\, N_e(t) \times \frac{d^2N_{ph}}{dX\,d\lambda} = 6 \times 0.31\sqrt{y}X_0 \times \frac{E_0}{E_c} \times \frac{d^2N_{ph}}{dX\,d\lambda} \int \frac{ds}{(3-s)^2} \exp\left(\frac{2s}{3-s}\left(1 - \frac{3}{2}\ln s\right.\right.$$

ection technique

aging Air Cherenkov IACT



rescence light

ɜnergy loss by ionisation can excites some nitrogen
ɜd states with then de-excite via fluorescence light

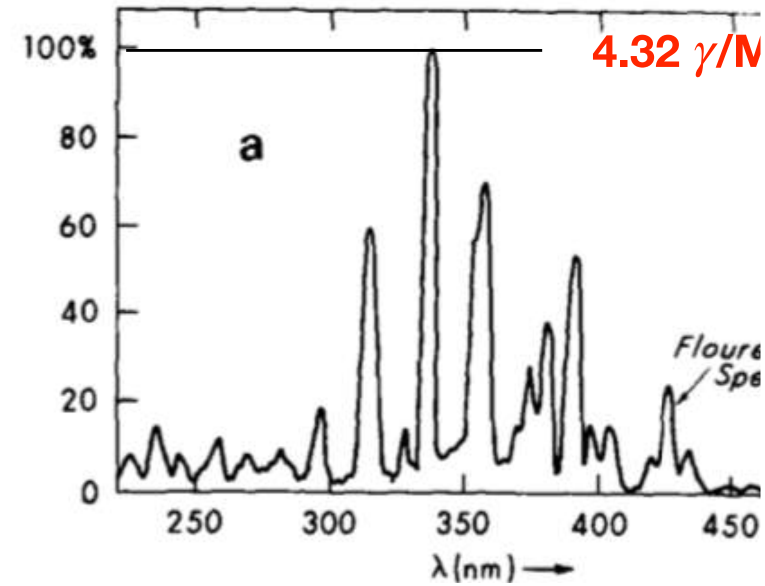
sion is isotropic $\frac{d^2 N_{ph}}{dx d\Omega} = \frac{N_\gamma N_e}{4\pi}$

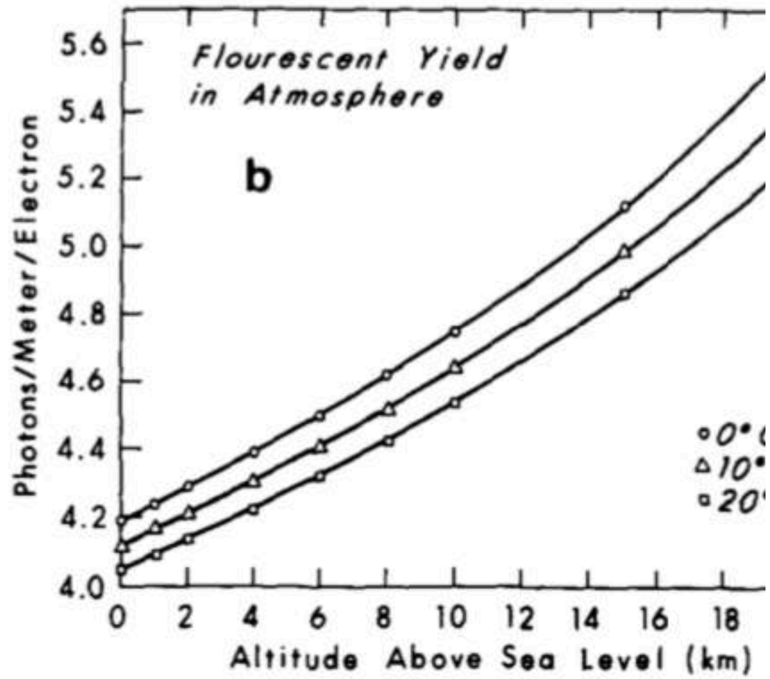
ɜame dependence affect also energy per meter track
h deposited by ionisation but it is almost perfectly
eled by the pressure dependence of the fluorescence

$$\Delta E \propto p_{\mathrm{ATM}}$$
$$\frac{dN_\gamma}{dE} \;\square\; \frac{1}{p_{\mathrm{ATM}}} \qquad N_\gamma = \frac{dN_\gamma}{dE} \cdot \Delta E \approx const.$$

yield is quite low ~0.5% but a lot of energy is released
eV ~ 1J in 30 µs

LEVEL 2P OF N_2 & 1N OF N_2^+





rescence

emission is isotropic, can be seen from far distant

ıowers above 10^{17} eV can be detected from impact parameter > 30 km.

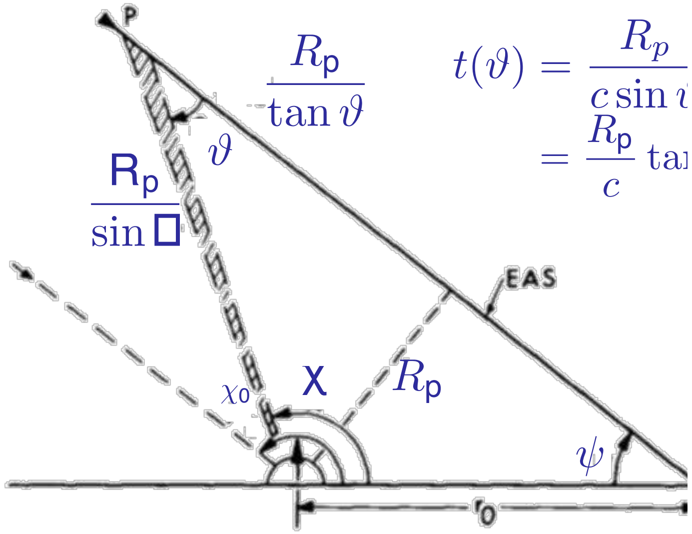
kinematics constrain the shower angle and impact point, which be fitted from data

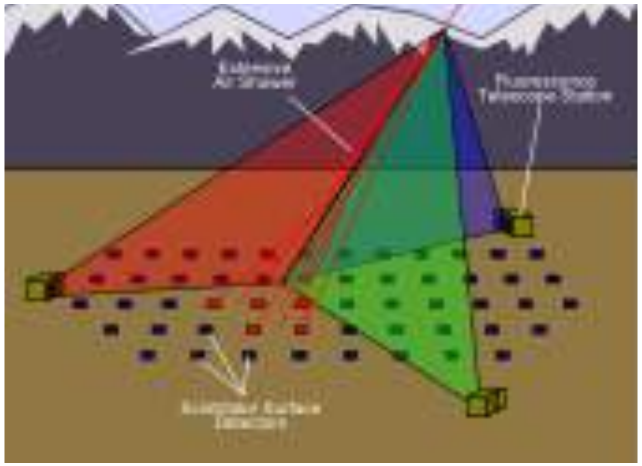
$$\chi_0 = \chi + \vartheta \qquad \chi_i(t_i) = \chi_0 - 2\tan^{-1}\left(c\frac{t_i - t_0}{R_p}\right)$$

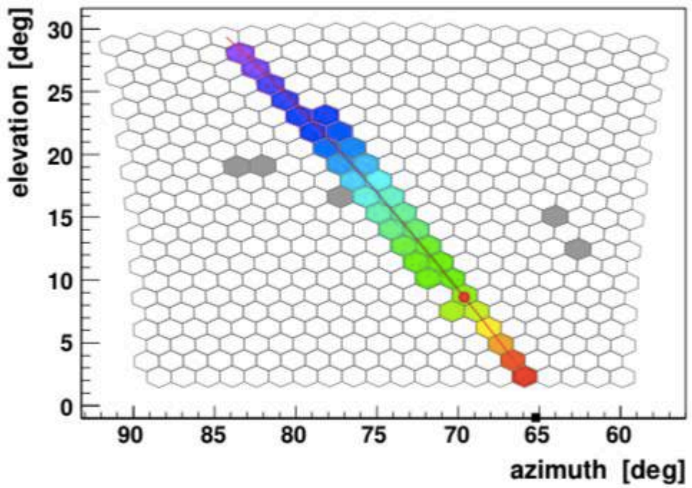
ȷle telescope can achieve ~30% precision for track lenght ~50

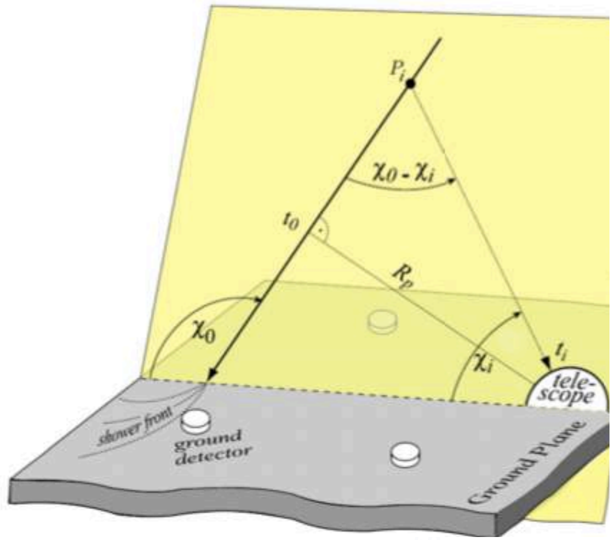
ro technique increase precision and allow to simultaneous fit rgy, Xmax, and shower axis

s is further improved by Hydrid measurements



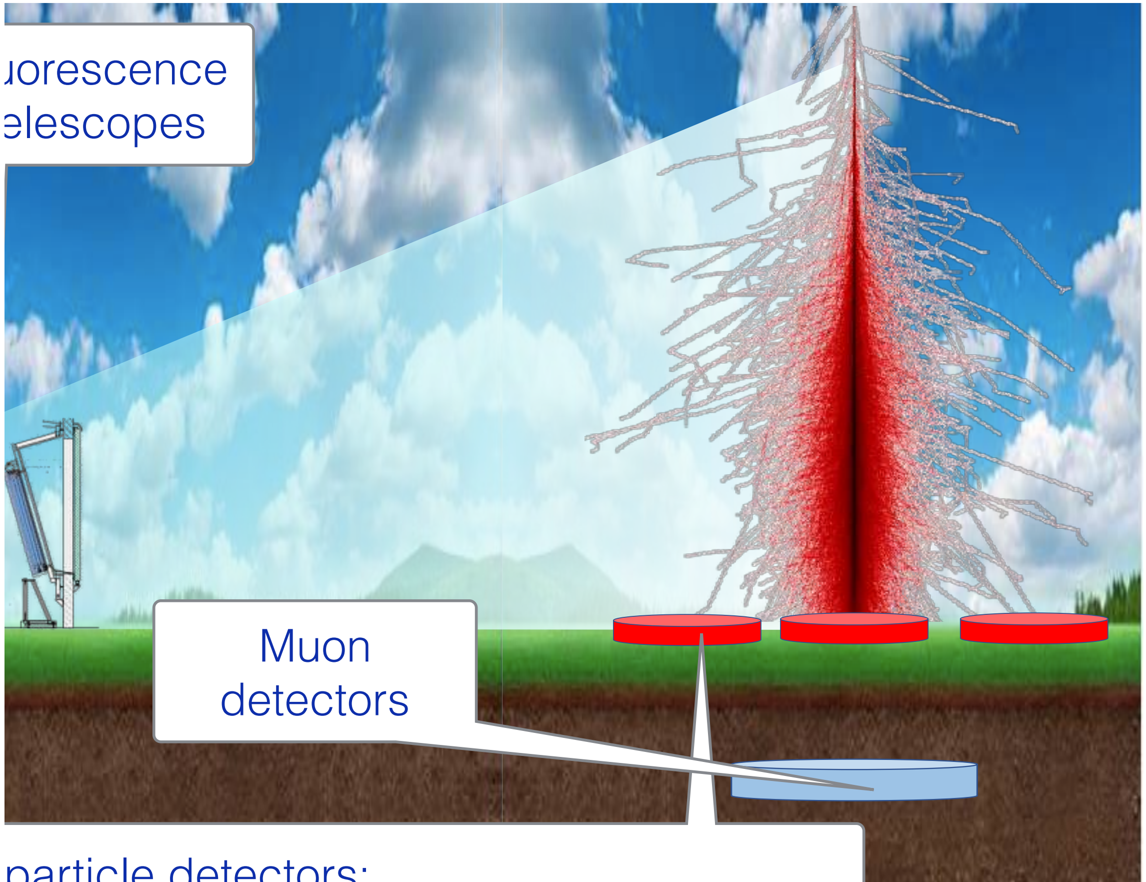


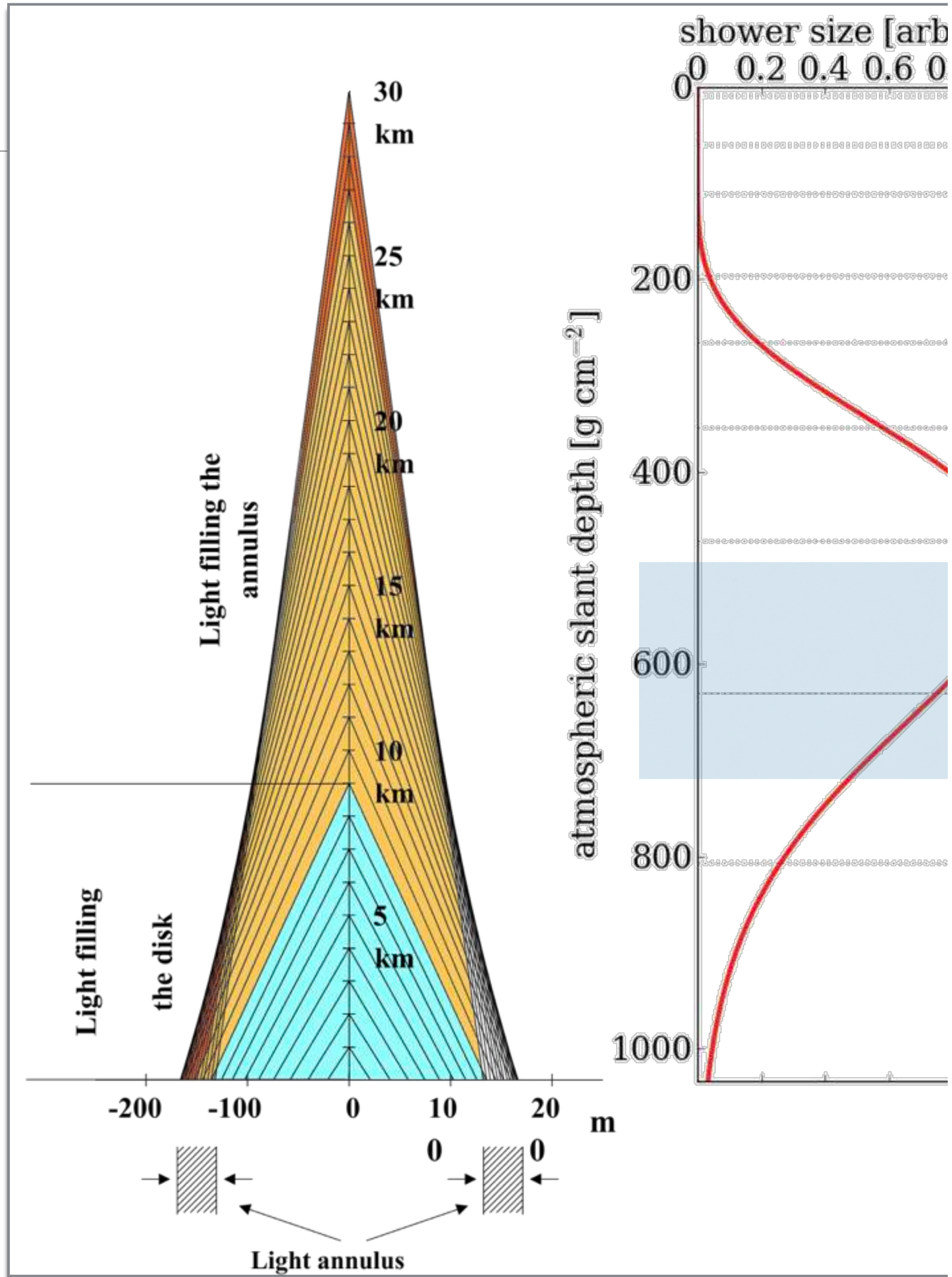




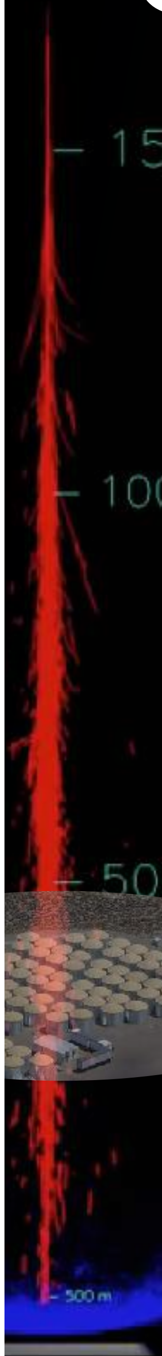
ection technique

EAS detectors



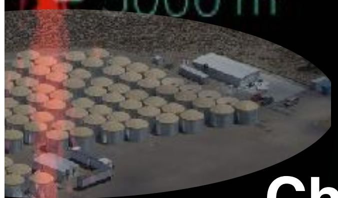


Ground-base Cosmic ray physics



Satellites
FERMI, AMS, DAMPE

EAS Detectors
(HAWC, LHAASO)

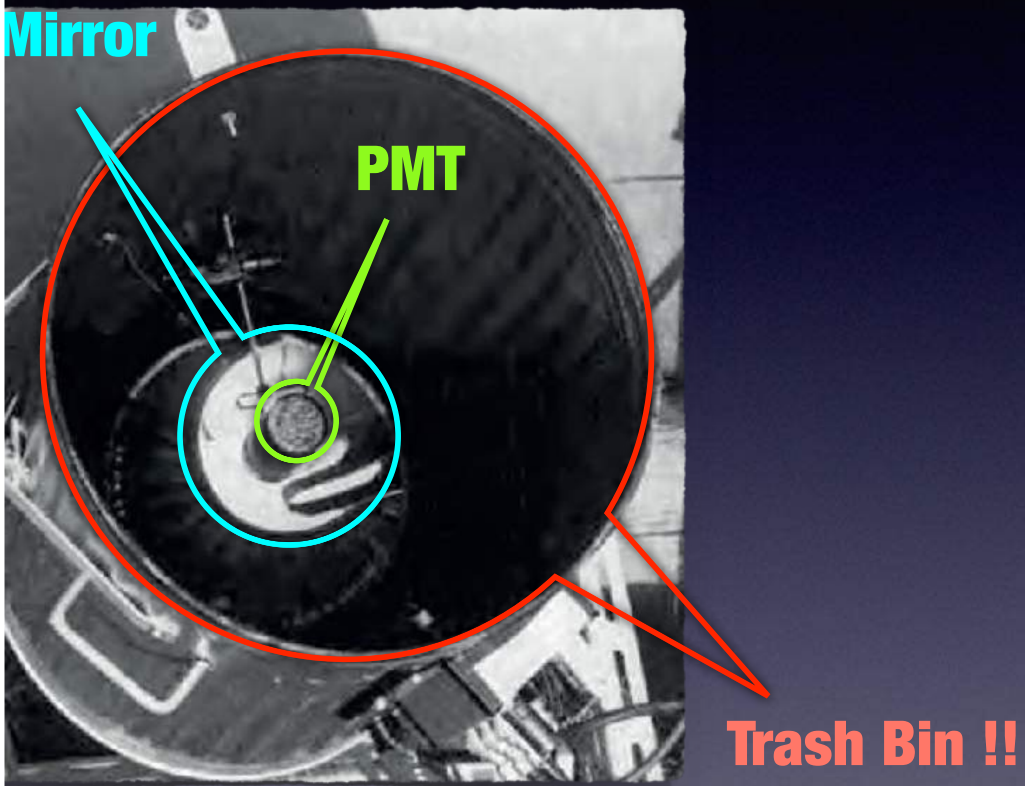


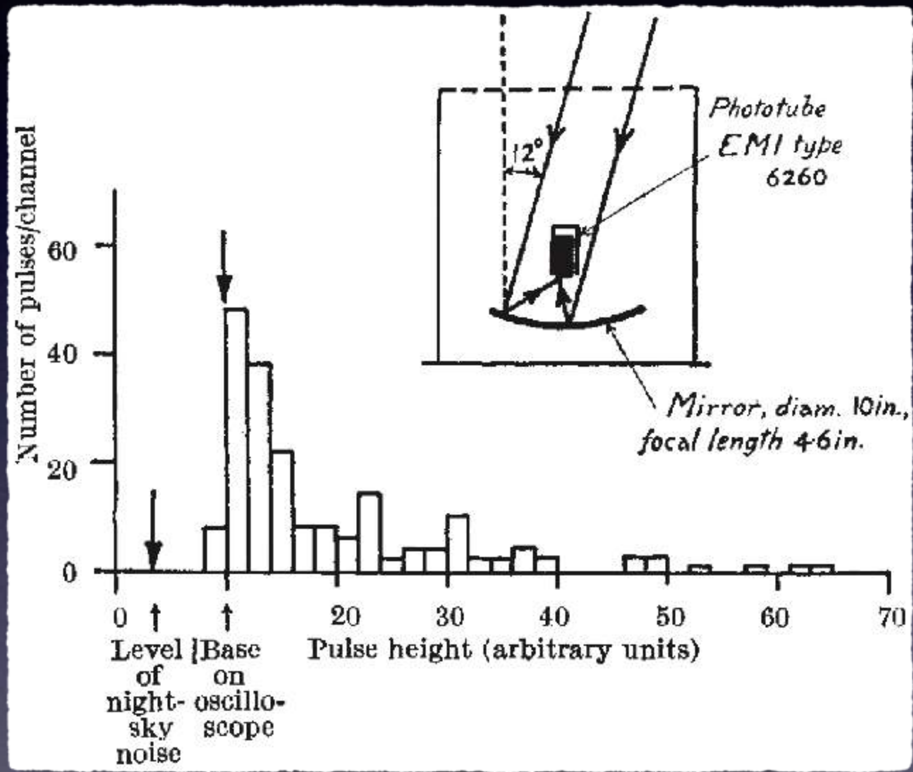
Cherenkov Telescopes
HESS, MAGIC,VERITAS, CTA

	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 de
Effective Area	decrease with zenith	increase with zenit
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
CTA
North - Canary Island
South - Paranal -Chile
Pierre Auger
Argentina
H.E.S.S. Namibia

amma-ray astronomy - The pionee





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

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

The first array Attempt

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

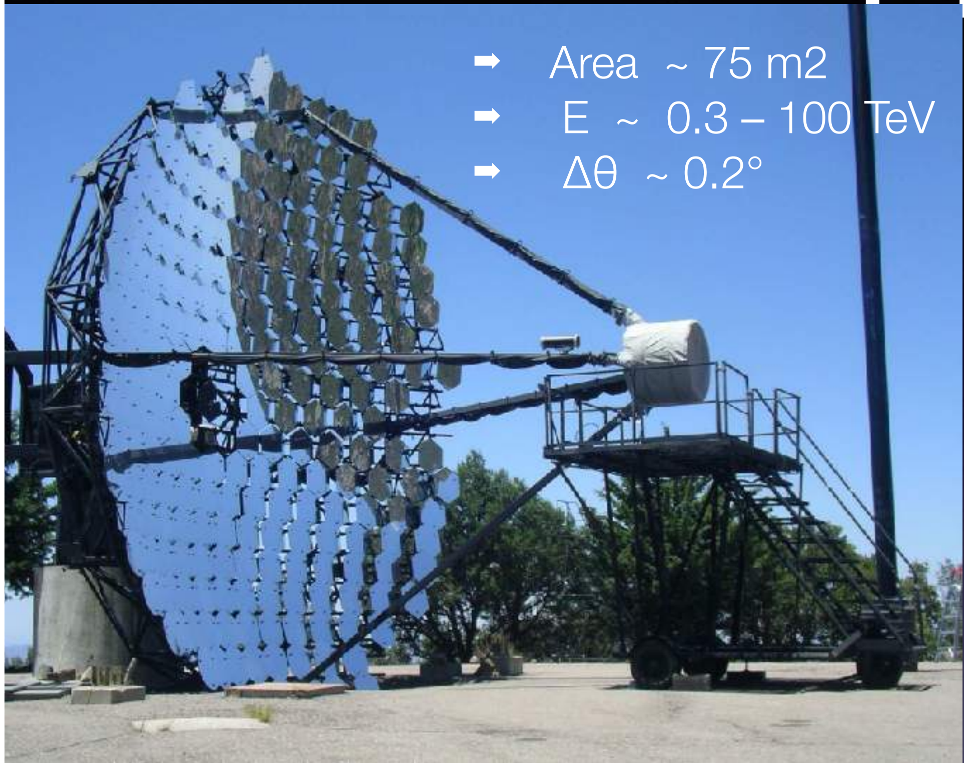
Each of those units can be positioned al
railway system and view the air showers
under slightly different angles.

This arrangement allowed both coincide
measurements and simple multi-telesco
observations.

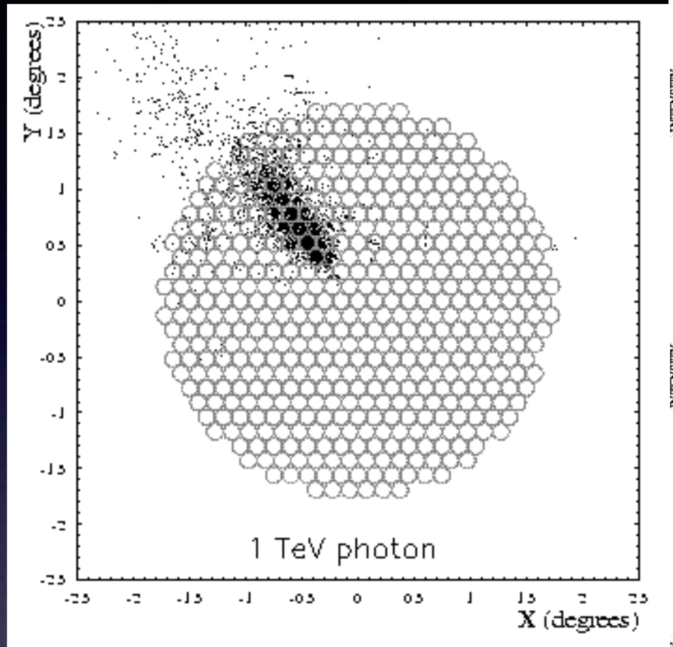
system was used from 1960 until 1963 but unsuccessfully. Why?

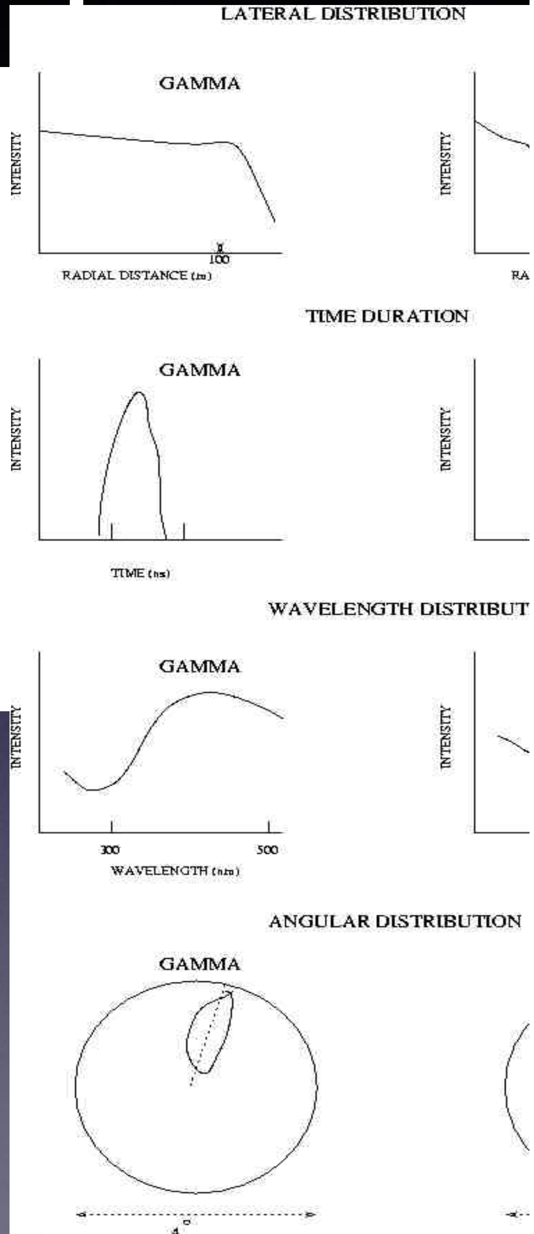
High background rate due to hadronic showers (about a factor of 10^3 more than gammas).
Light contamination from NSB, moon, stars.

The Whipple telescope

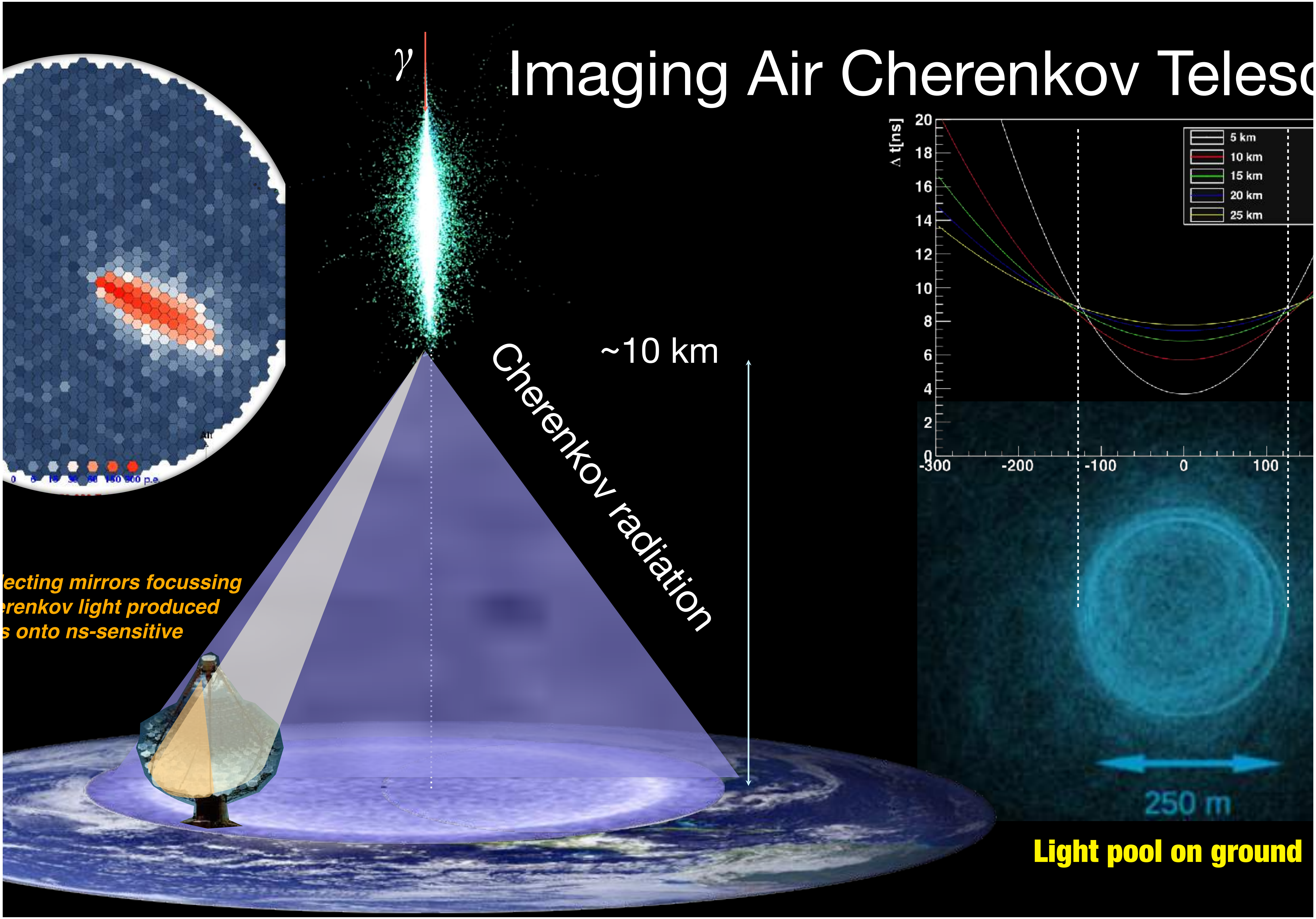


- ➡ Area ~ 75 m2
- ➡ E ~ 0.3 – 100 TeV
- ➡ Δθ ~ 0.2°

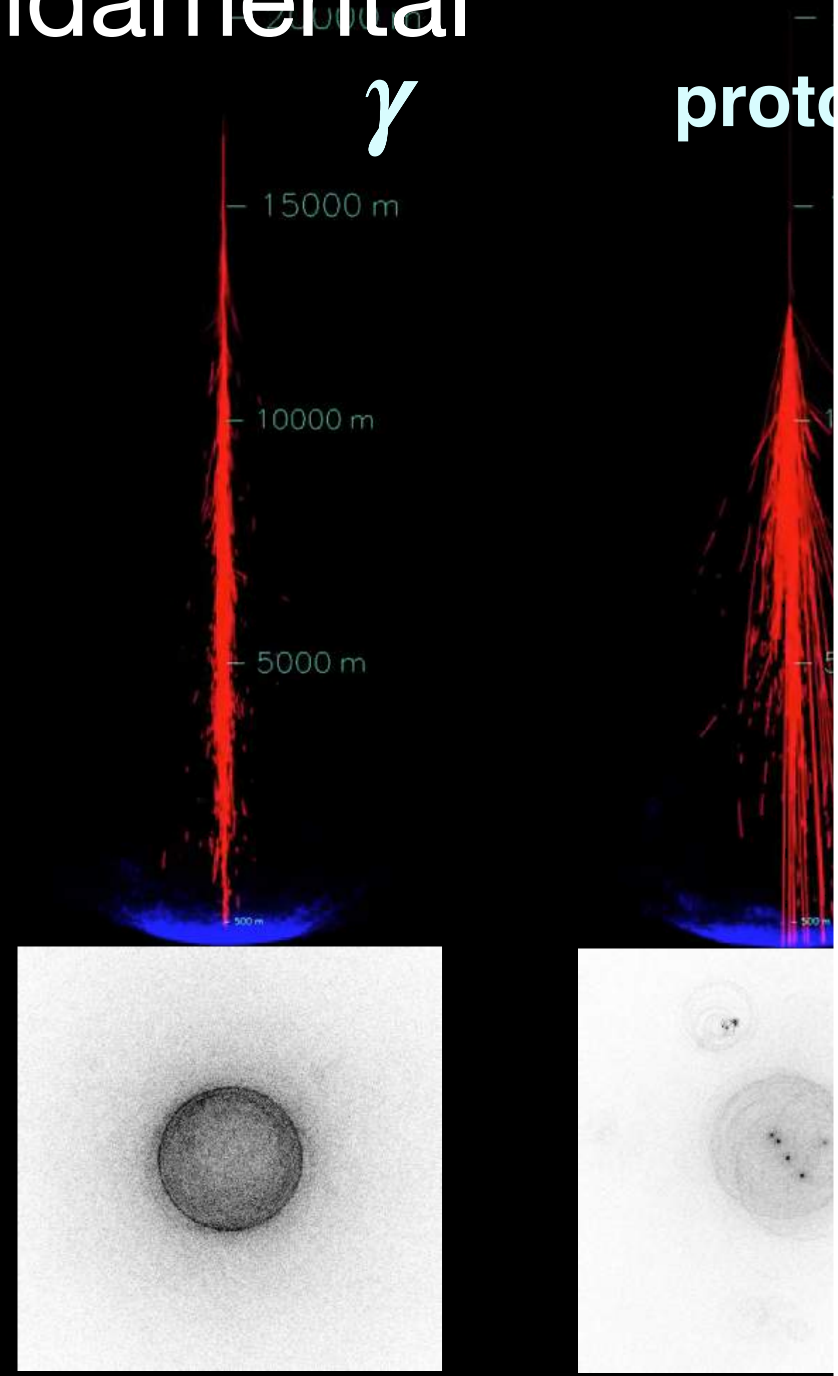




eys of success
rge light collection area and imaging camera (37 PMTs) covering a
ld of view of 3.5 degrees
significant of effort to improve the analysis and gamma/hadron
scrimination methods, based on image first and second moments 3
mmonly known as Hillas parameters
cused on Crab Nebula …strongest steady state gamma-ray emitter!!


Imaging Air Cherenkov Telesc
γ
~10 km
Cherenkov radiation
lecting mirrors focussing
renkov light produced
s onto ns-sensitive
Δ t[ns]
5 km
10 km
15 km
20 km
25 km
-300
-200
-100
0
100
250 m
Light pool on ground

Hadrons/γ separation is fundamental



Hadrons/γ separation is fundamental

age Shape

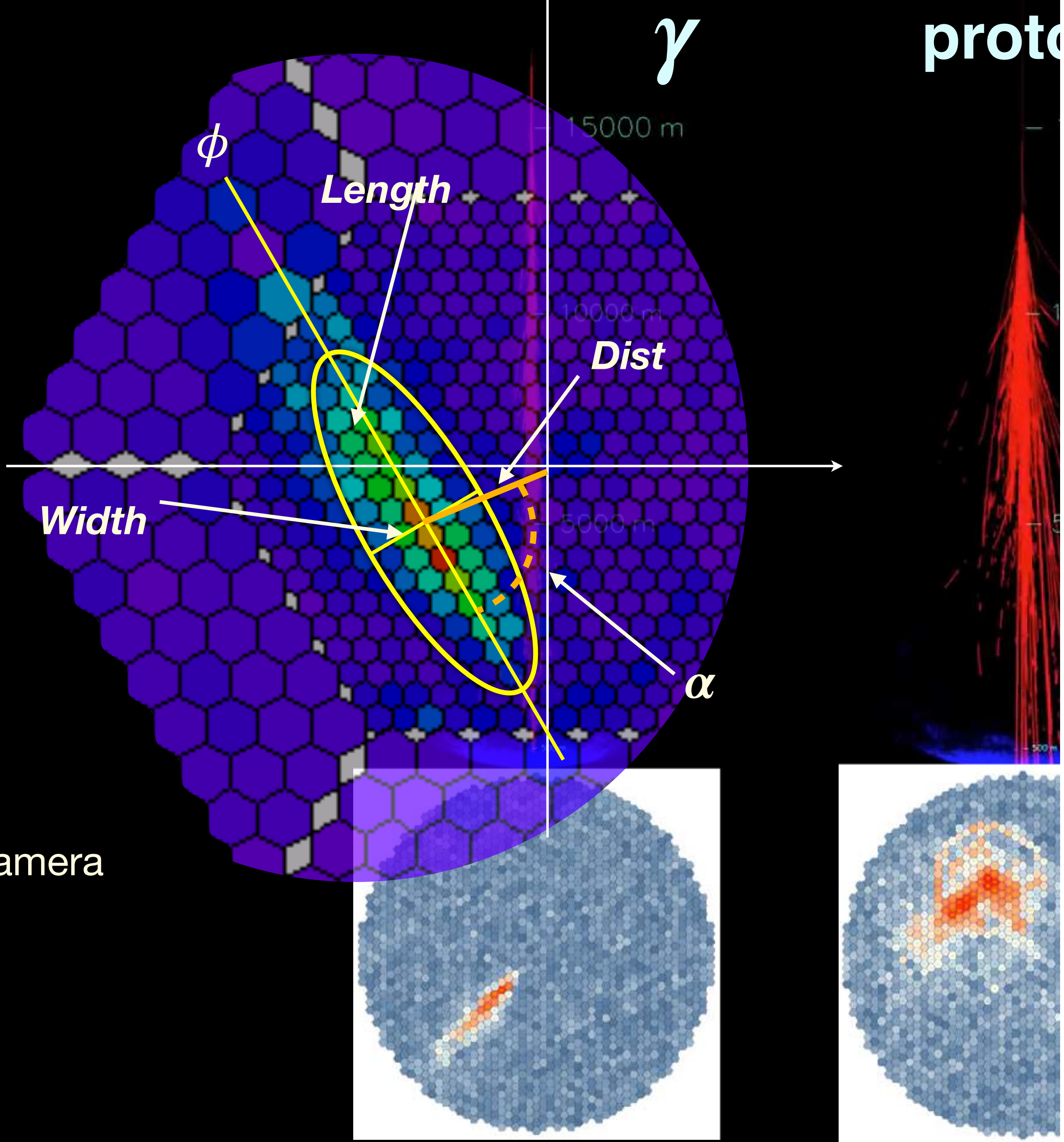
Particle type

ensity of the Image

Shower Energy

ientation of the image

Shower Direction



s Parameters

= length and **W**= width of the ellipse

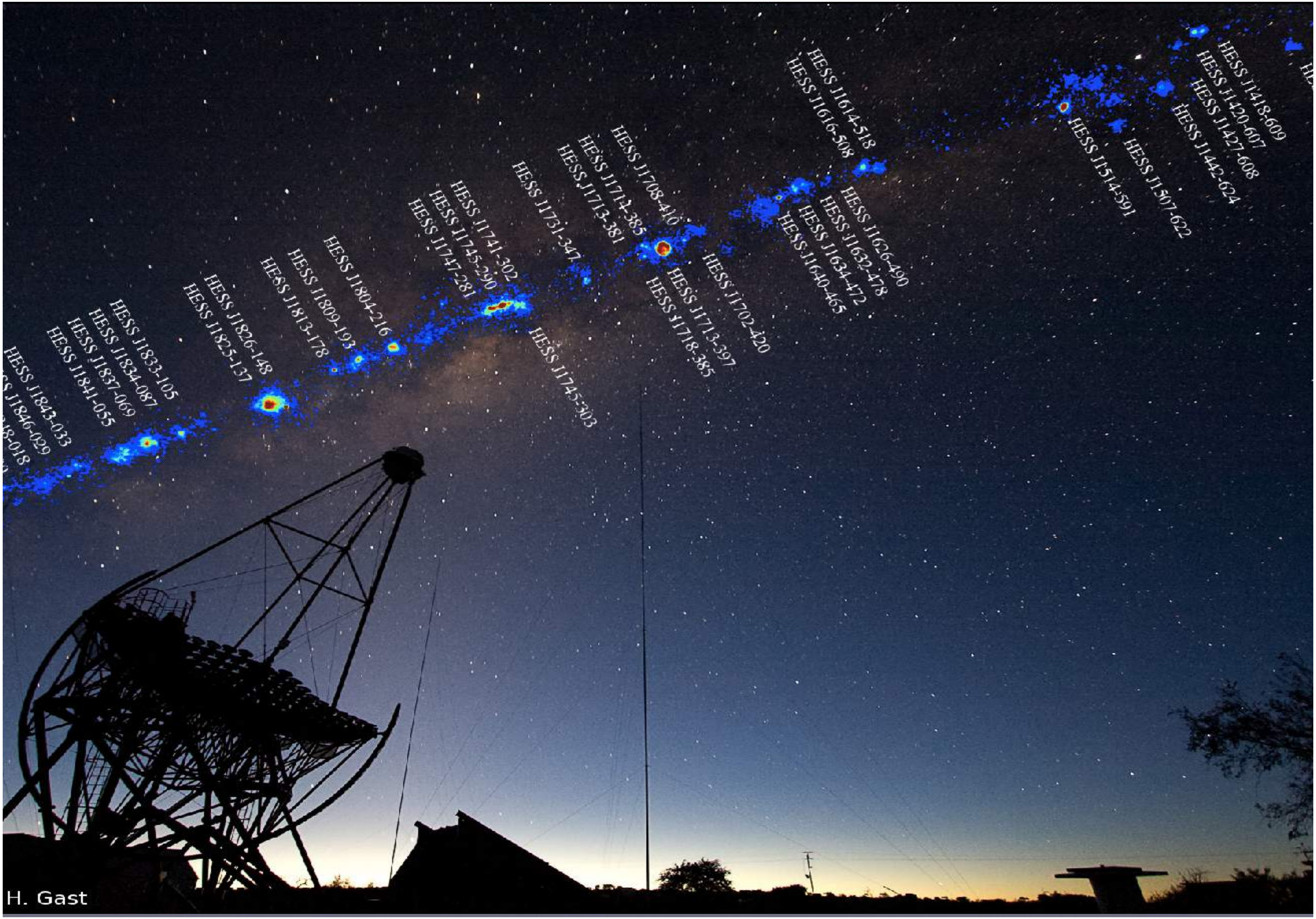
ZE (total image amplitude)

nominal distance (between the centre of the camera

nd the image centre of gravity)

azimuthal angle of the image main axis

orientation angle


HESS J1418-609
HESS J1420-607
HESS J1427-608
HESS J1442-624
HESS J1507-622
HESS J1514-591
HESS J1614-518
HESS J1616-508
HESS J1626-490
HESS J1632-478
HESS J1634-472
HESS J1640-465
HESS J1708-410
HESS J1714-385
HESS J1713-381
HESS J1702-420
HESS J1713-397
HESS J1718-385
HESS J1731-347
HESS J1741-302
HESS J1745-290
HESS J1747-281
HESS J1745-303
HESS J1804-216
HESS J1809-193
HESS J1813-178
HESS J1826-148
HESS J1825-137
HESS J1833-105
HESS J1834-087
HESS J1837-069
HESS J1841-055
HESS J1843-033
H. Gast

ow to do better with IACT arrays

More events

- More photons = better spectra, images, fainte

  ✓ Larger collection area for gamma-rays

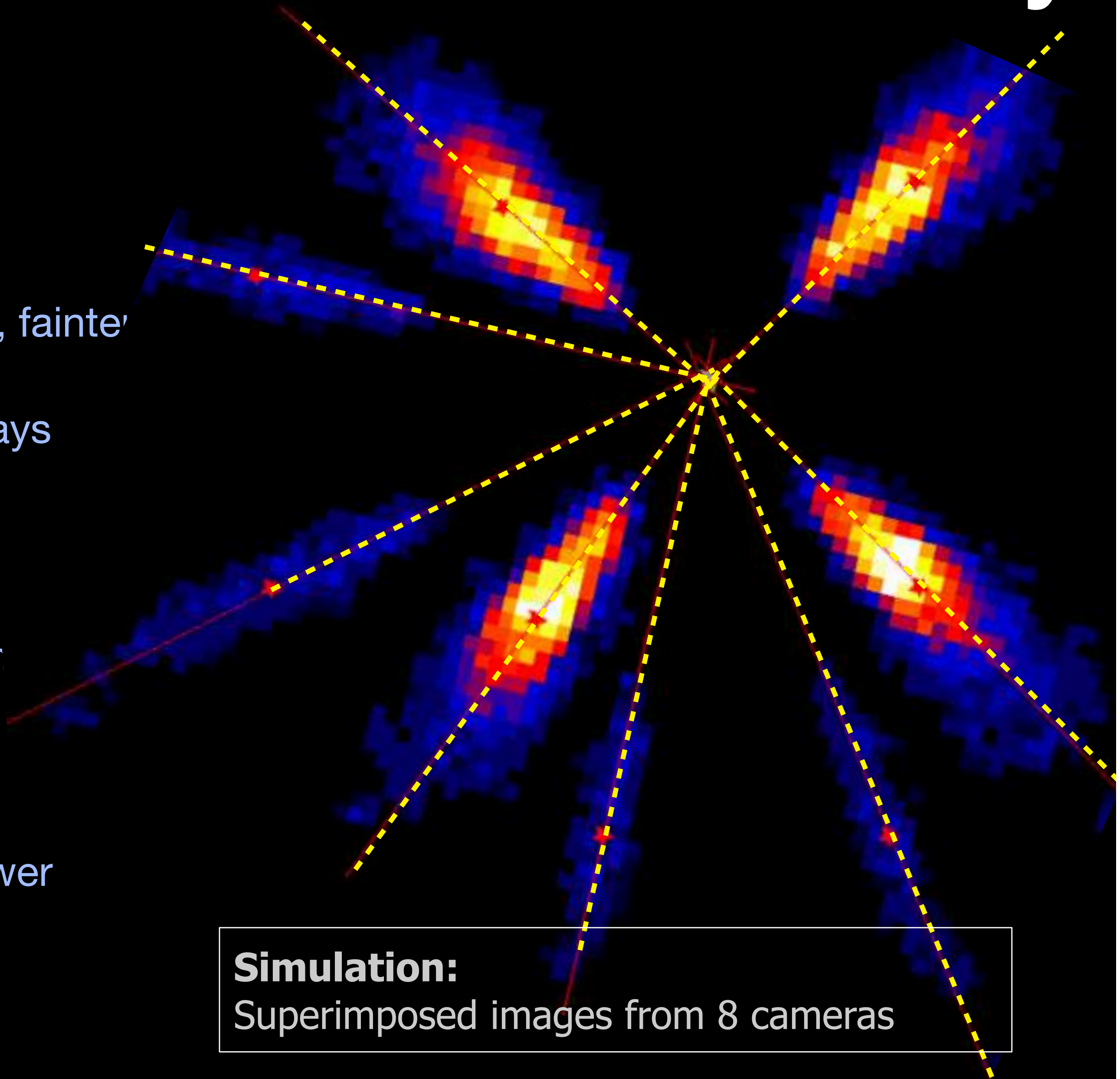
Better events

- More precise measurements of atmospl

  ✓ Improved angular resolution

  ✓ Improved background rejection power

More telescopes!



Simulation:
Superimposed images from 8 cameras

CTA Reach

. Galactic objects

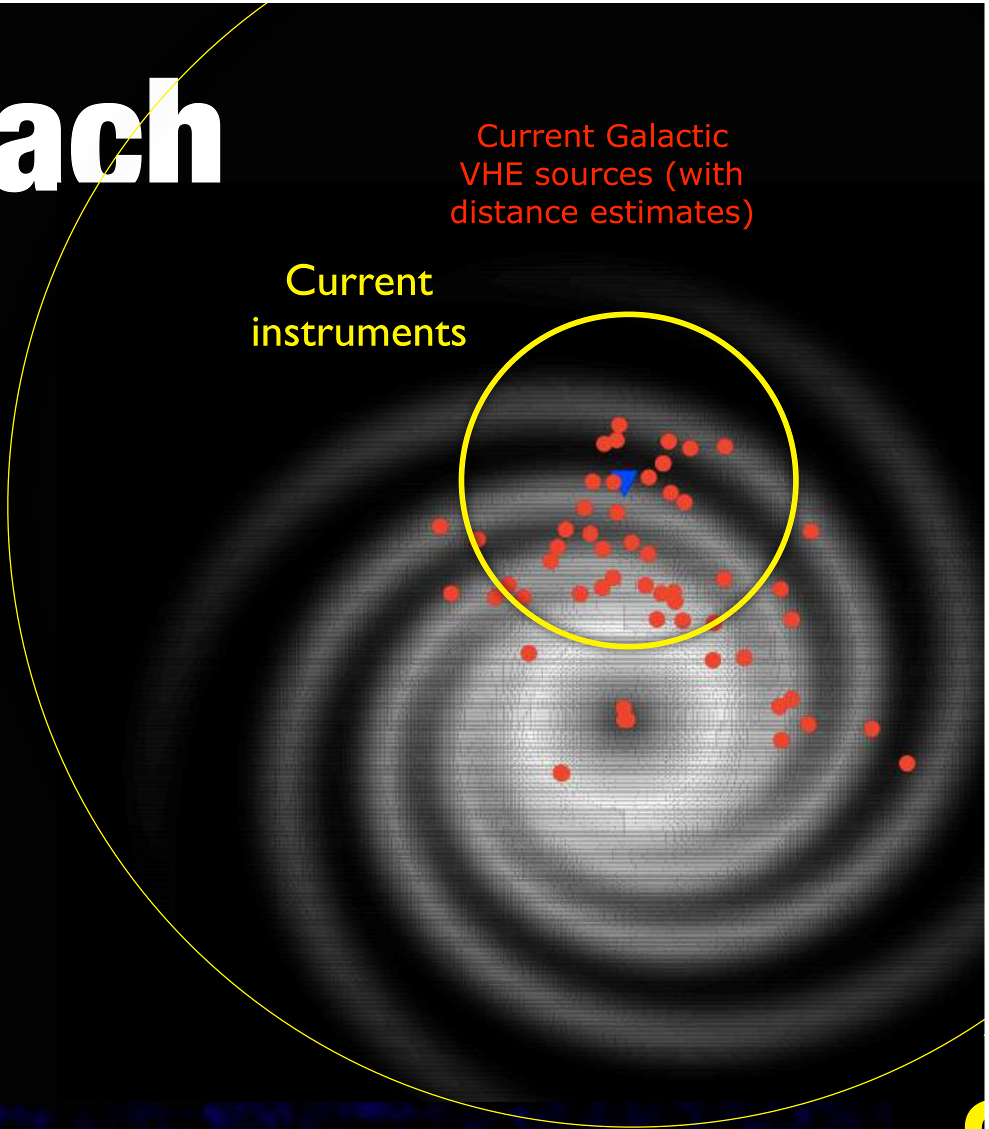
wly born pulsars and the supernova remnants

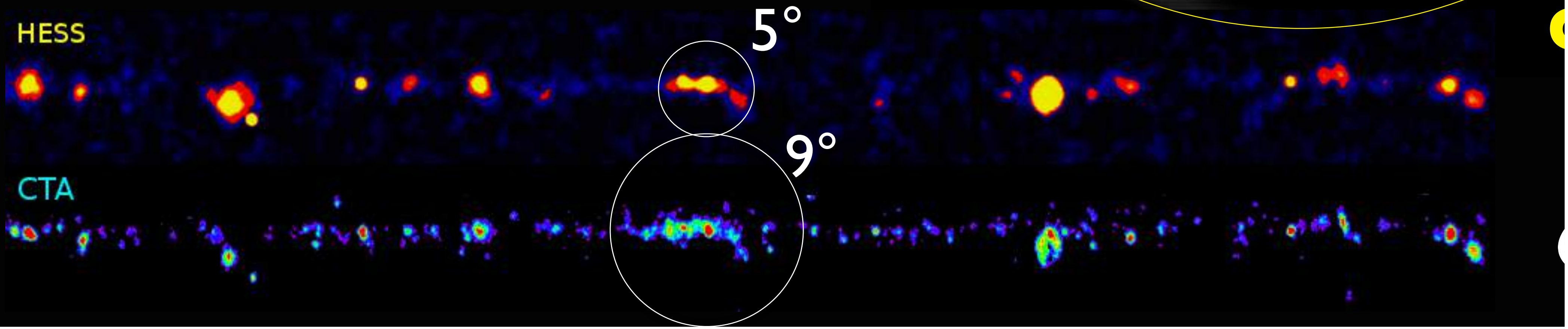
have typical brightness such that HESS etc can see only relatively local (typically at a few kpc) objects

A will see **whole** Galaxy

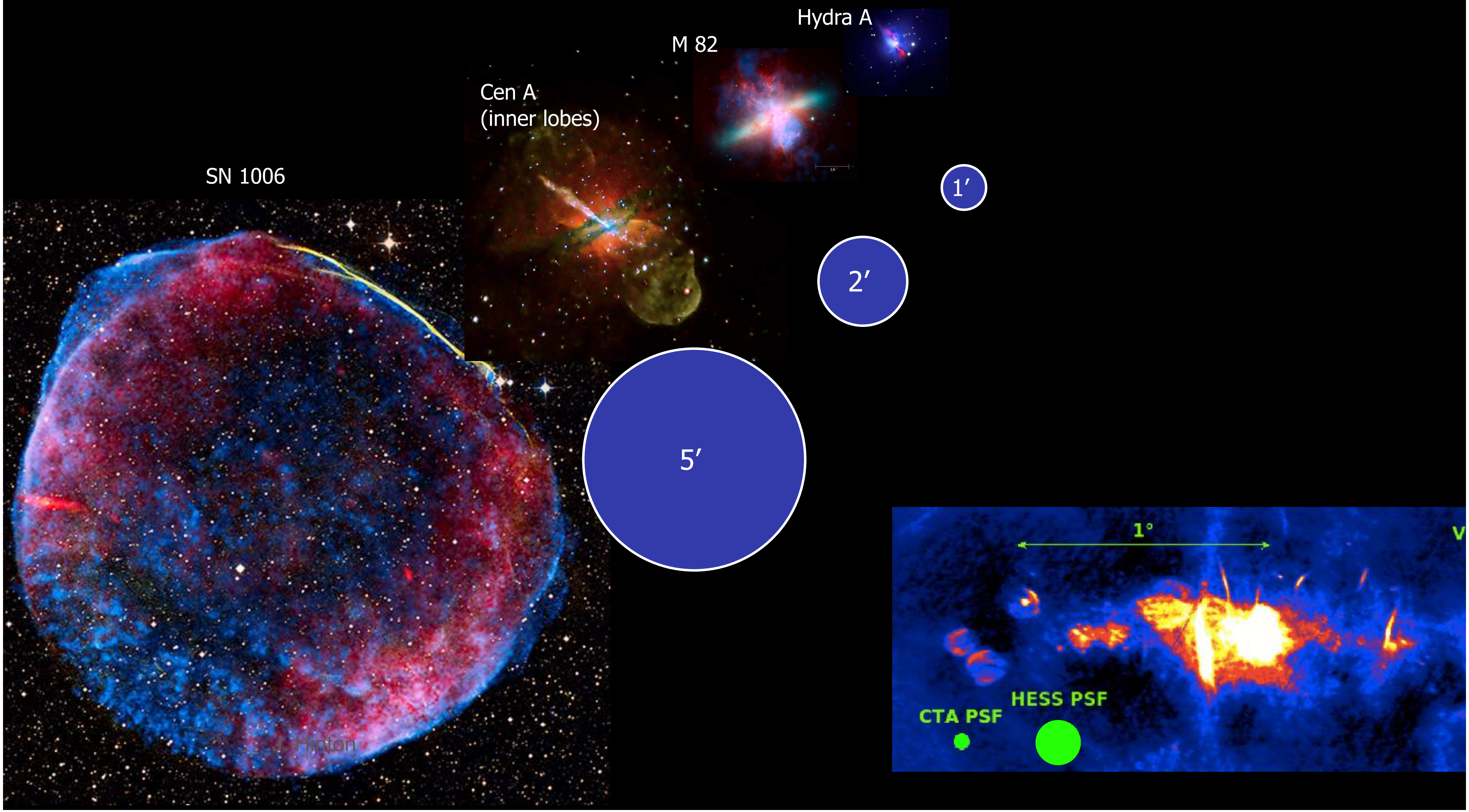
ld of view + sens.

vey speed ~300×HESS

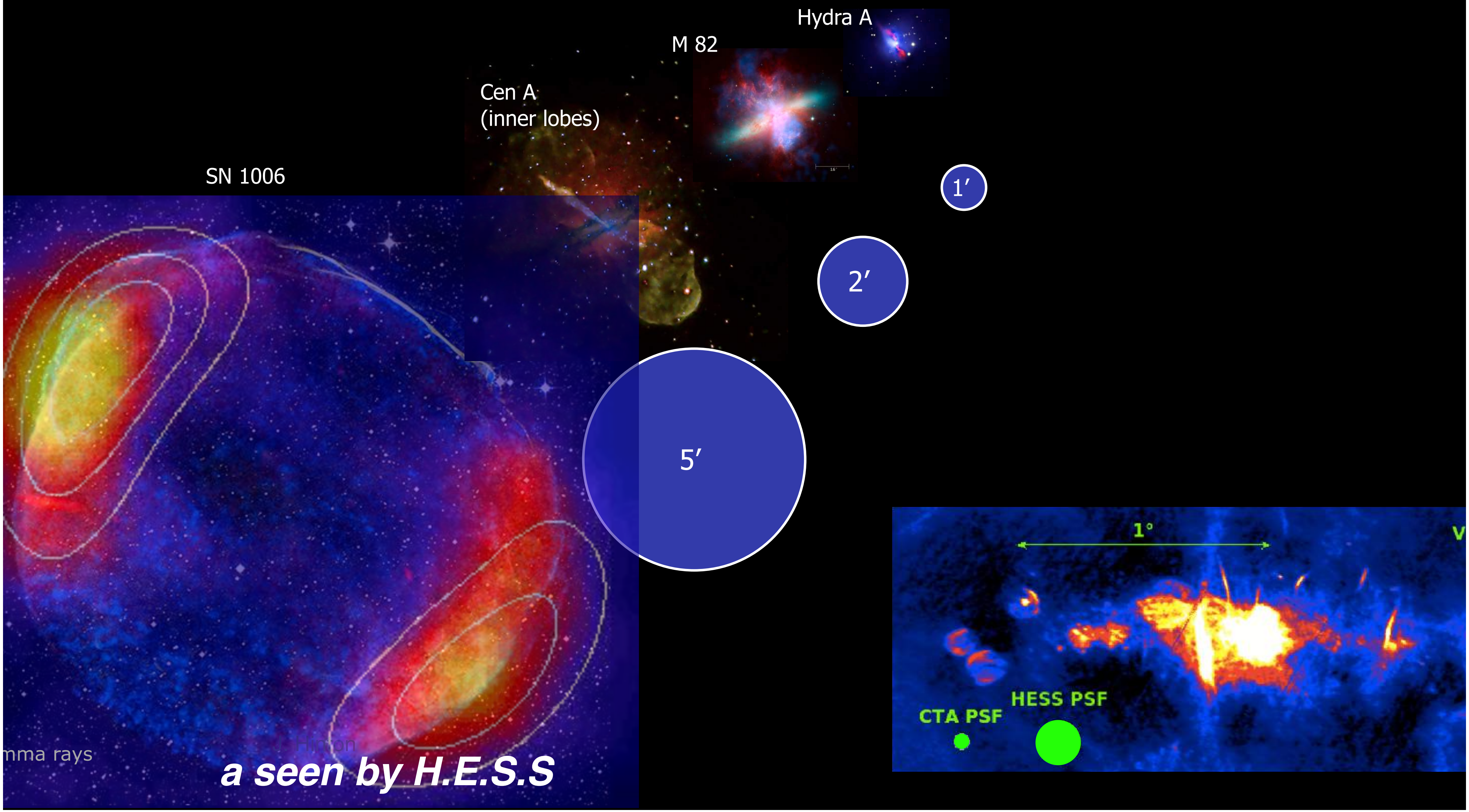




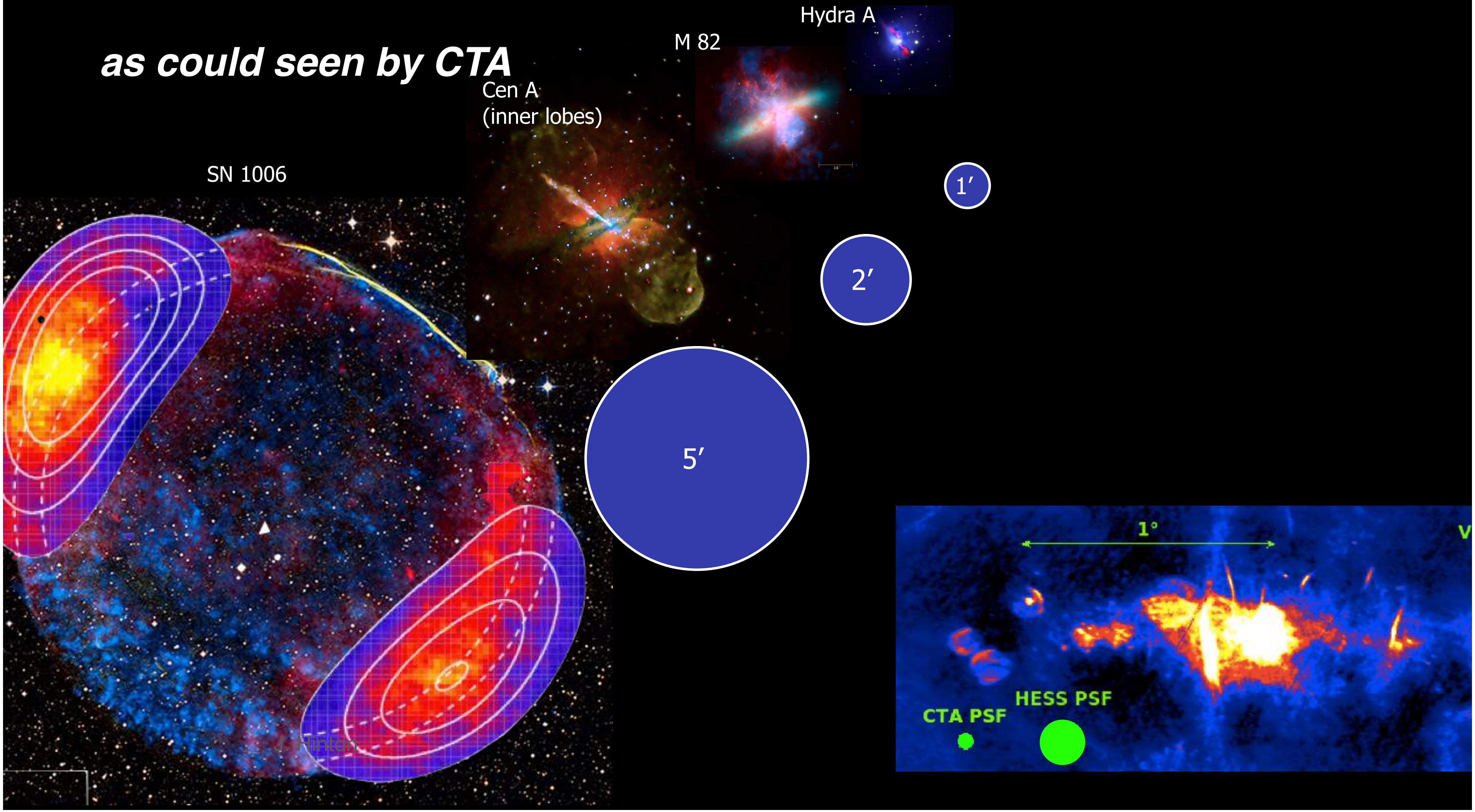
Better Angular Resolution



BETTER ANGULAR RESOLUTION



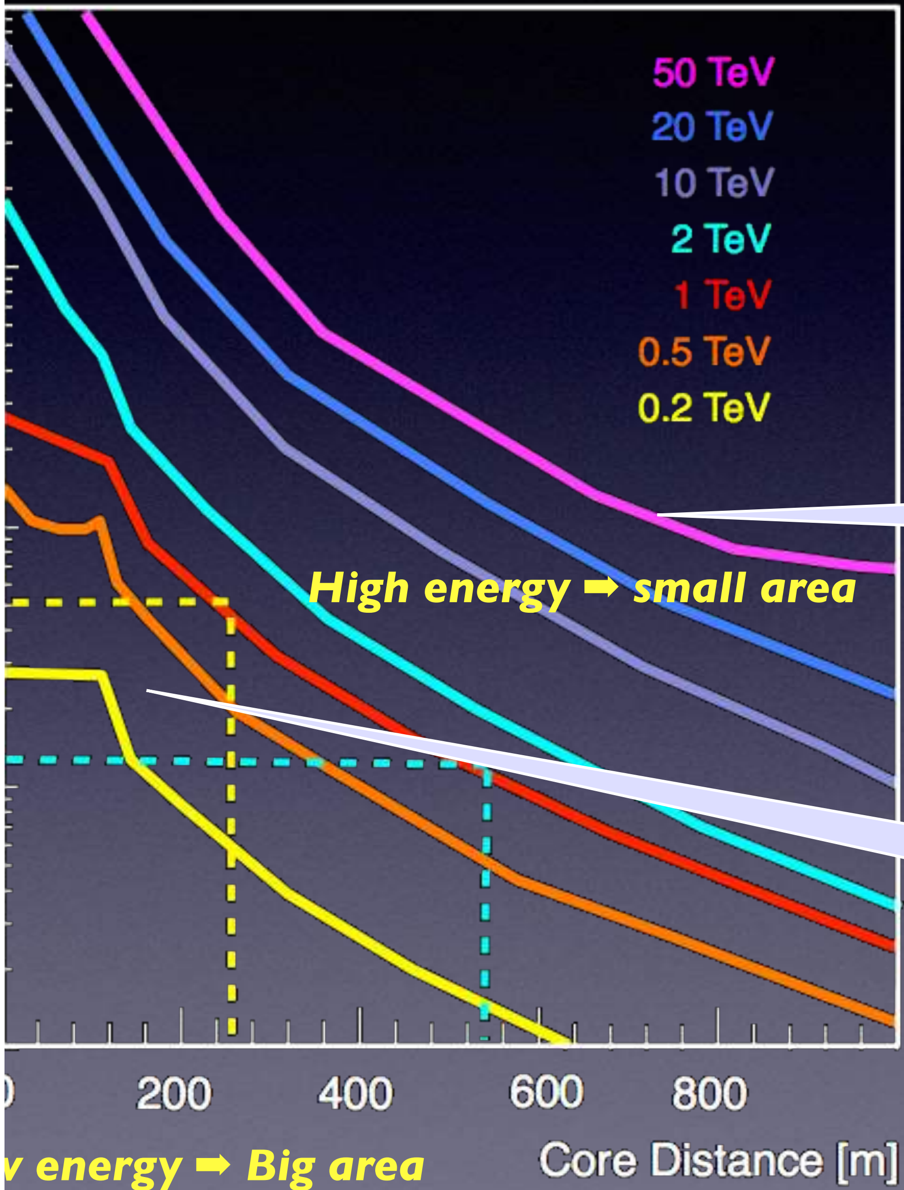
BETTER ANGULAR RESOLUTION



Energy Coverage and Area

Energy threshold depends on collection ar
of a single telescope

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



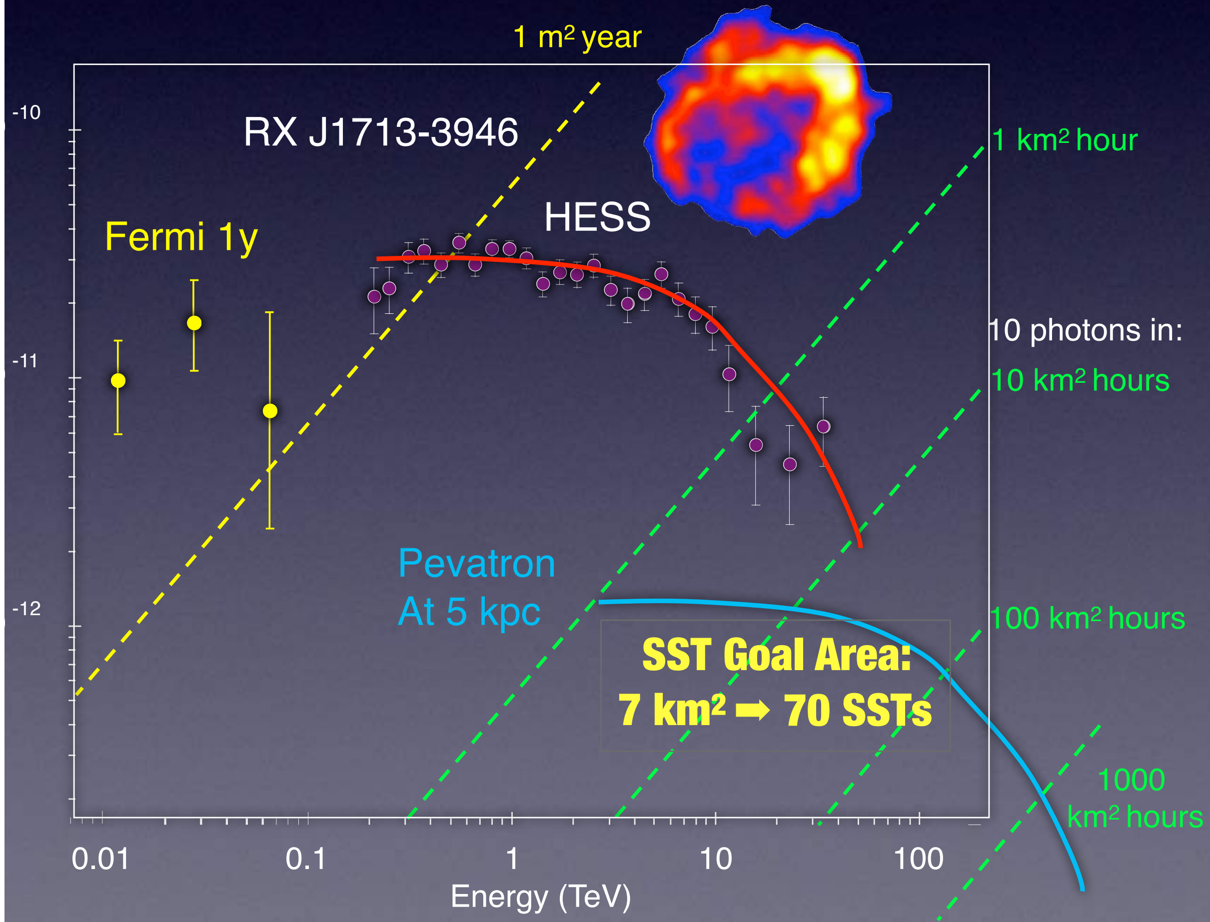
At the highest energies, images will be visible at large distances

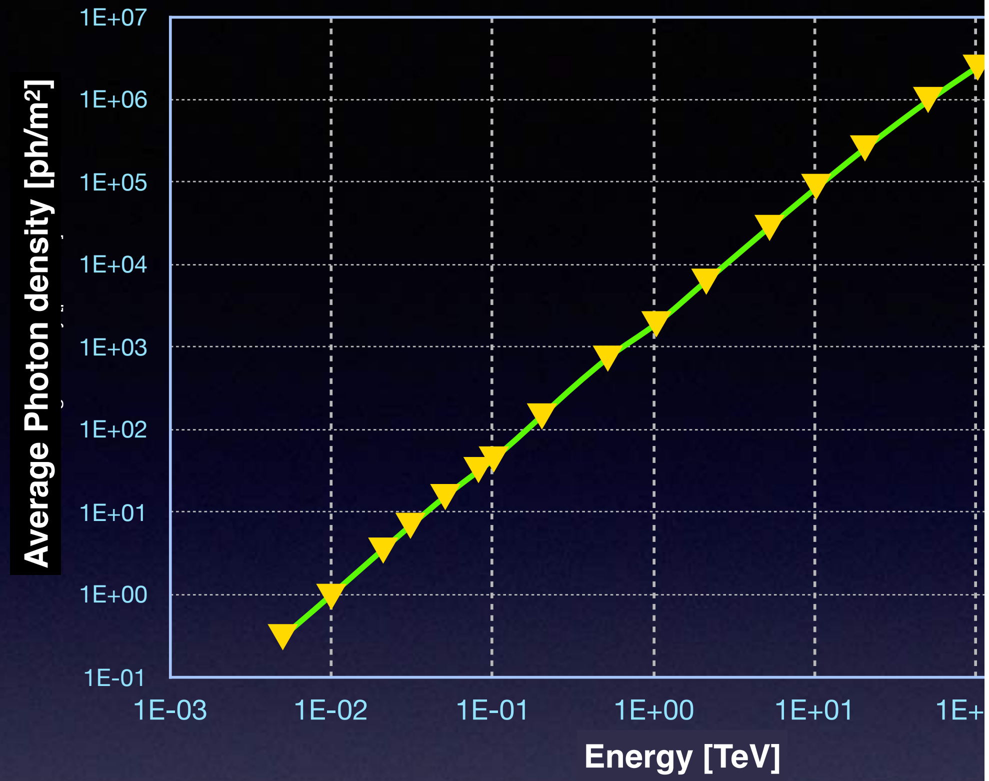
At lowest energies, few photons even in the core of the shower

rgy threshold depends on collection
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

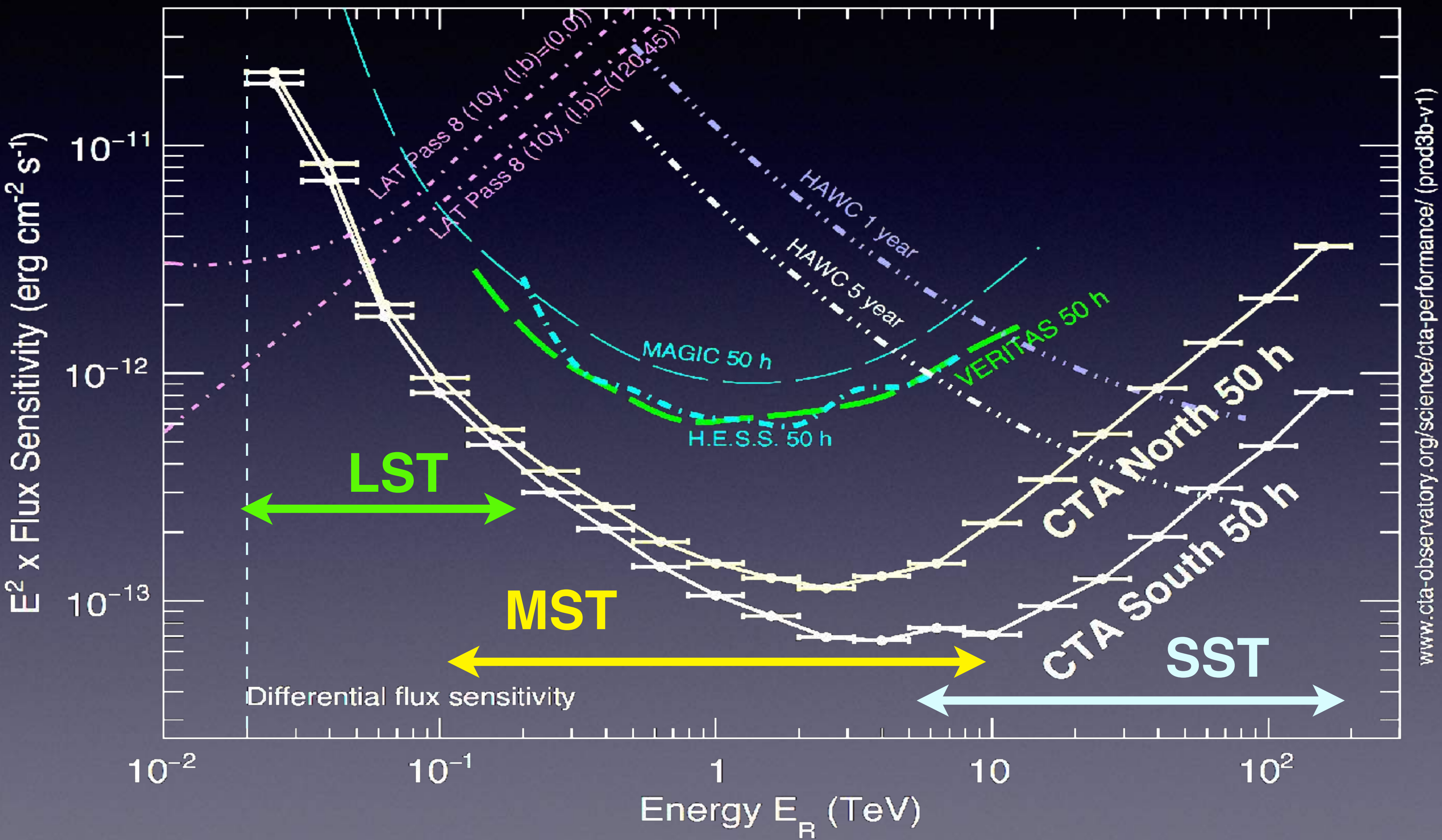
	100 GeV	1 TeV	10 TeV	100 TeV


100 GeV
1 TeV
10 TeV
100 TeV
/h·km²
10 γ/h·km²
0.
4 N: 23 m ∅ Large Size Telescopes (LST)
Souther
of Cherenkov tele
- about 3 km

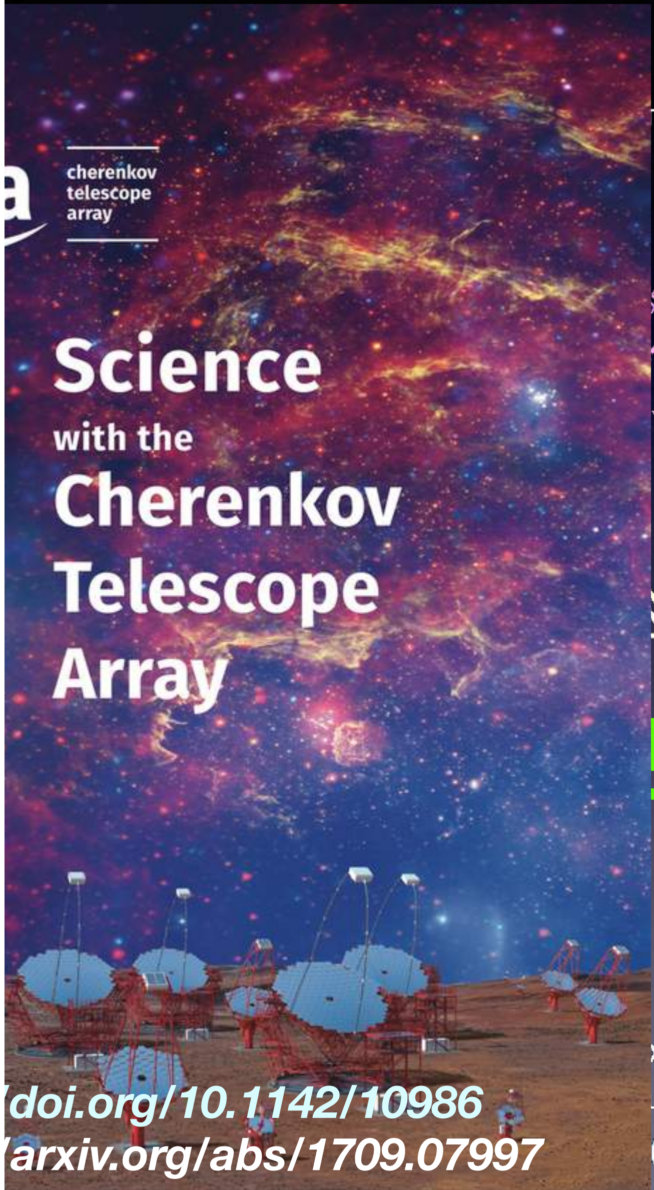

100 GeV
1 TeV
10 TeV
100 TeV
km²
10 γ/h·km²
0.
15 N: 12 m ∅ Medium Size Telescopes (MST)
Souther
of Cherenkov tele
- about 3 km

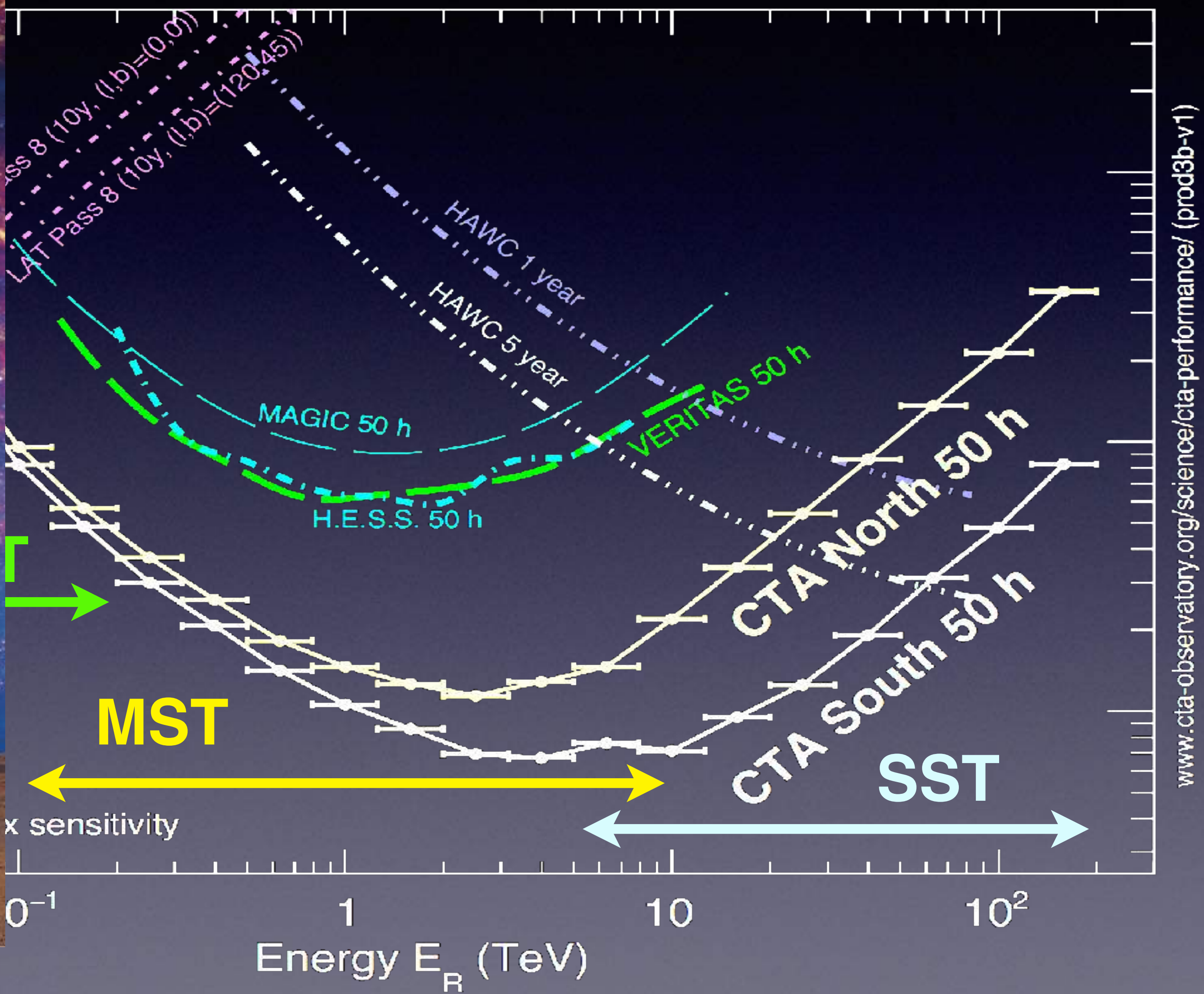

100 GeV
1 TeV
10 TeV
100 TeV
m²
0.1 γ/
4 m ∅ Small Size Telescopes (SST)
Souther
of Cherenkov tele
- about 3 km

CTA Sensitivity

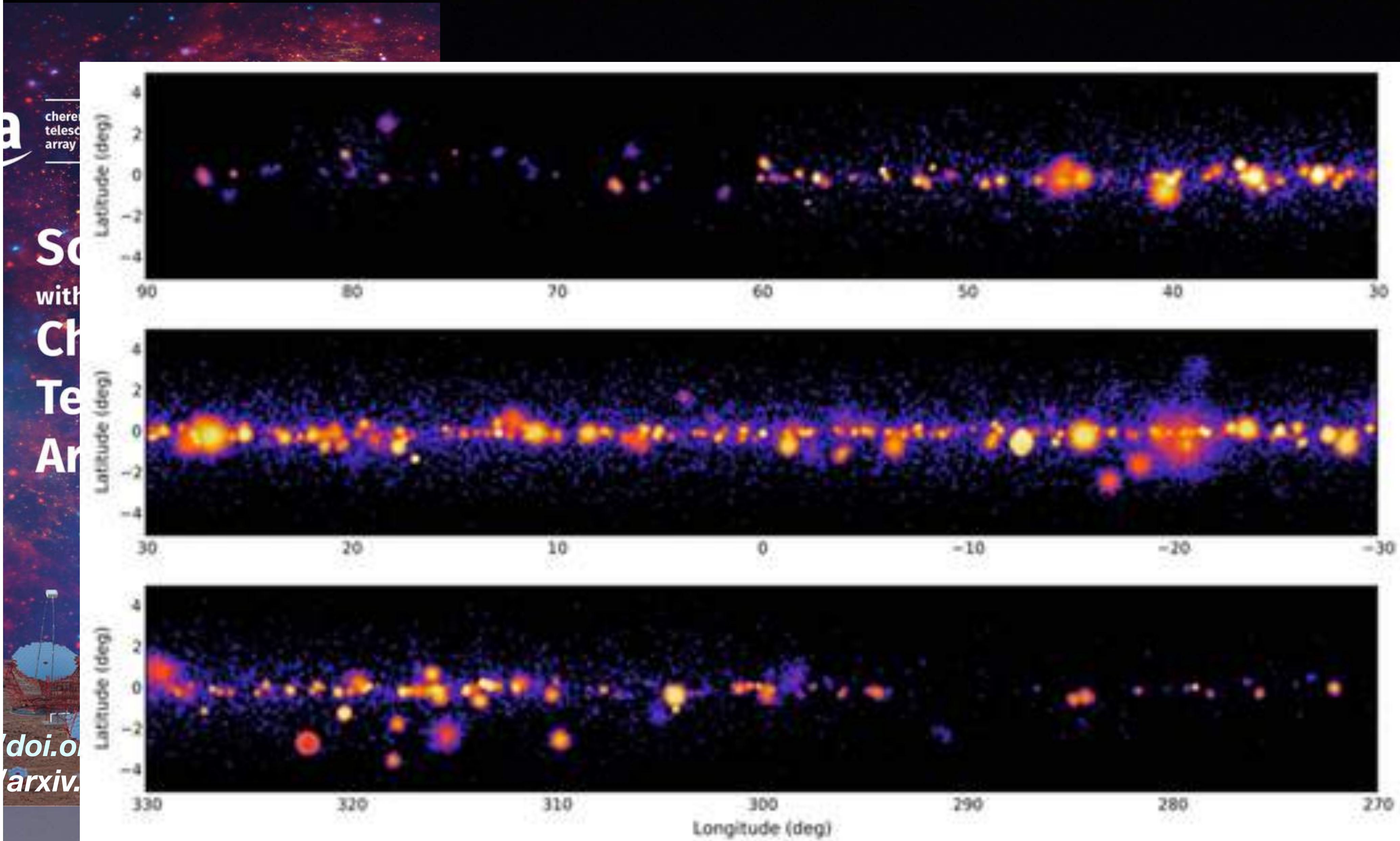


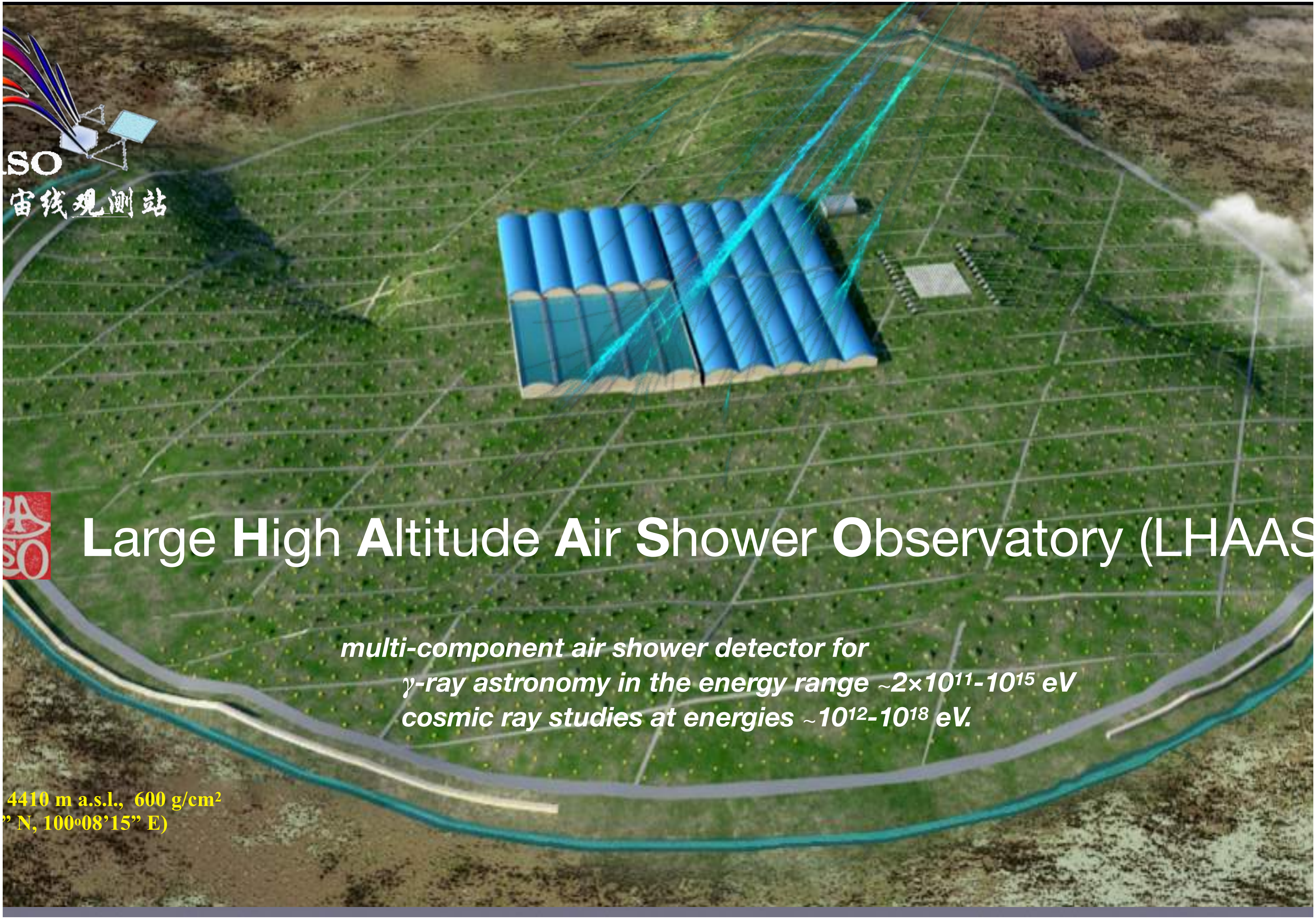
CTA Sensitivity

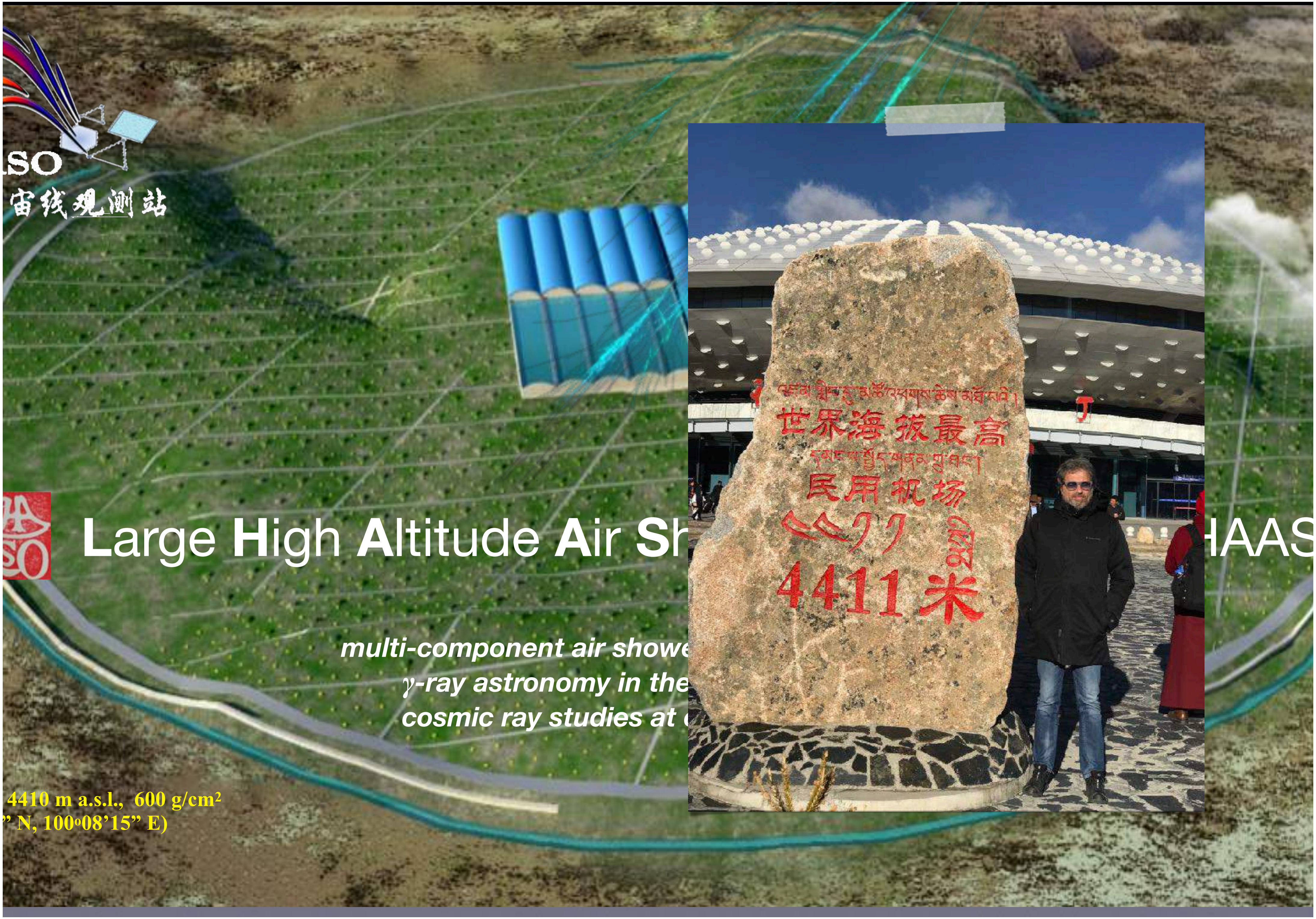




CTA Sensitivity




SO
宙线观测站
Large High Altitude Air Shower Observatory (LHAAS
multi-component air shower detector for
γ-ray astronomy in the energy range ~2×10^11-10^15 eV
cosmic ray studies at energies ~10^12-10^18 eV.
4410 m a.s.l., 600 g/cm^2
” N, 100°08’15” E)



SO
宙线观测站
Large High Altitude Air Sh
HAAS
multi-component air showe
γ-ray astronomy in the
cosmic ray studies at
4410 m a.s.l., 600 g/cm²
” N, 100°08’15” E)
世界海拔最高
民用机场
4411米

Physics of LHAASO

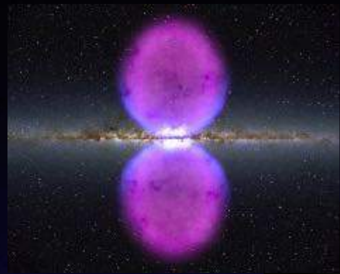
HE gamma sky survey (100 GeV-1 PeV):

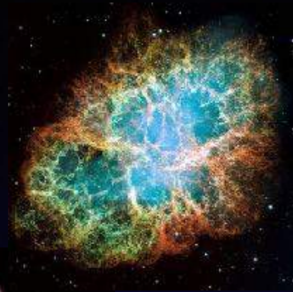
Galactic sources;

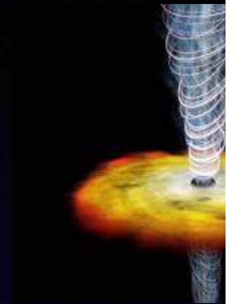
Extragalactic sources & flares;

VHE emission from Gamma Ray Bursts;

Diffused Gamma rays.



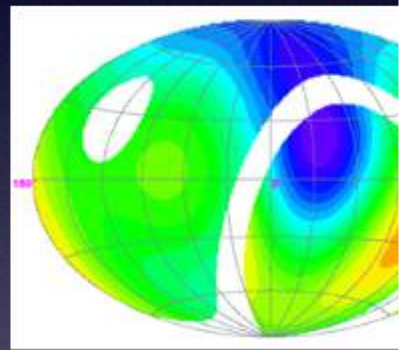


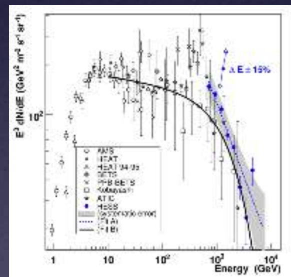


pectrum measurement at the high end:

Nature of the acceleration: leptonic or hadronic;

Origin of cosmic rays – 100 years' mystery.



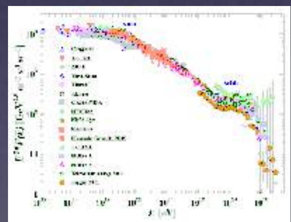


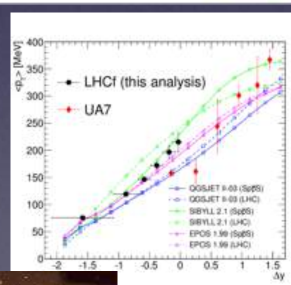
osmic rays

Spectra of CR Species;

Anisotropy of VHE cosmic rays;

Cosmic electrons / positrons;

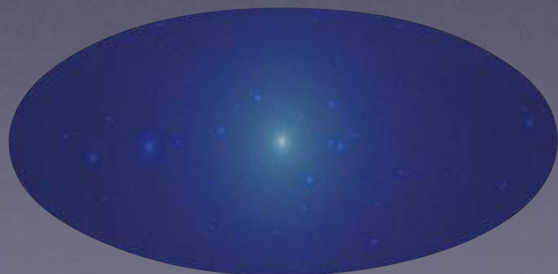


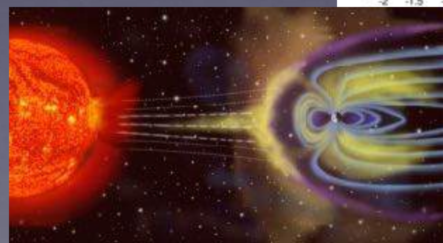


iscellaneous:

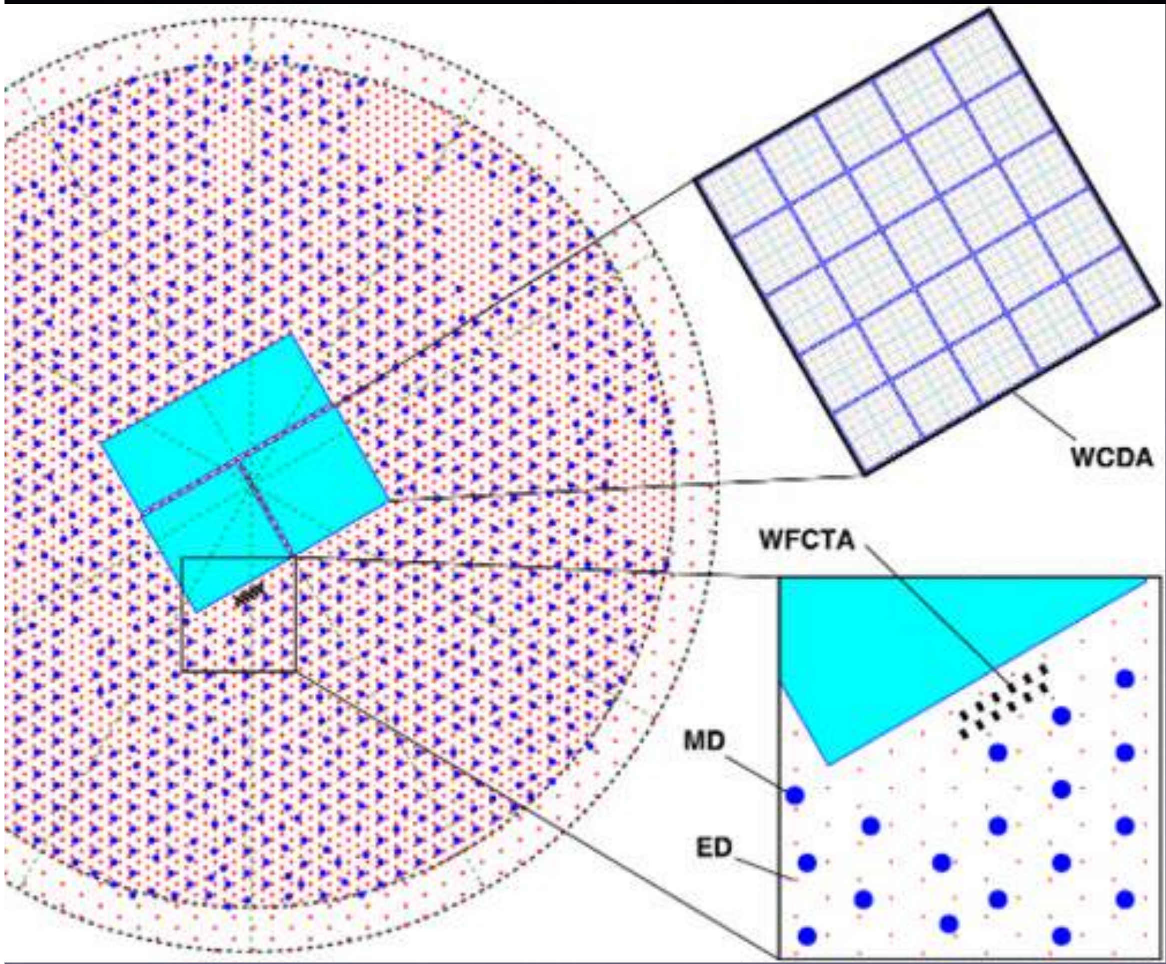
Gamma rays from dark matter;

Sun storm & IMF.





LHAASO Layout



WCDA - Water Cherenkov Detector A

- Measuring shower direction and loc

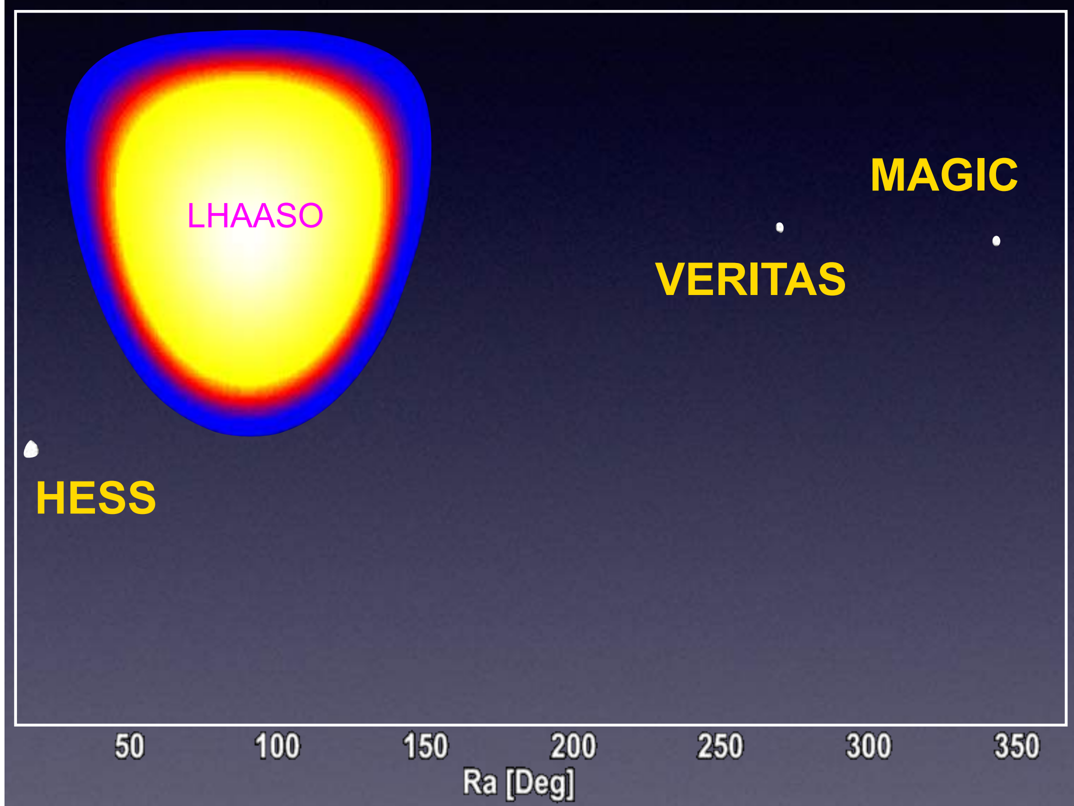
KM2A - Km-square array

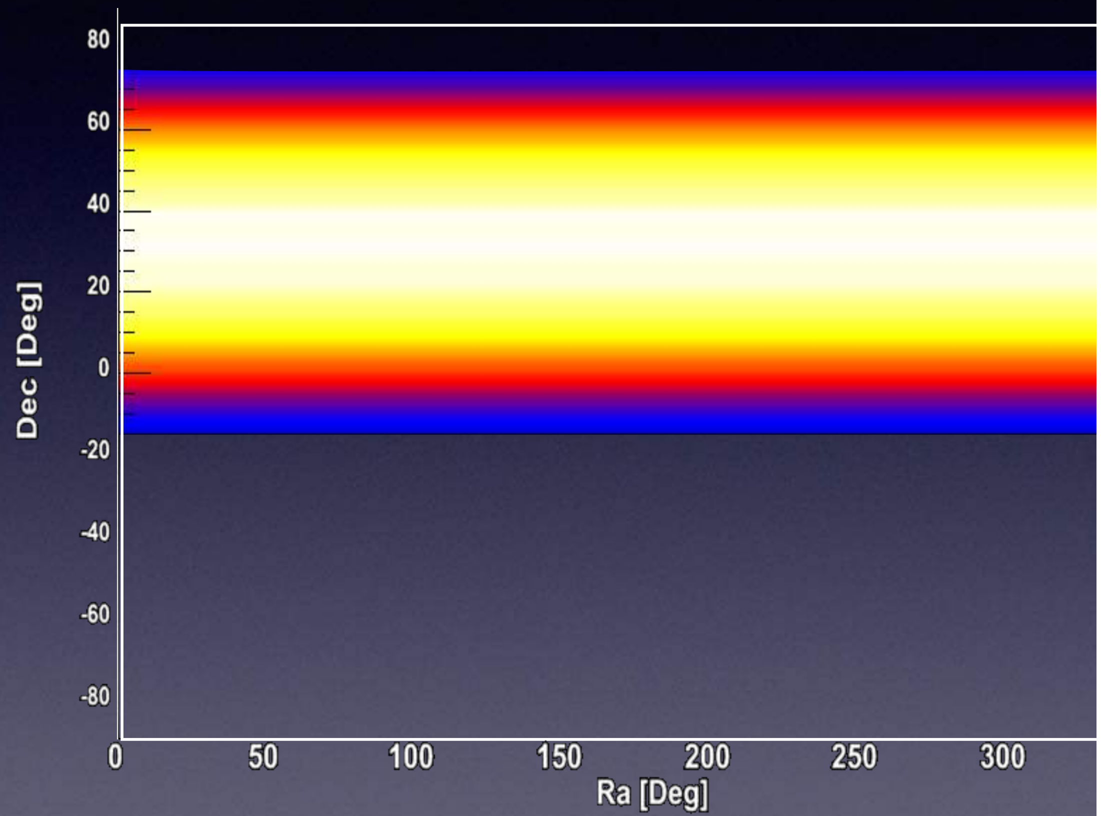
- Measuring shower direction and loca
- Measuring μ–content with the larges array ever
- Clean γ selection

WFCTA - Wide Fielf-of-view Cherenk

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

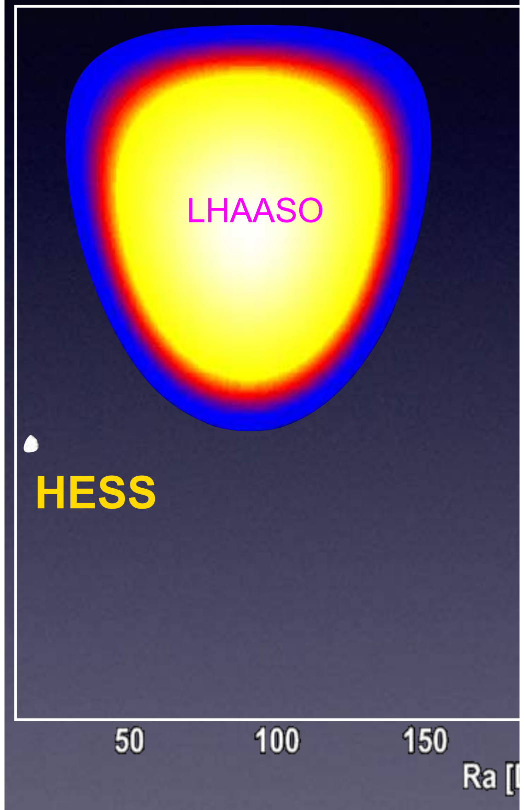
Wide FOV γ-ray Astronomy

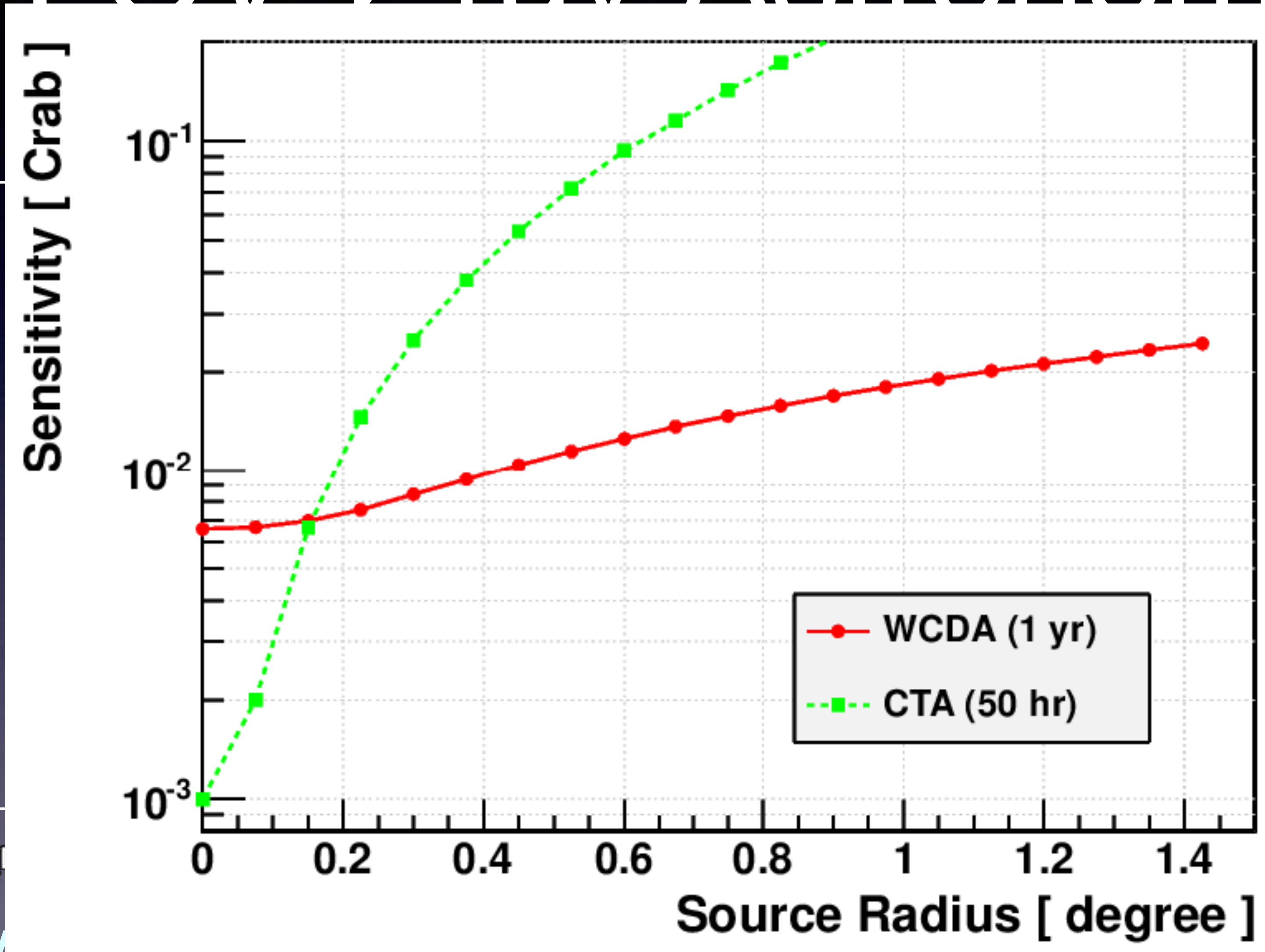


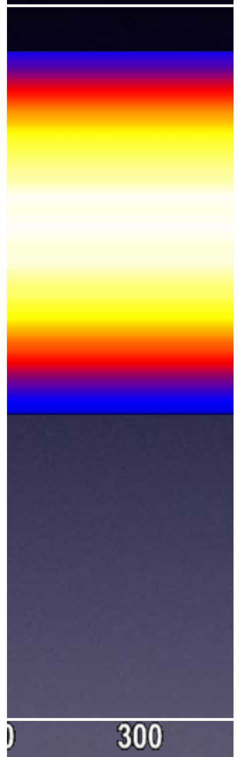


- 1/7 of the sky at any moment
- 60% in the sky per day day (24h)

Wide FOV γ-ray Astronomy

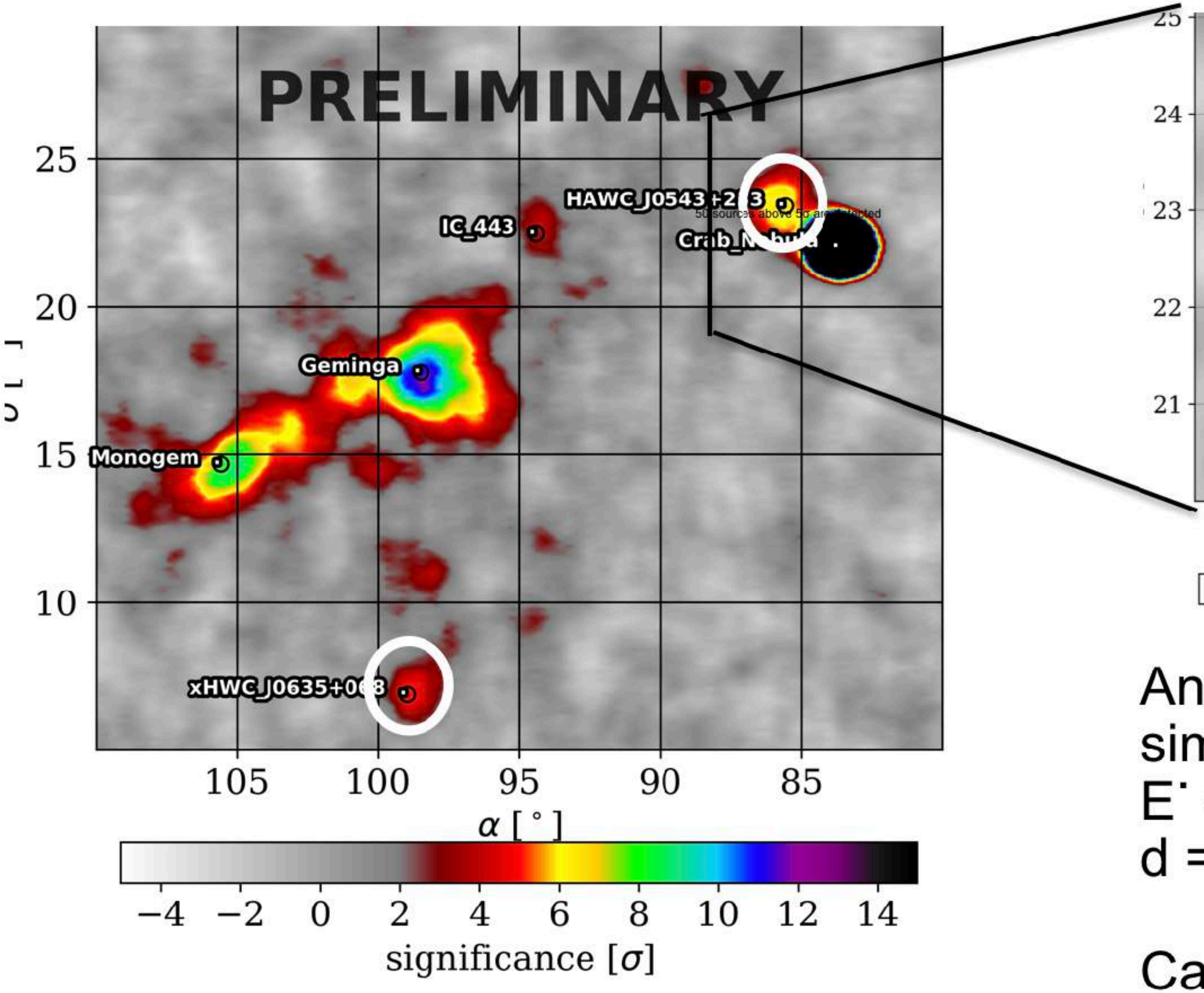


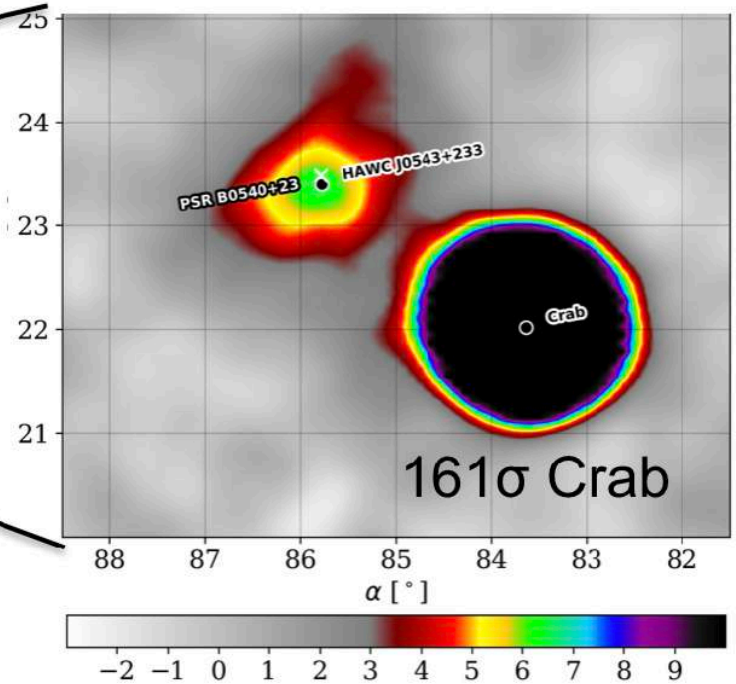




- 1/7 of the sky at any moment
- ... day (24h)

Discovery Potential: Hiding in Plane Sight

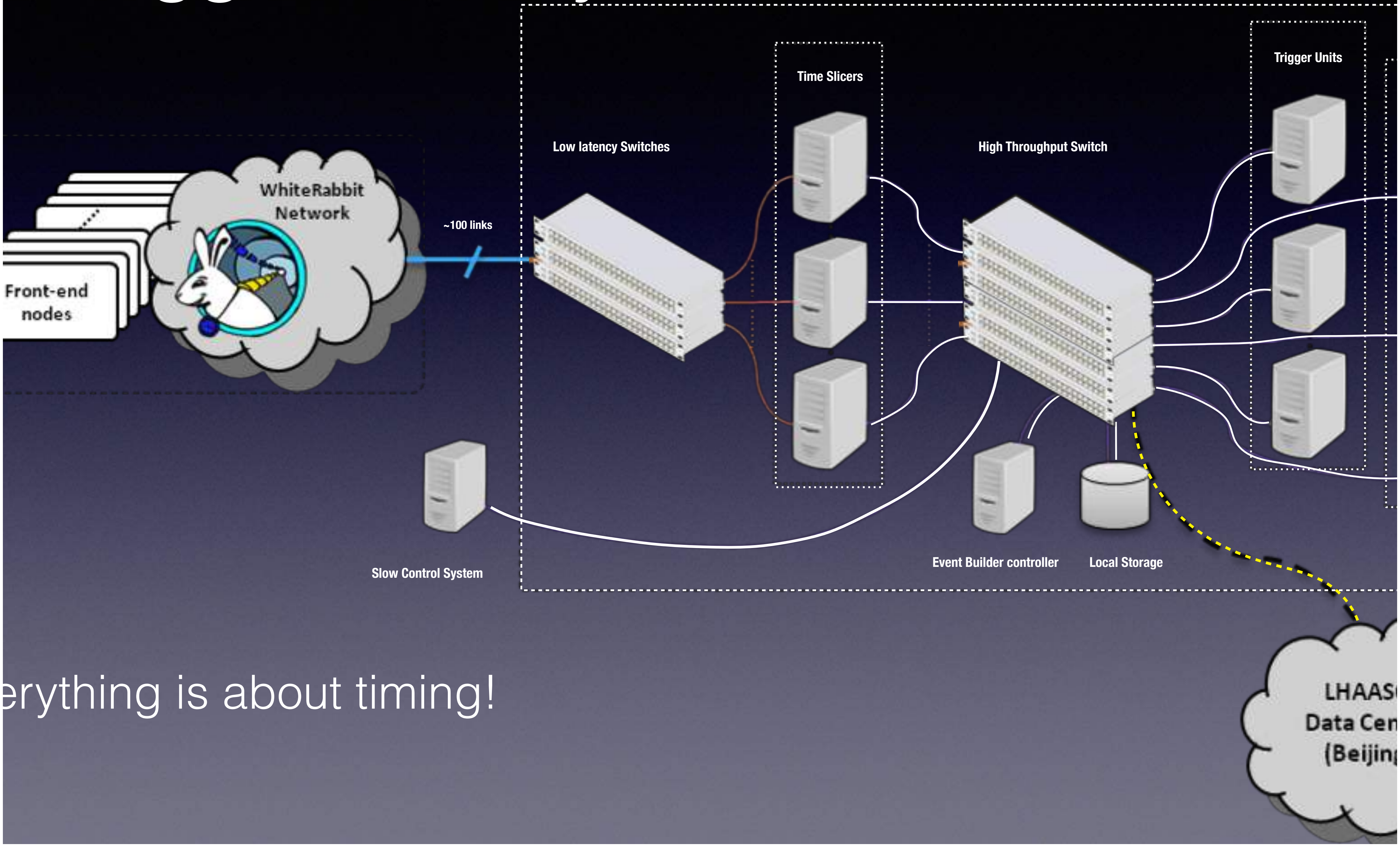




Another middle age PWN
similar to Geminga and B0656+14
$\dot{E}$ = 4.1 × 10^{34} erg s−1,
d = 1.56 kpc, τ = 253 kyr

Can test if all are Geminga-like

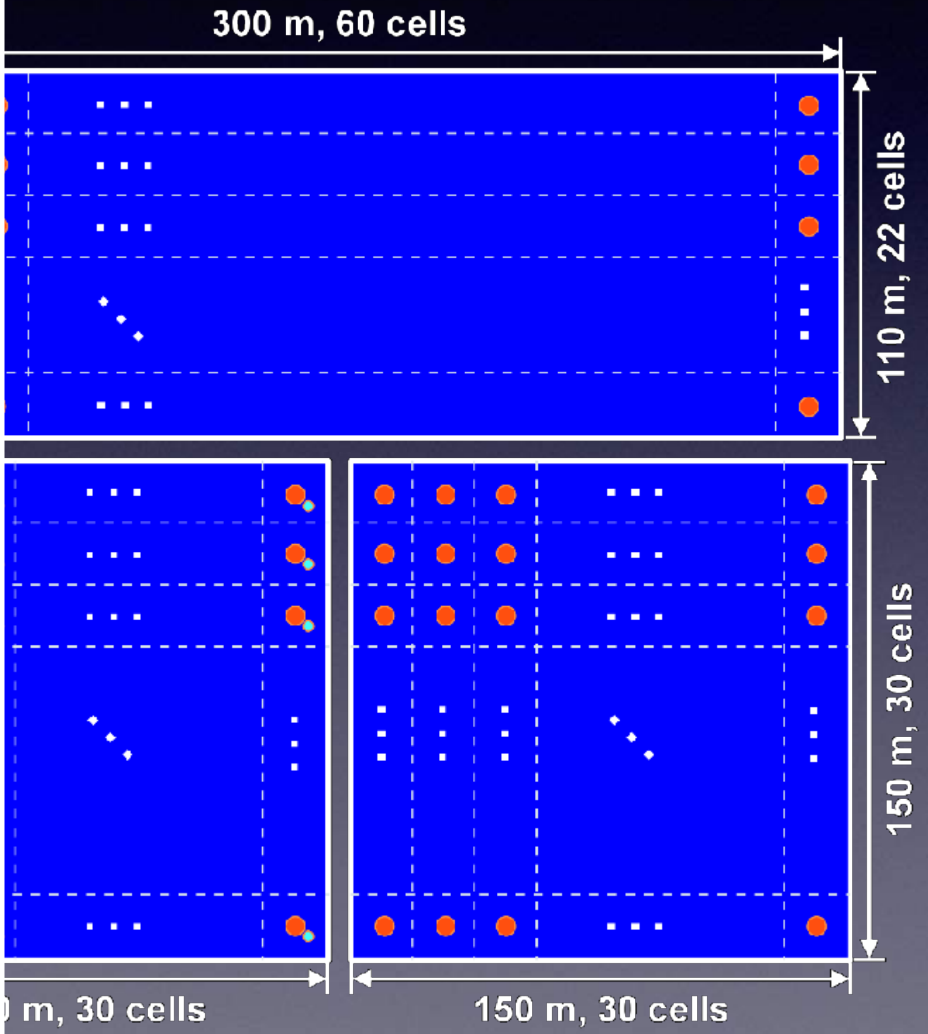
Trigger-less System

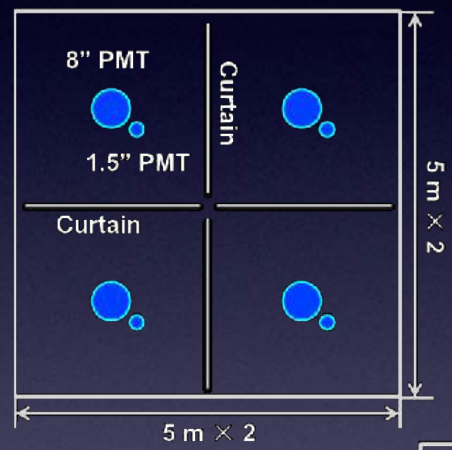


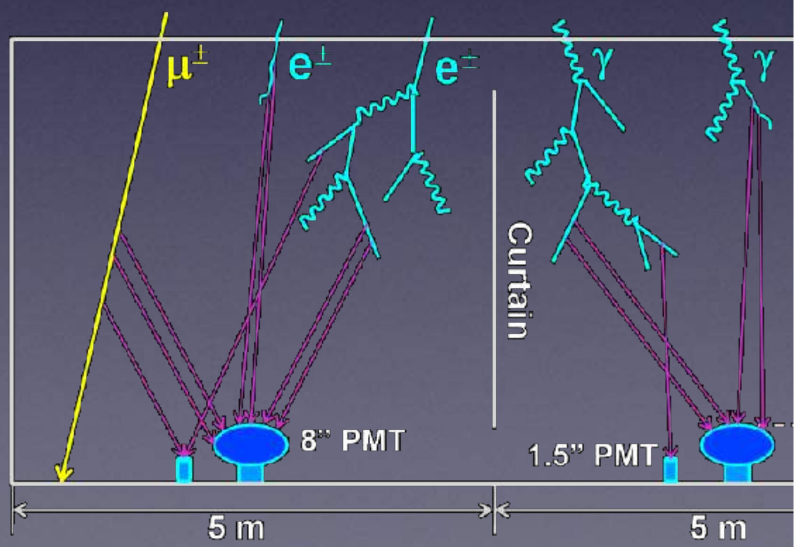
erything is about timing!

er Cherenkov Detector Array

Cell Size	5 mx
Effective water depth	4
Water transparency	> 20 m (
Precision of time measurement	0.5
Dynamic range	1-4’00
Time resolution	<2
Charge resolution	40%@ 5% @ 4
Accuracy of charge calibration	< 2
Accuracy of time calibration	<0.2
Total # cells	31
Total Area	78’00







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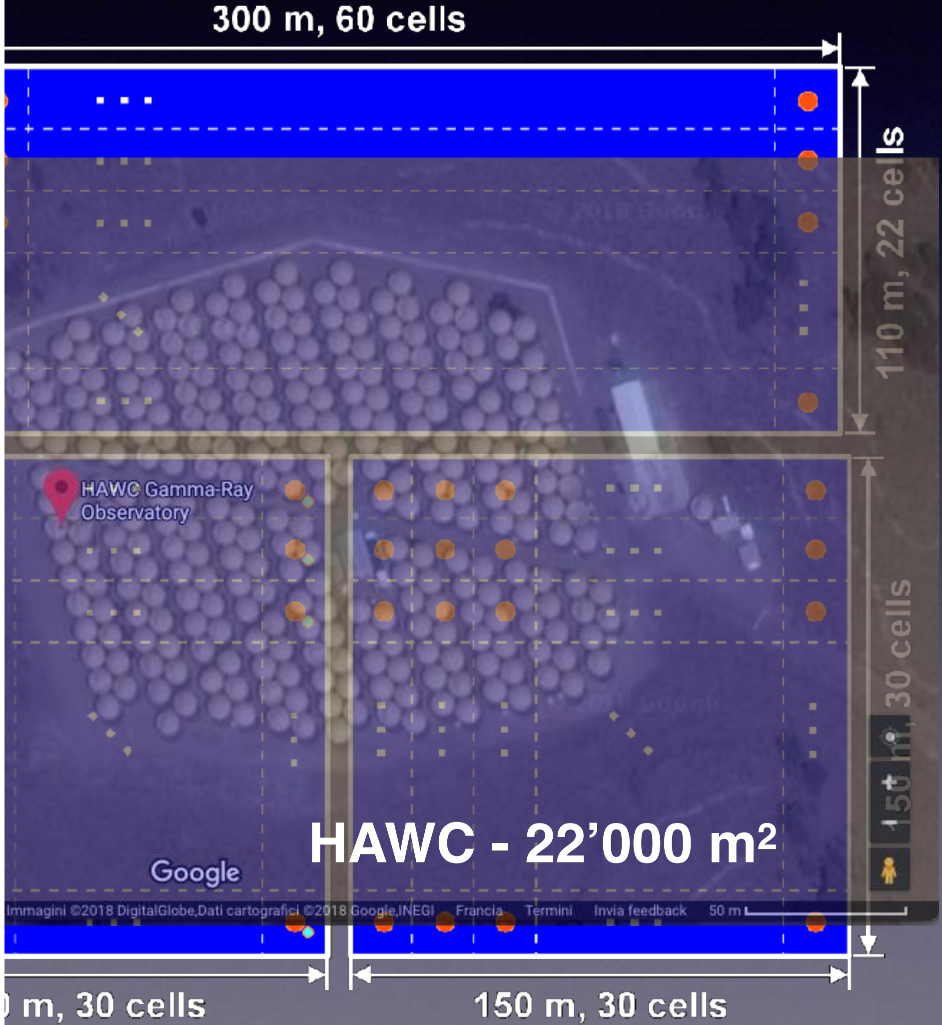

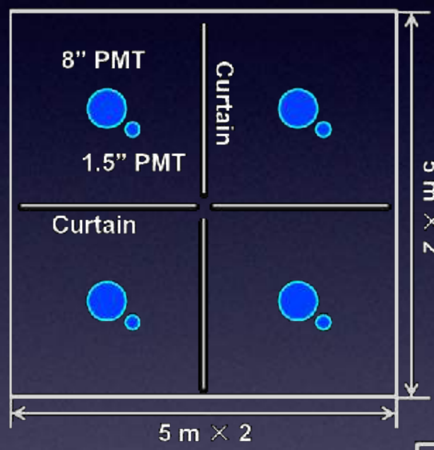

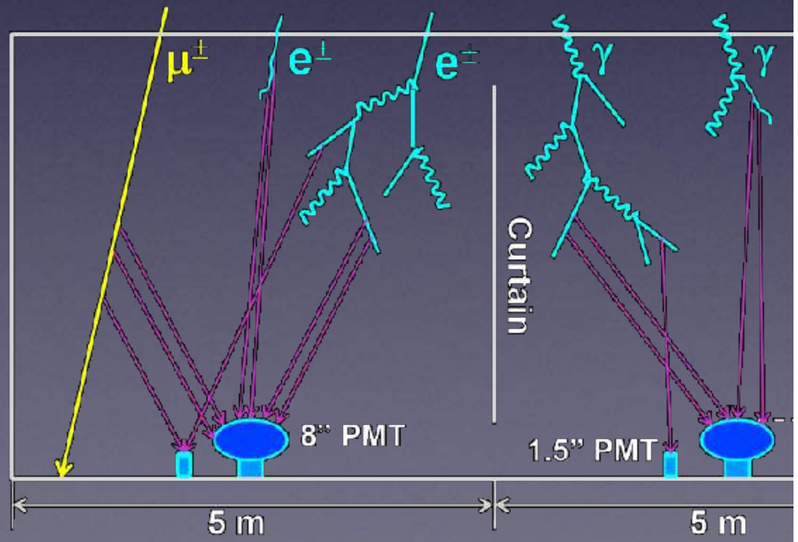

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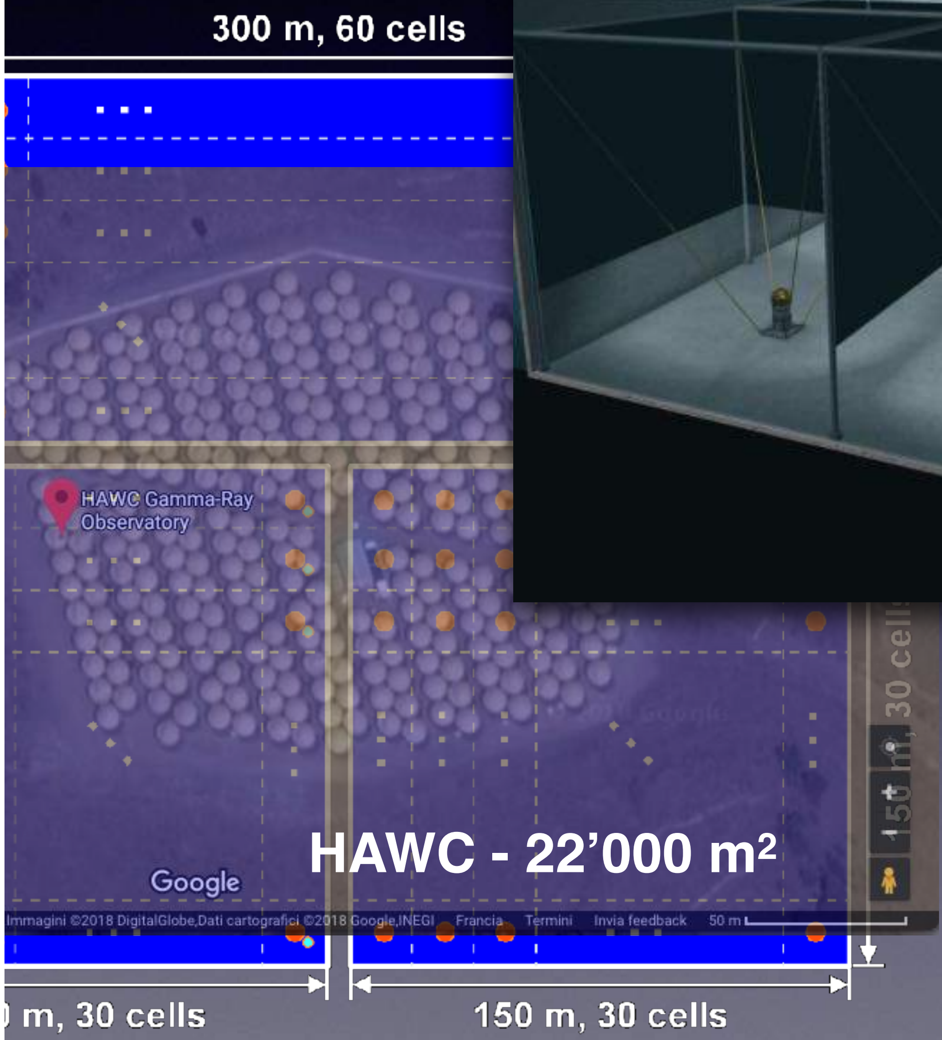

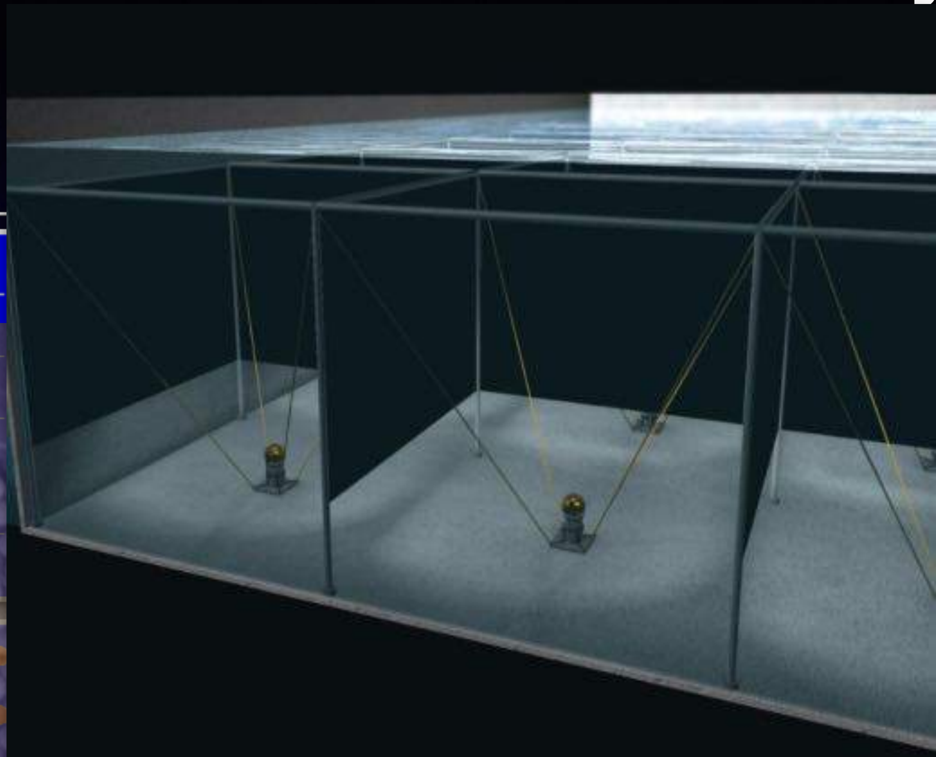

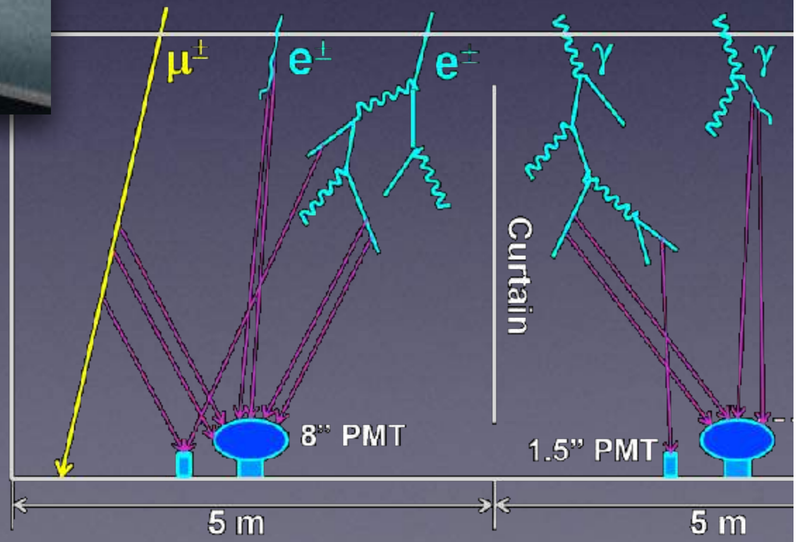

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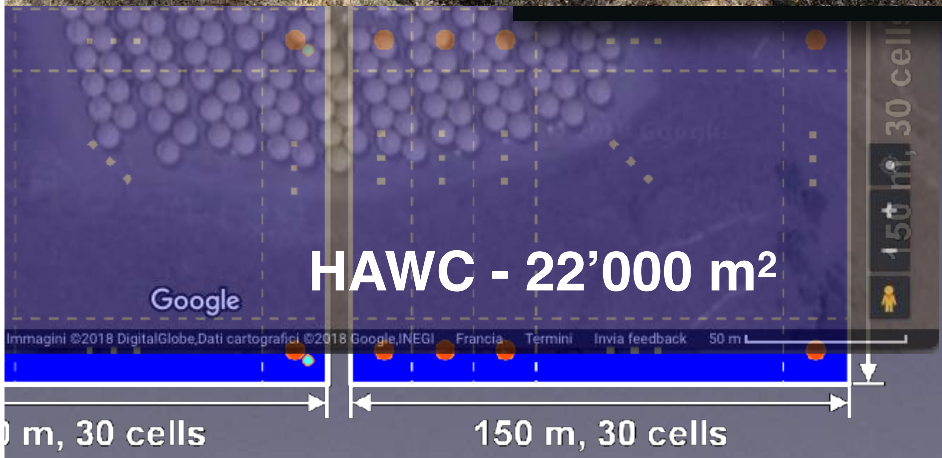
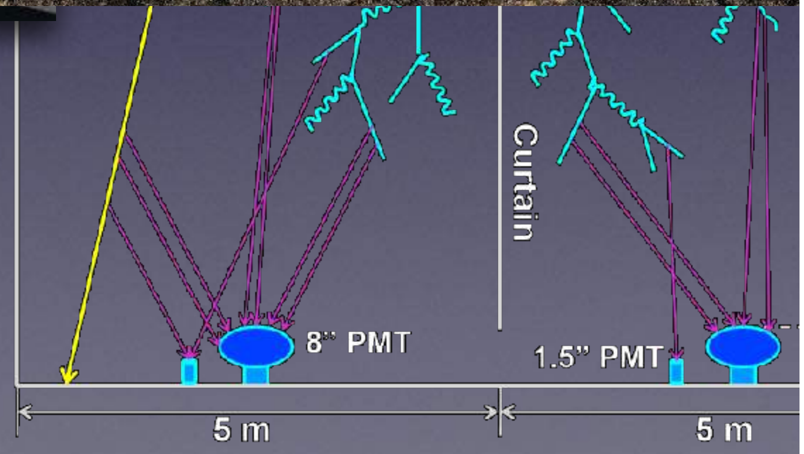
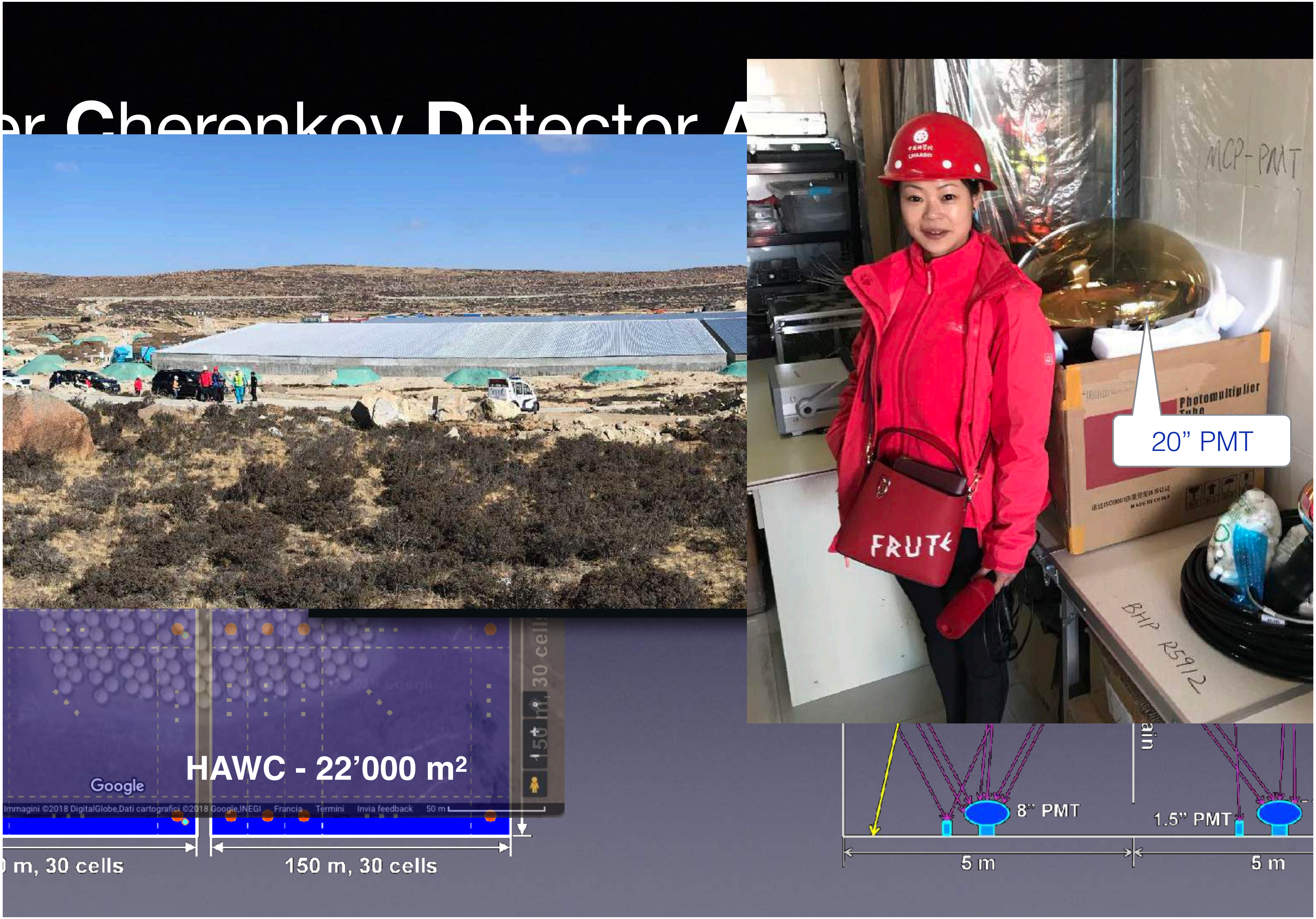
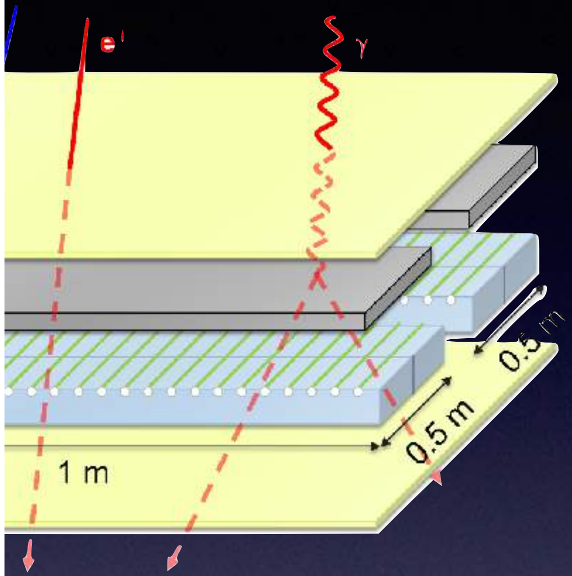
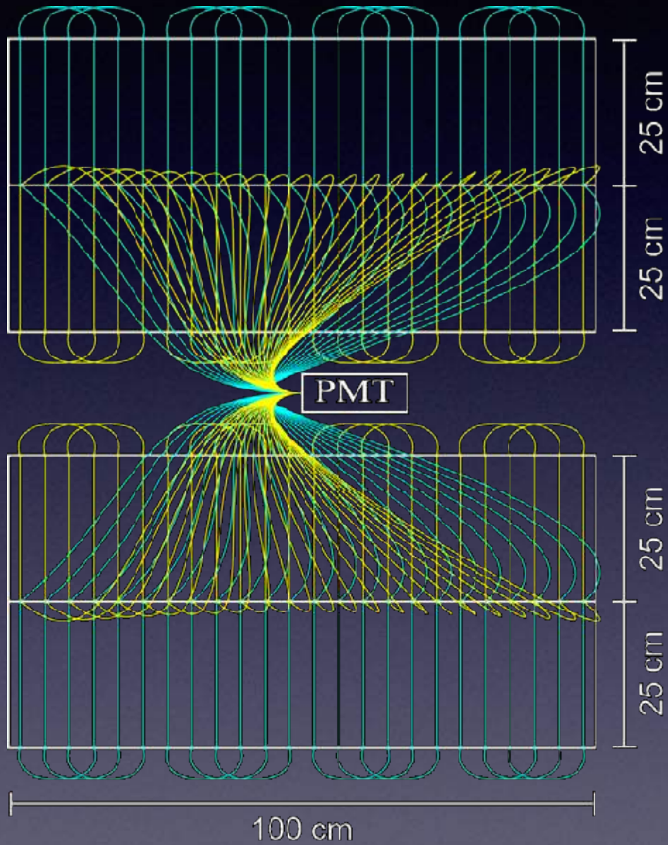





er Cherenkov Detector A
MCP-PMT
Photomultiplier
20” PMT
BHP R5912
HAWC - 22’000 m²
Google
150 m, 30 cells
m, 30 cells
8” PMT
1.5” PMT
5 m
5 m

M2A - Electromagnetic Detector

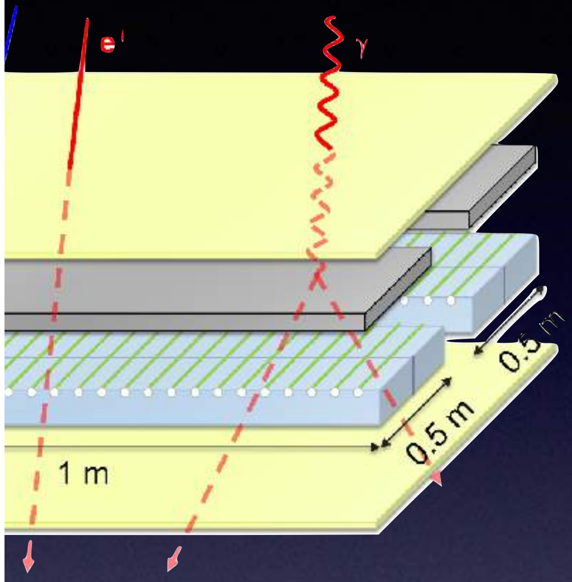




Effective Area	1 r
Tiles thickness	1 c
# WLS fibers	24/tile
Detection efficiency	>95
Dynamic range	1-10
Time resolution	<2
Particle counting resolution	25%@1 p 5% @ 10
Aging	<20% (1
Spacing	15
Total Number of ED	51

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

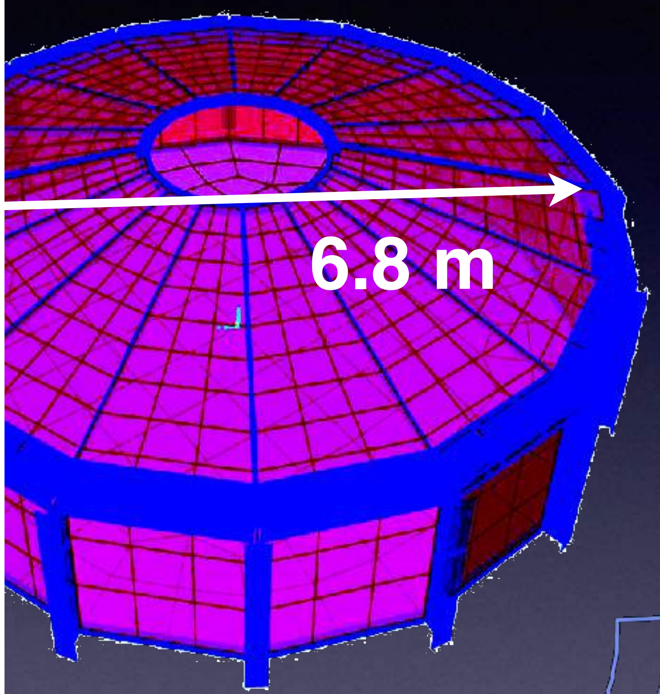
M2A - Electro

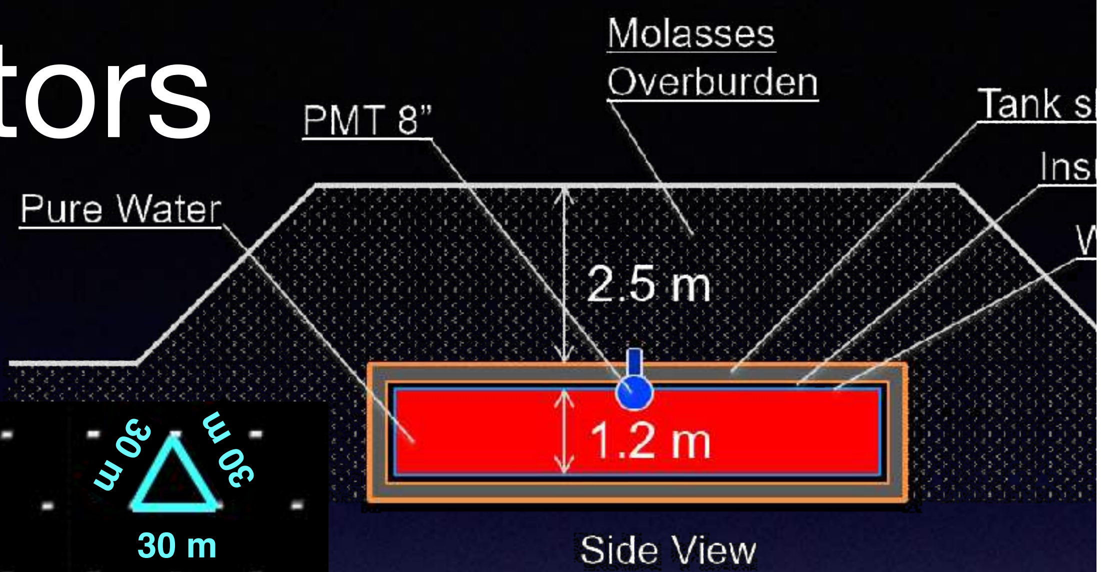


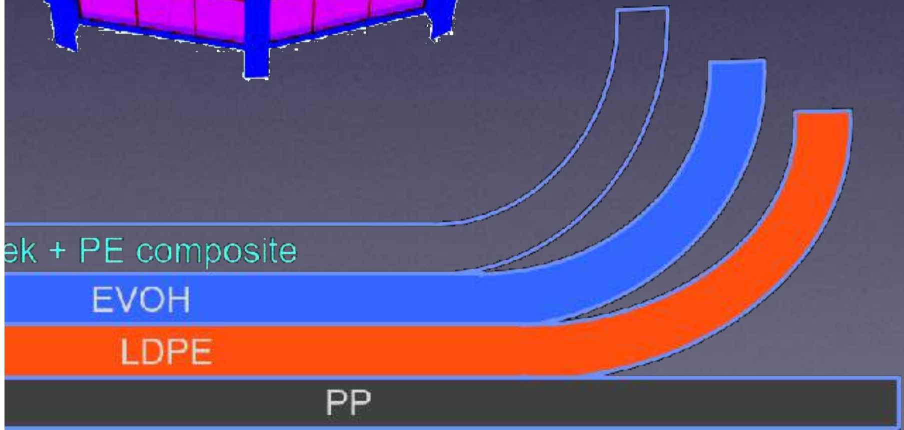
	1 m
s	1 c
	24/tile
ciency	>95
e	1-10
on	<2
ing	25%@1 p 5% @ 10
	<20% (1
	15
of ED	51

First 30 detectors has been installed on the site in Feb.- 2018

2A - Muon Detectors

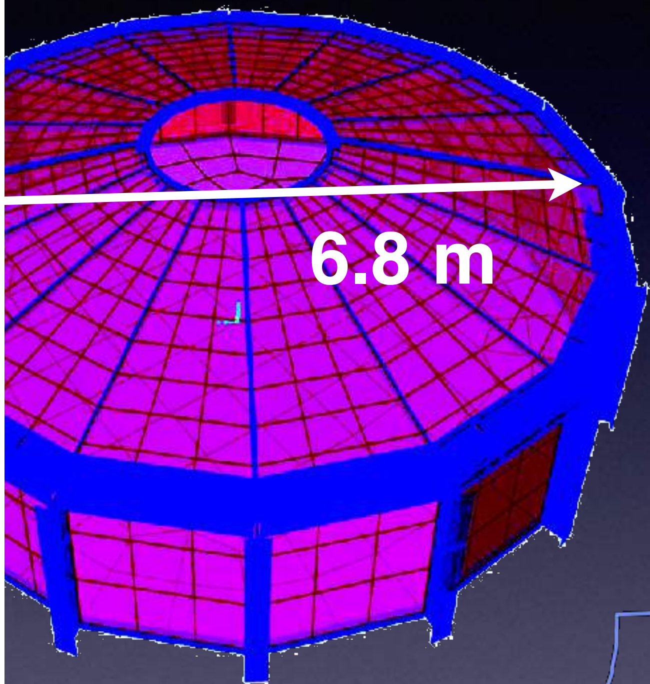


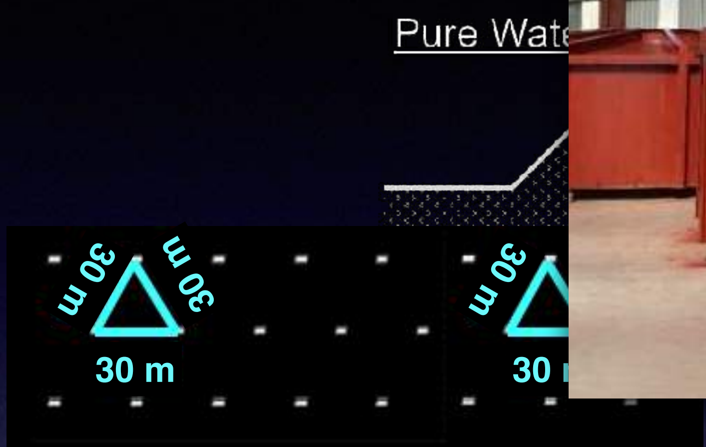


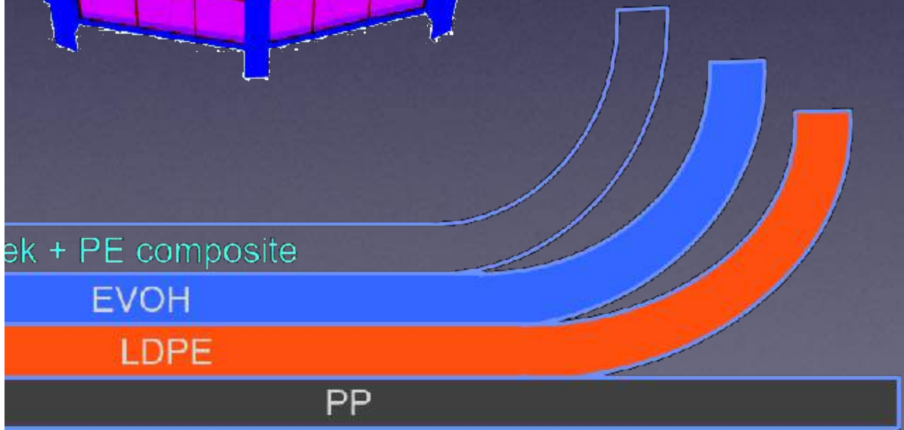


Area	36 m²
Depth	1.2 m
Molasses Overburden	2.5 m
Water Attenuation length	> 30 m (400 nm)
Reflection coeff.	>95%
Time resolution	<10 ns
Dynamic range	1-10'000
Particle counting resolution	25%@1 particle 5% @ 10'000 Particl
Lifetime	>20 years
Spacing	30 m
Total Number of ED	1171

2A - Muon Detectors







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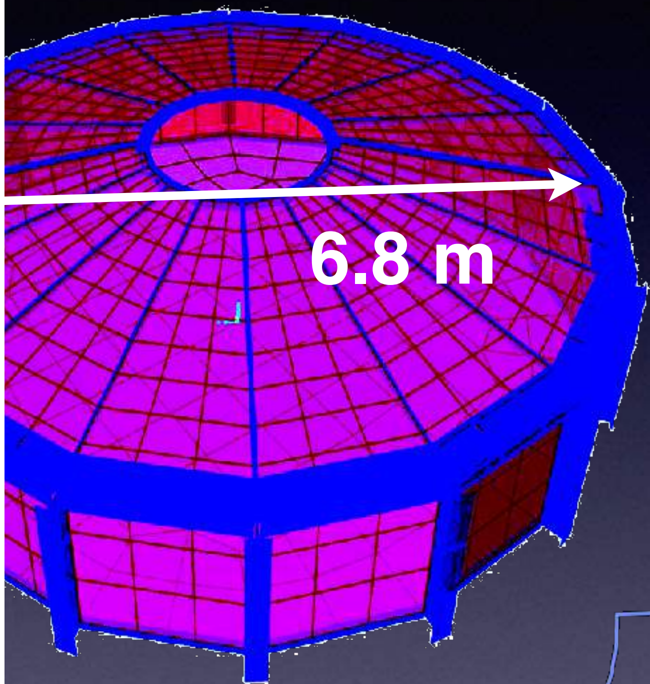

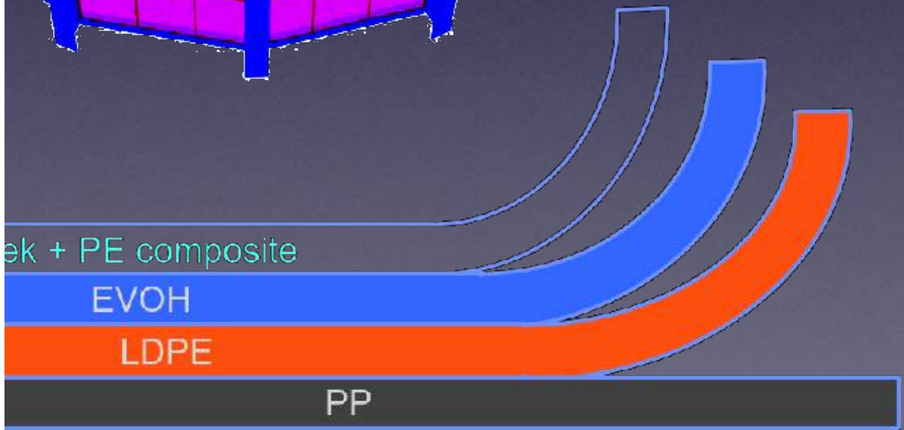

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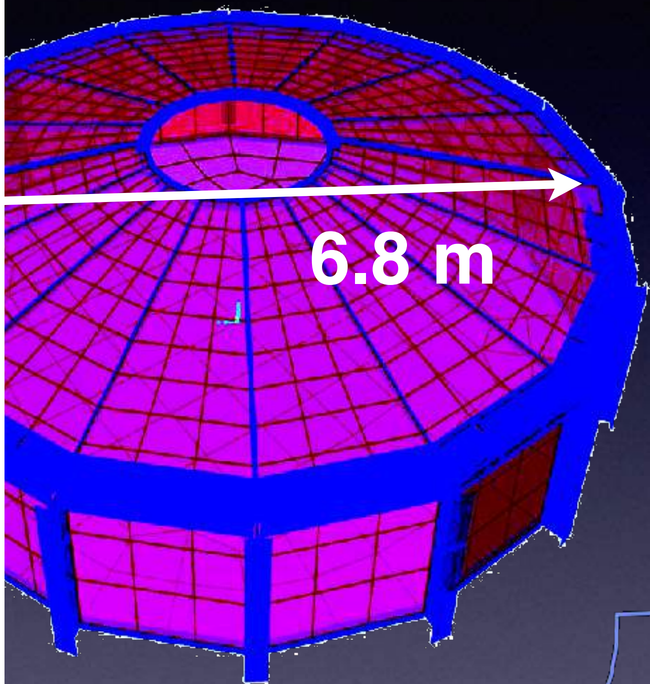

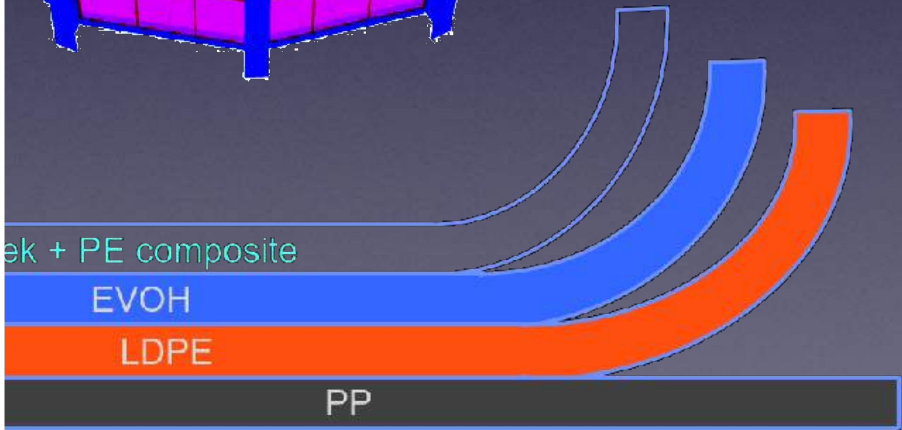

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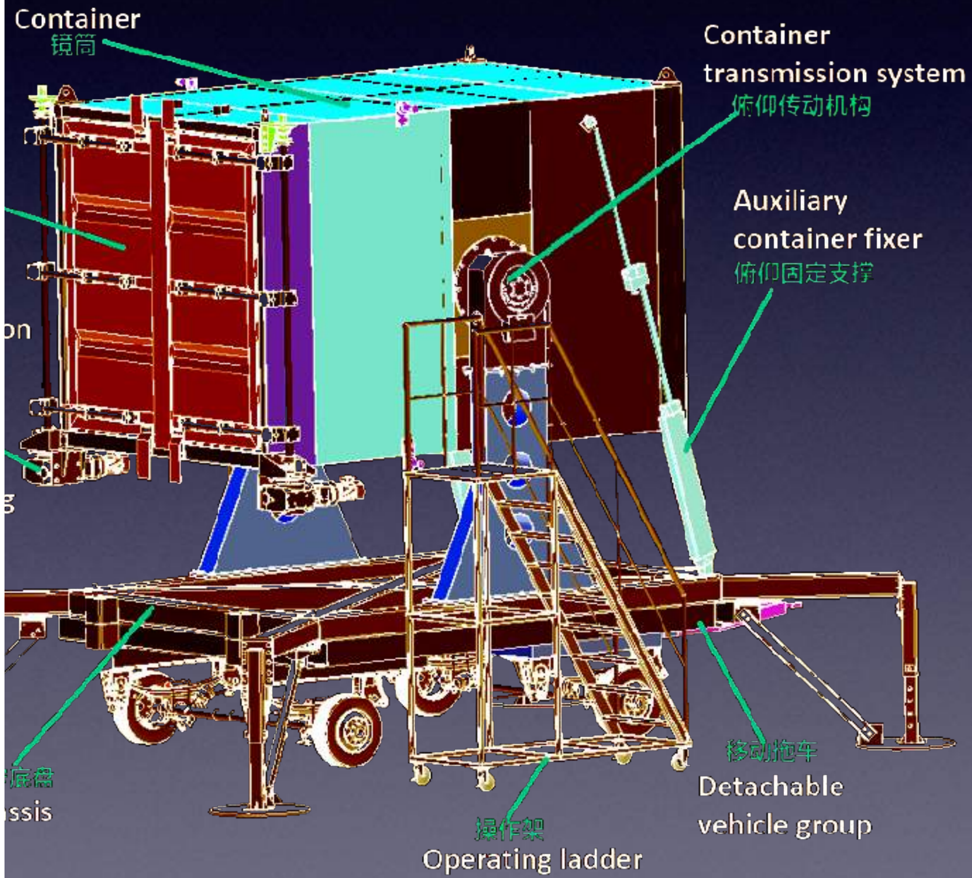
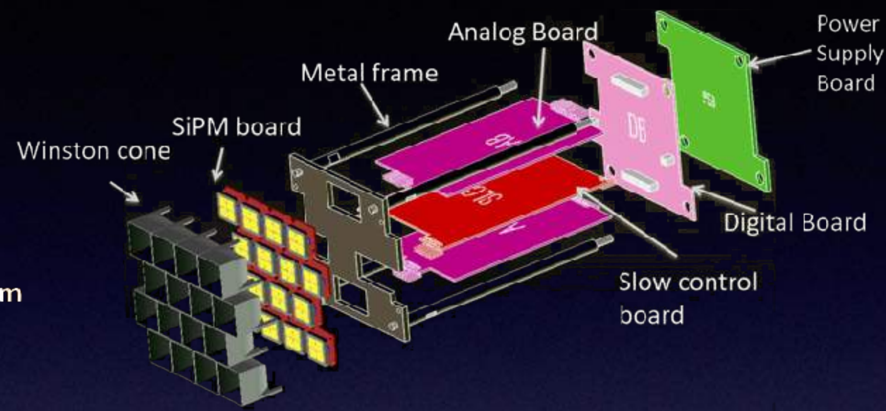
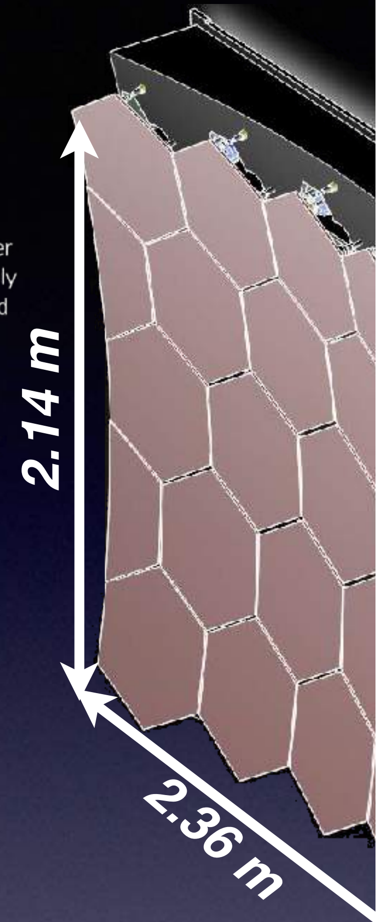
e Field Cherenkov Telescope Array

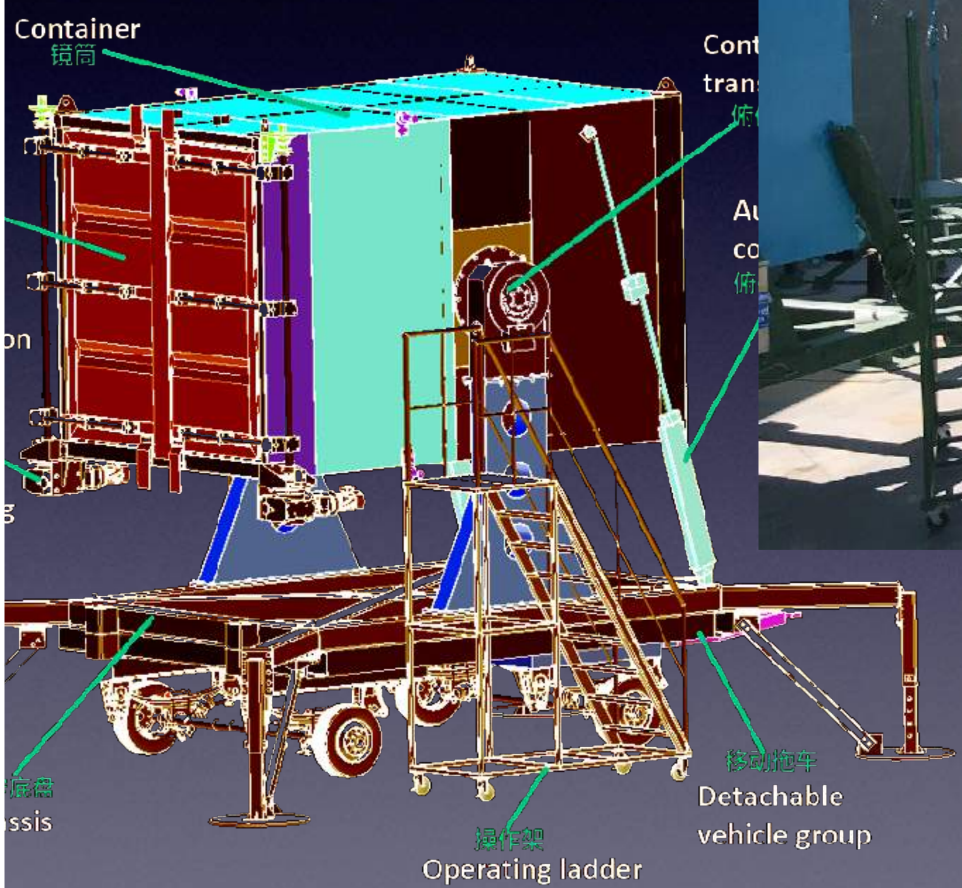






Mirror Size	5 m^2
Pixel Size	0.5°
# Pixels	1024
FoV	14”x16”
Dynamic range	1-32’000 PE/pixels (<10% nonlinearity)
Time resolution	<2 ns
PDE	>28%@400nm >22%@350nm >17%@310 nm
Time resolution	< 10 ns
Charge resolution	<50%@10 PE <5 %@1000PE
Pointing Accuracy	<0.1%
# of telescopes	16(18)

e Field Cherenk



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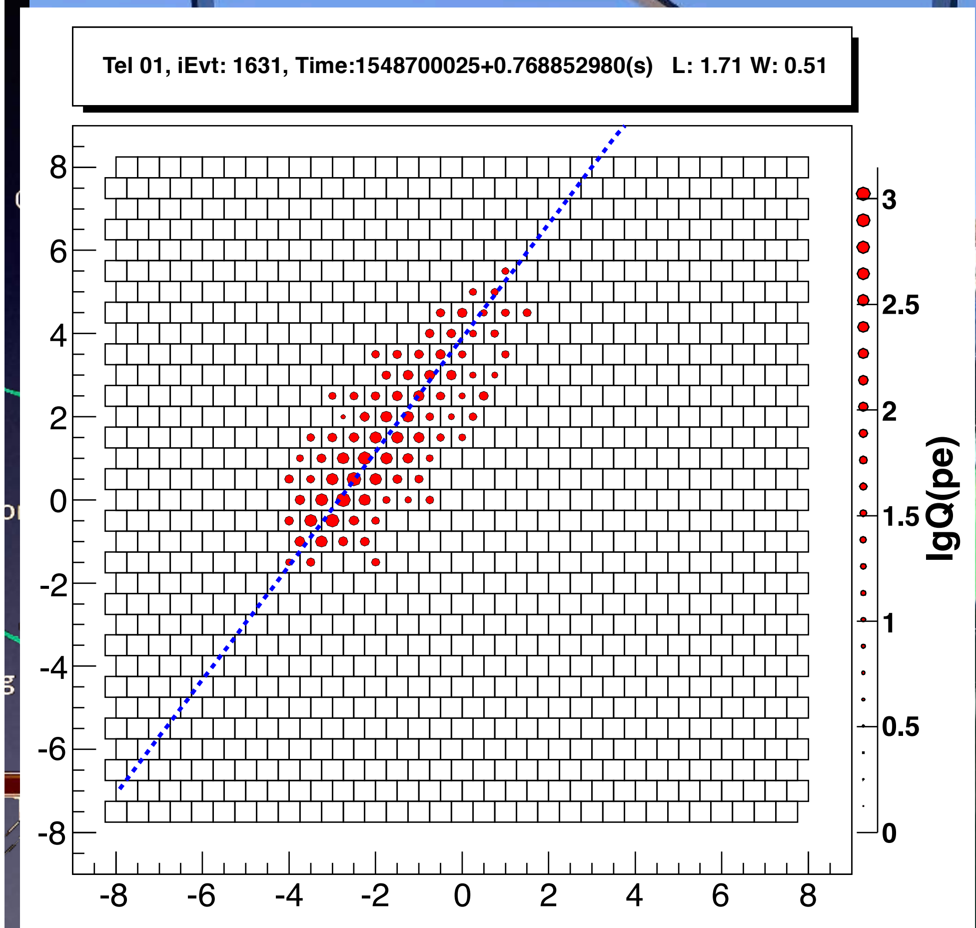

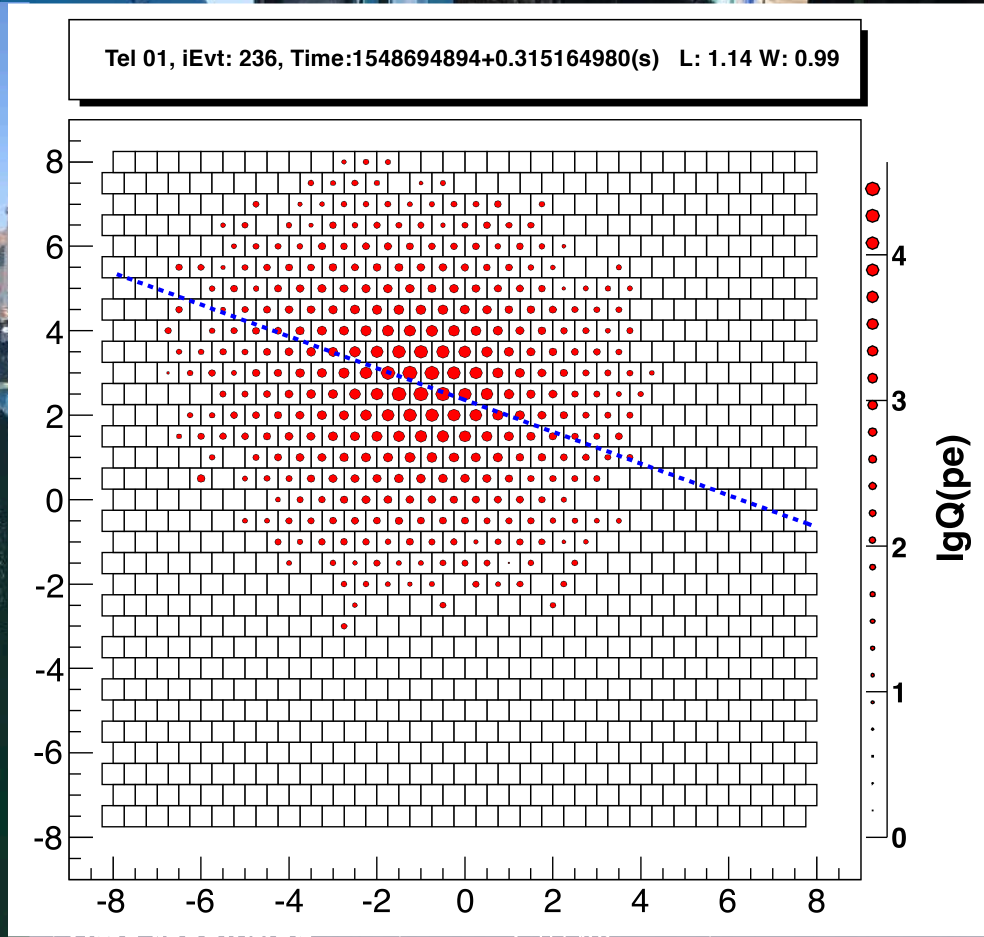

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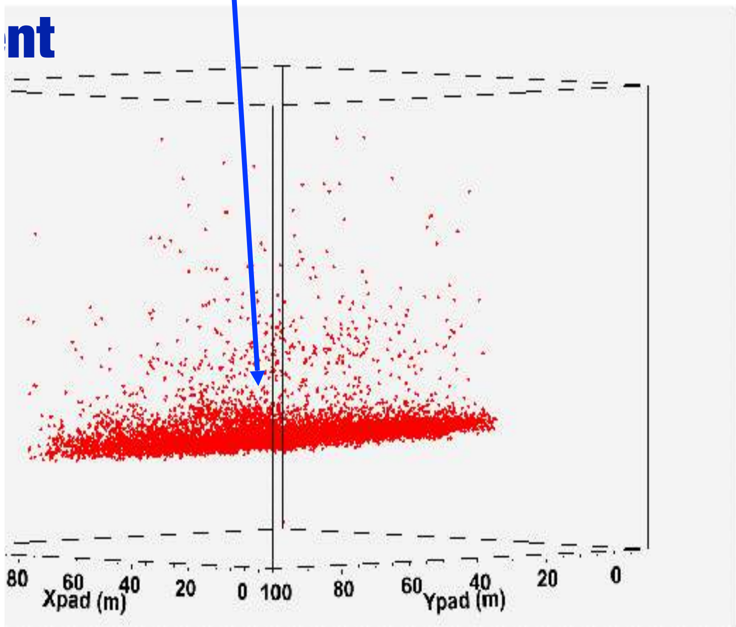
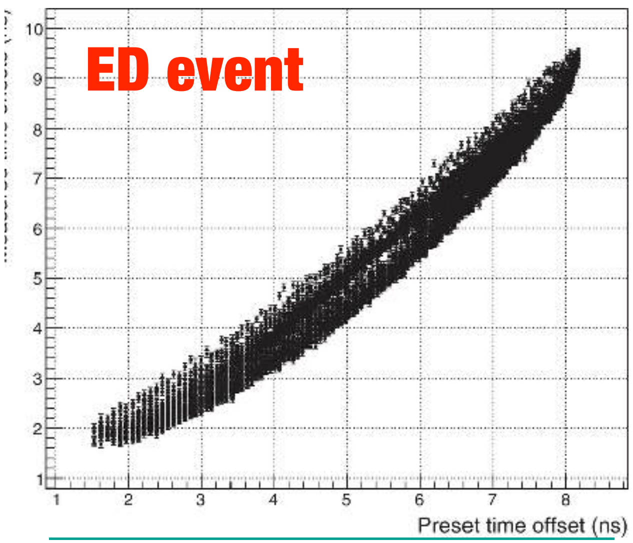
...wer reconstruction



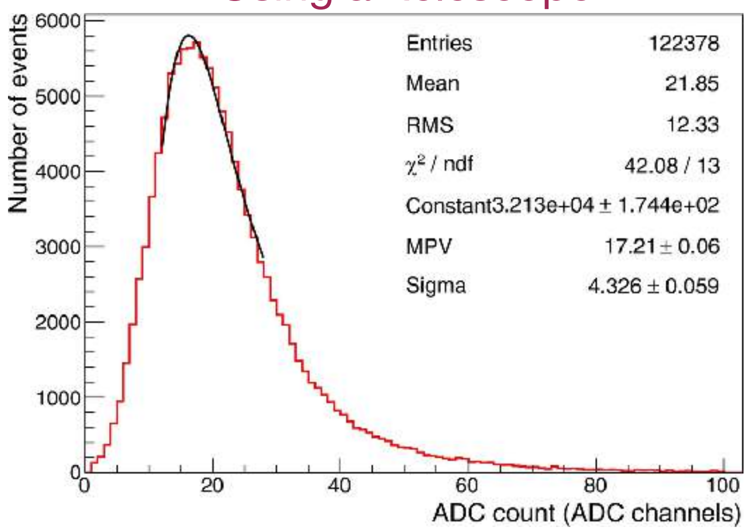


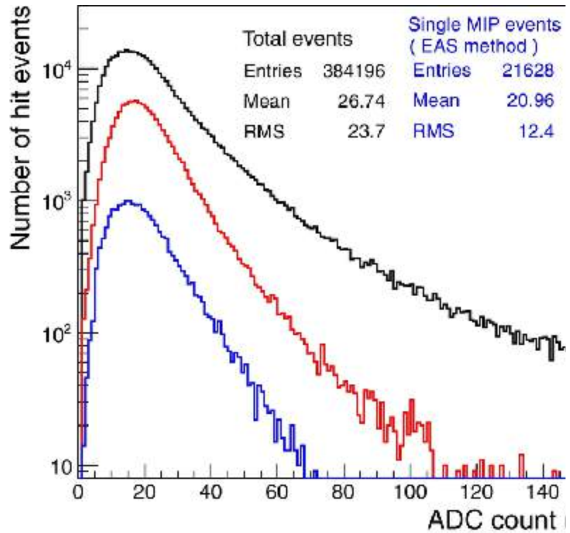
- Timing information allow to fit the shower front and derive d...

$$t_i^{\text{real}} = l^{\text{real}}\frac{x_i}{c} + m^{\text{real}}\frac{y_i}{c} + n^{\text{real}}\frac{z_i}{c} + \alpha r_i + t_0$$

$$(l, m, n) = (\sin\vartheta\cos\phi,\ \sin\vartheta\sin\phi,\ \cos\vartheta)$$

- Usually iterative fitting procedure are used to minimise resid... (~20 detector hit)
- Charge calibration is done using MIPs with 2 methods
  - Using a 'telescope'
  - Self calibrati...





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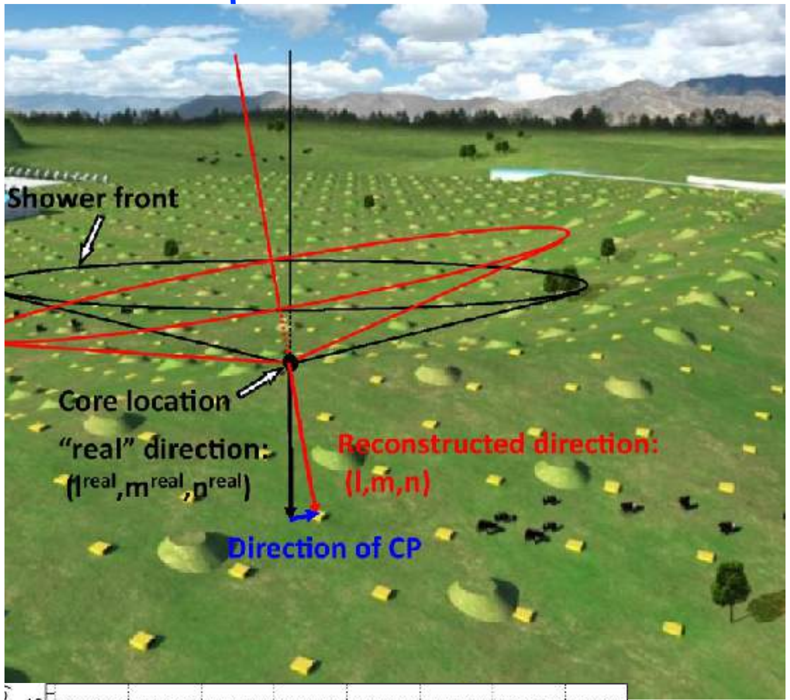

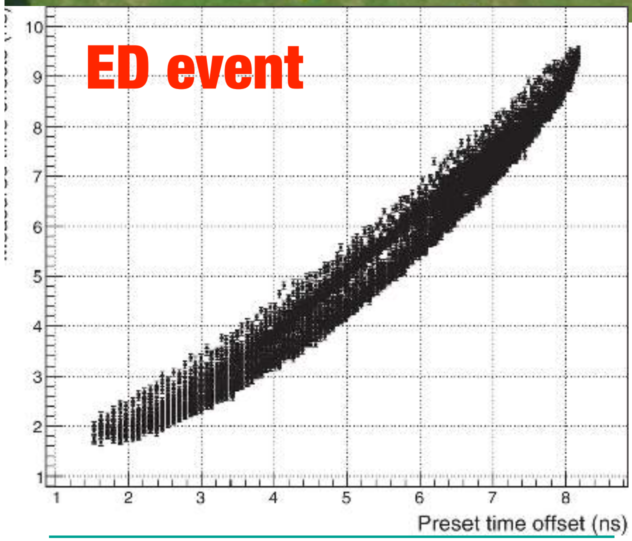

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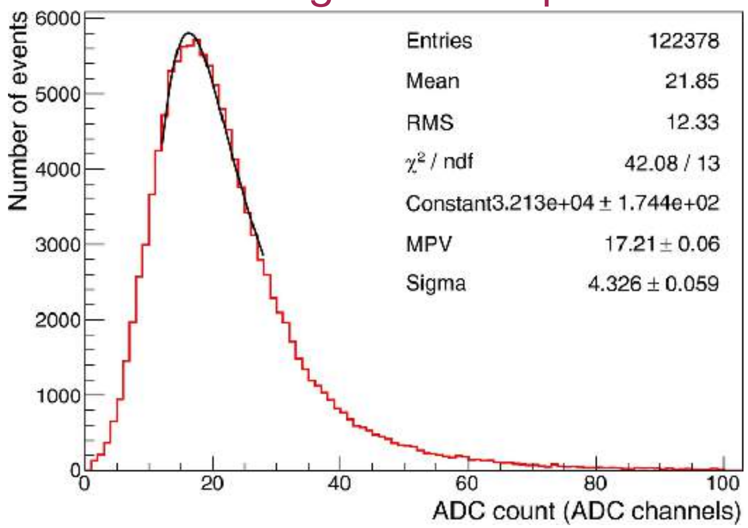

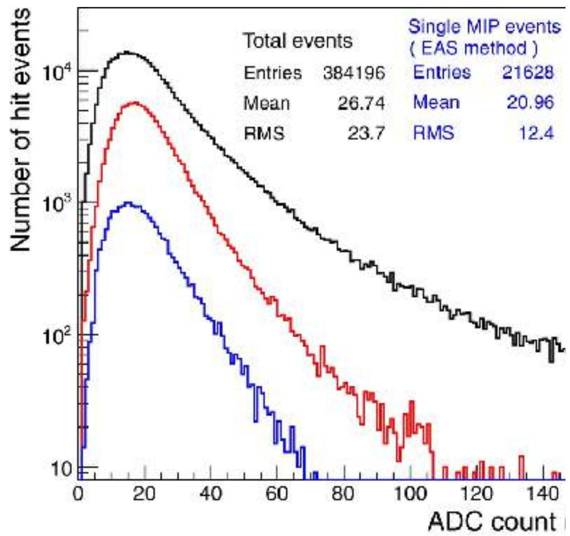

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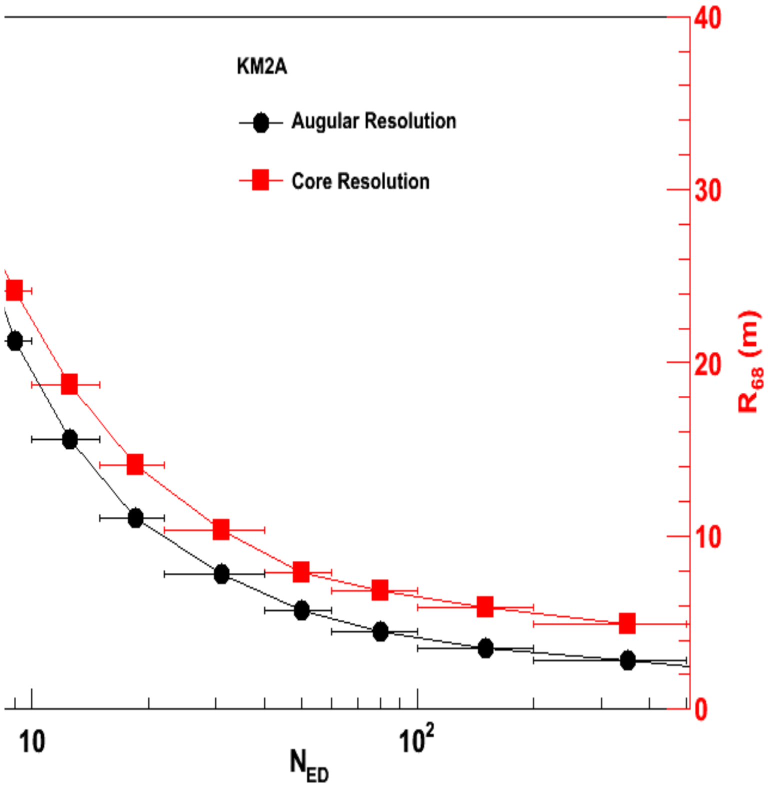

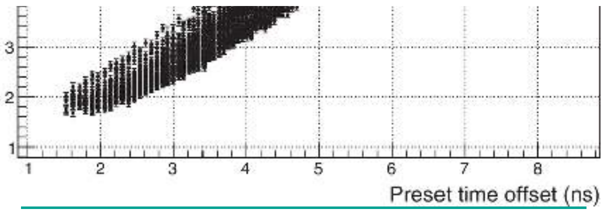

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$$(l, m, n) = (\sin\vartheta\cos\phi,\ \sin\vartheta\sin\phi,\ \cos\vartheta)$$

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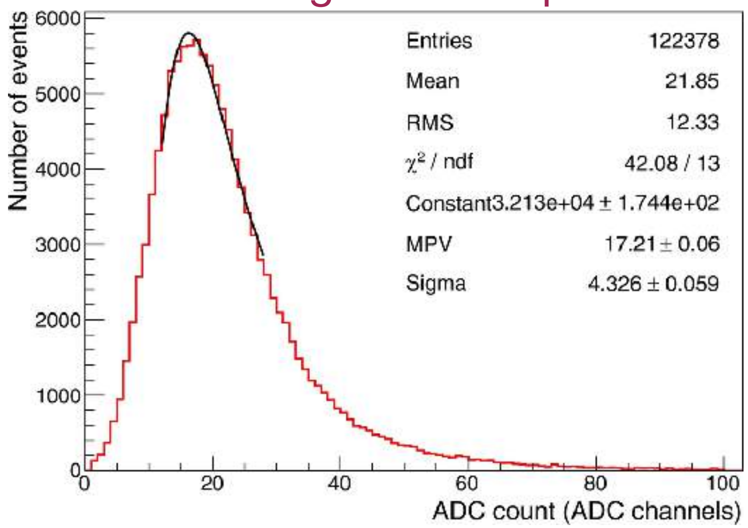
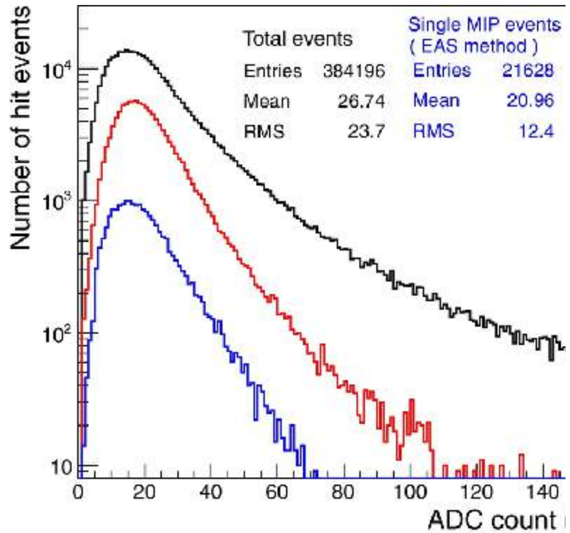
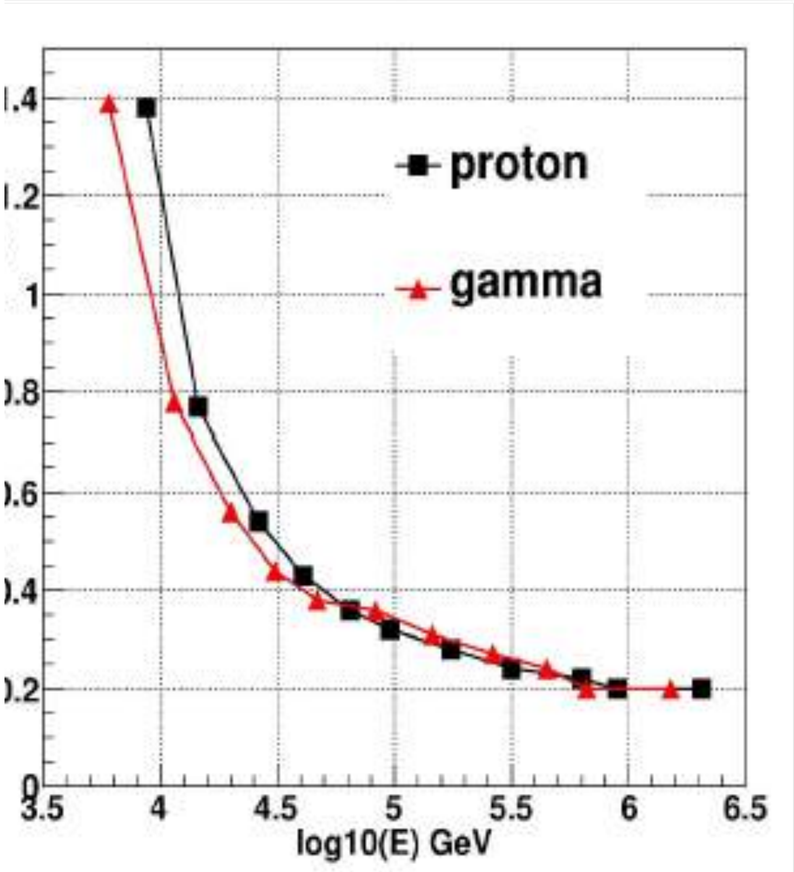
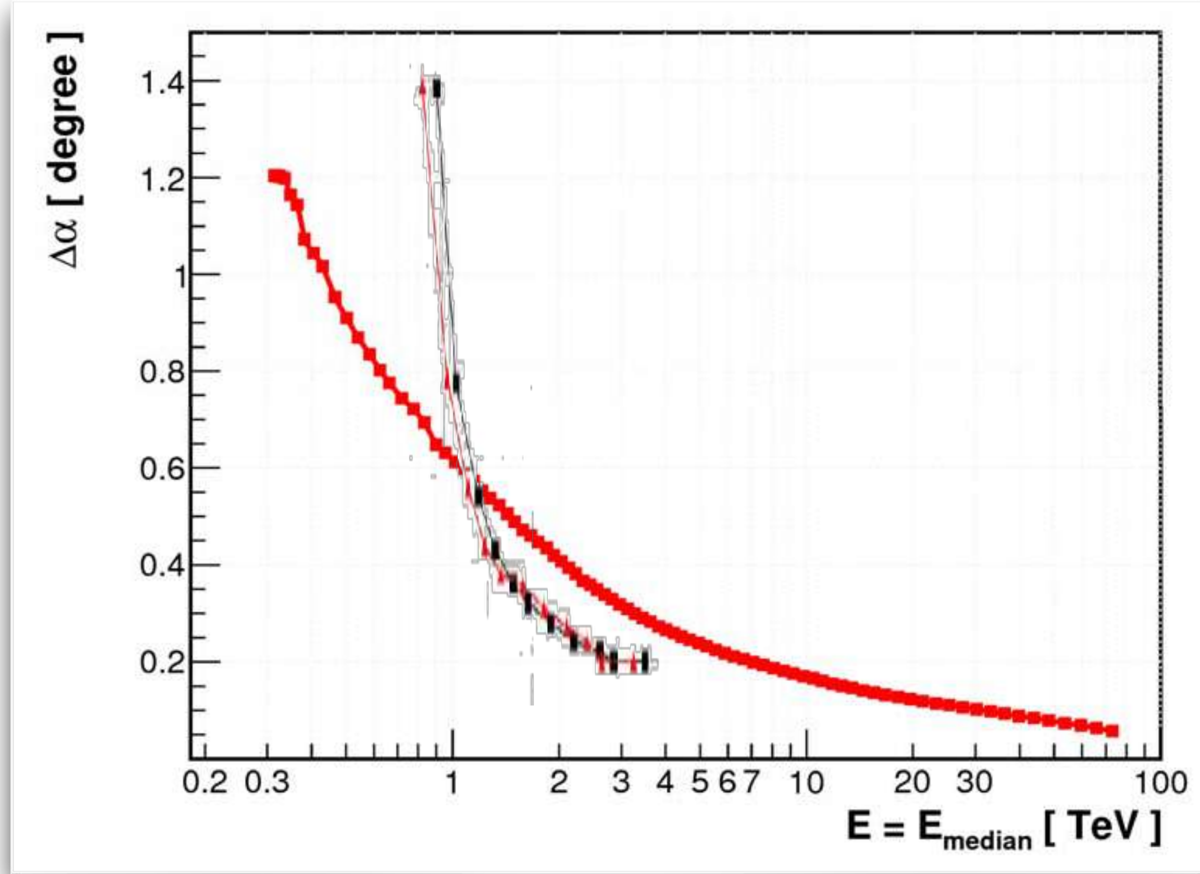




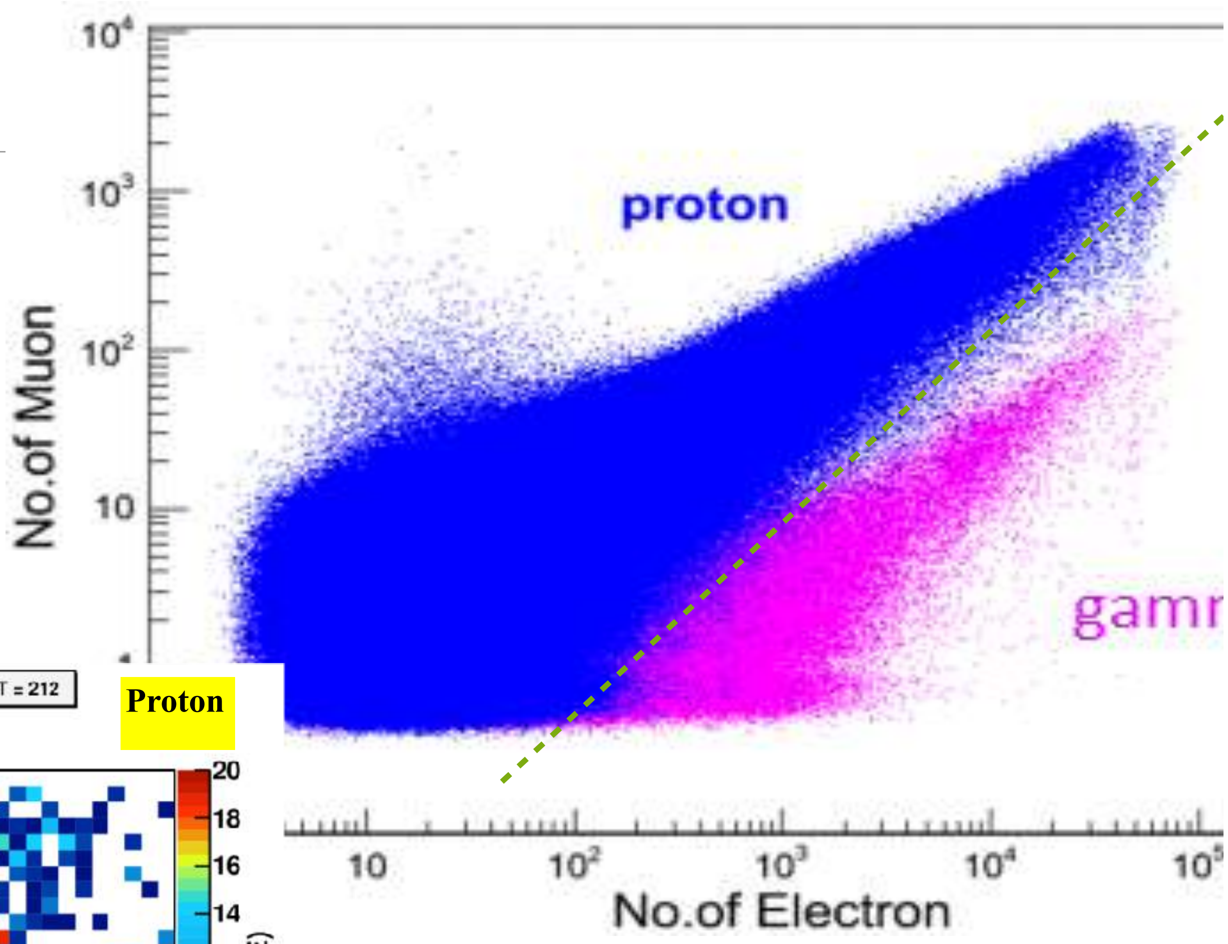
ılar resolution

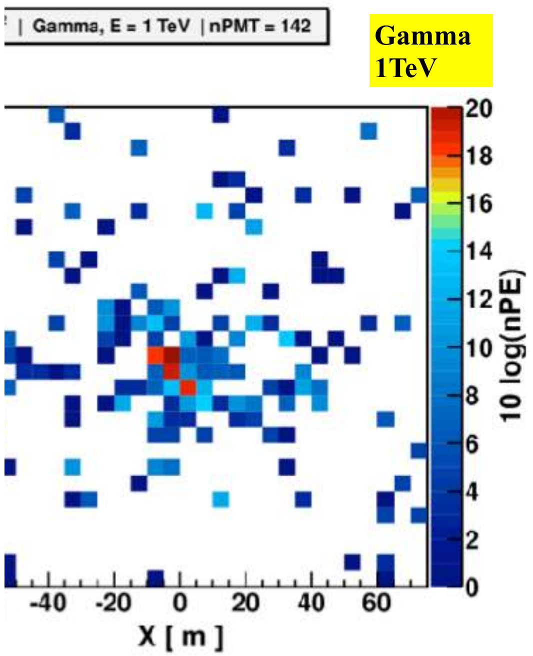


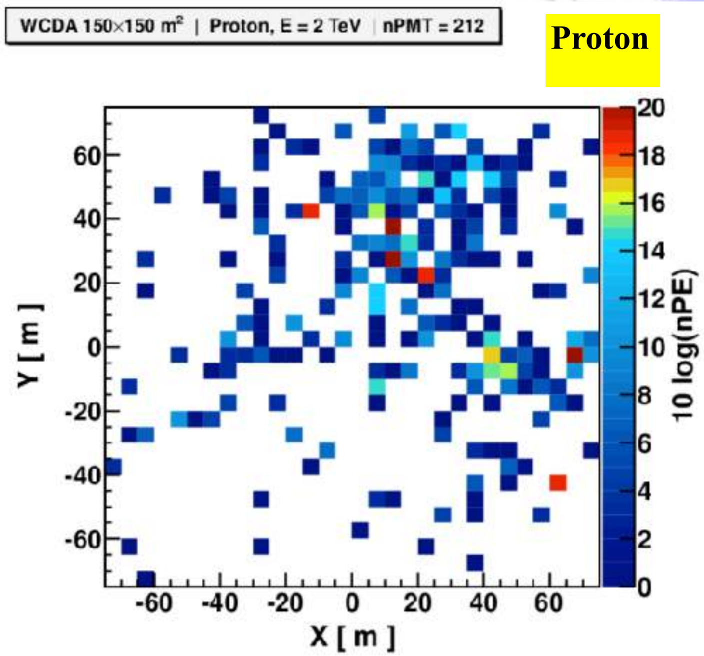


ma/Hadron separation

- er shape can be used to separate ıa/from hadron (Low energy)
- ore powerful is the measurement of the uon content (High energy)

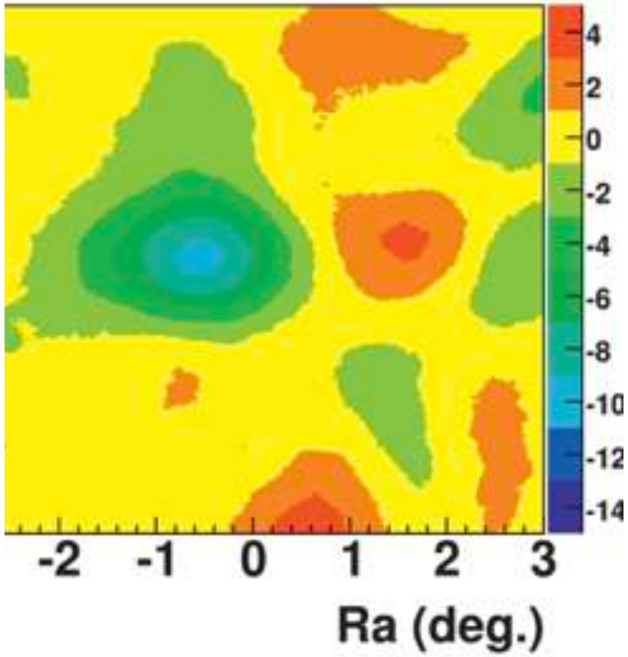




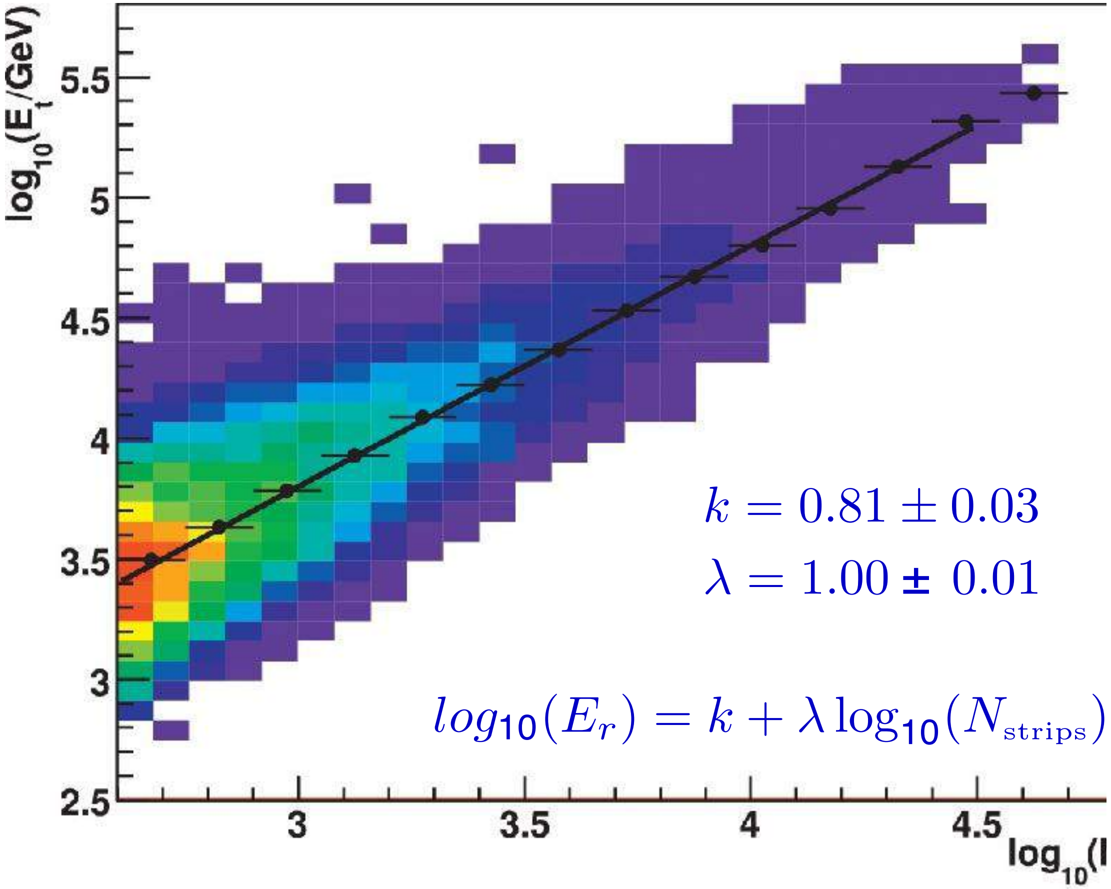


gy calibration with moon-shadows

Absolute-energy-scale calibration of ARGO-YBJ for
in multi-TeV region with the Moon shadow obs
Astr. Part. Phys 90 (2017)



2.5-3.8 TeV



$k = 0.81 \pm 0.03$

$\lambda = 1.00 \pm 0.01$

$log_{10}(E_r) = k + \lambda \log_{10}(N_{\rm strips})$

gy calibration with moon-shadows

Absolute-energy-scale calibration of ARGO-YBJ for
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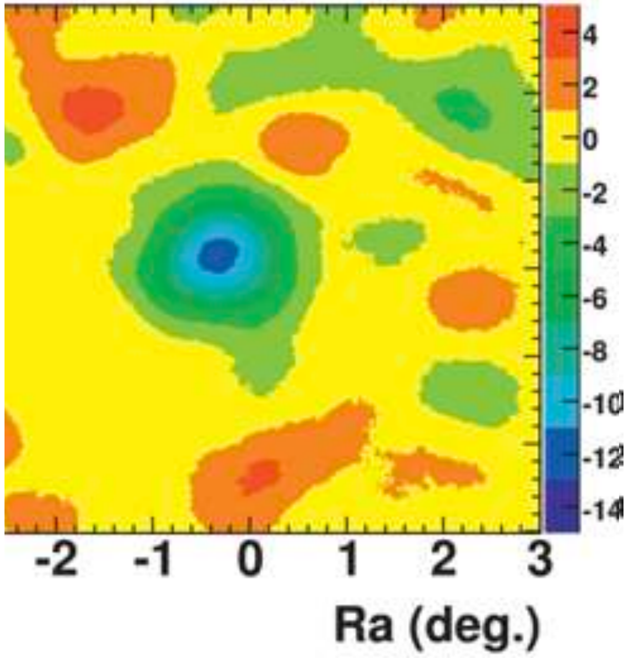
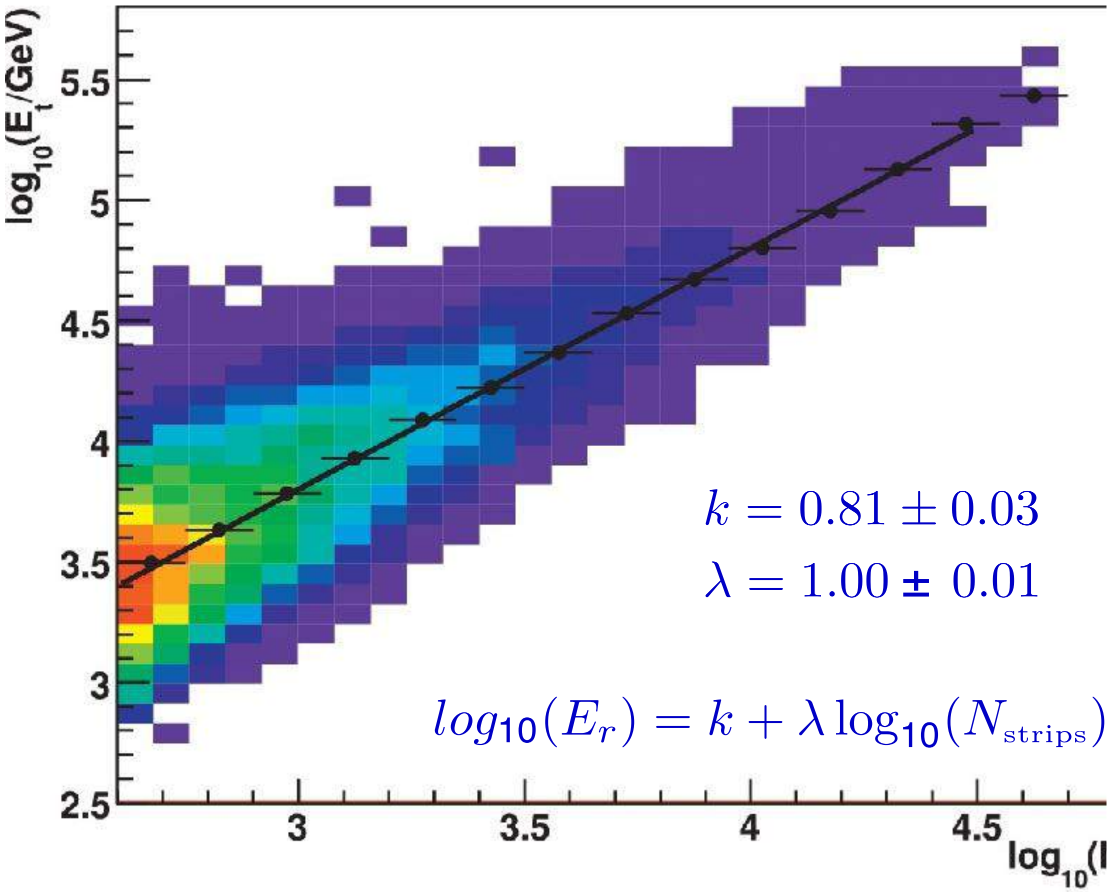
[Astr. Part. Phys 90 (2017)]



3.8-6.5TeV'



$k = 0.81 \pm 0.03$

$\lambda = 1.00 \pm 0.01$

$log_{10}(E_r) = k + \lambda \log_{10}(N_{strips})$

gy calibration with moon-shadows

Absolute-energy-scale calibration of ARGO-YBJ for
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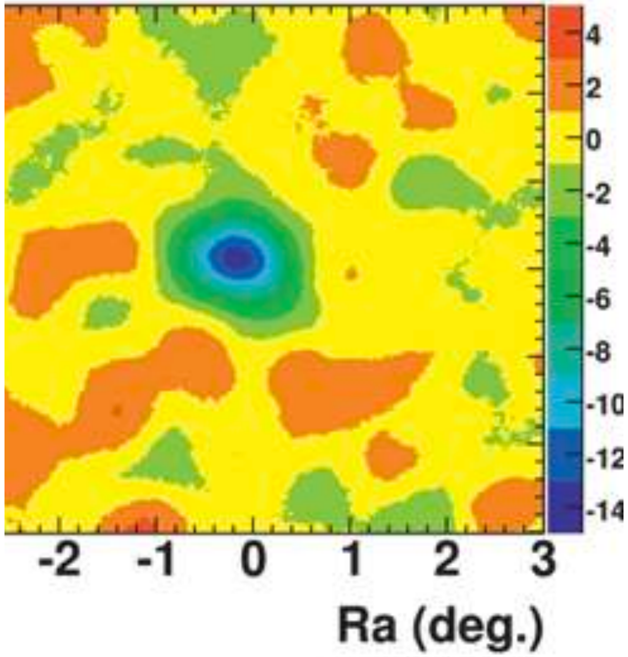
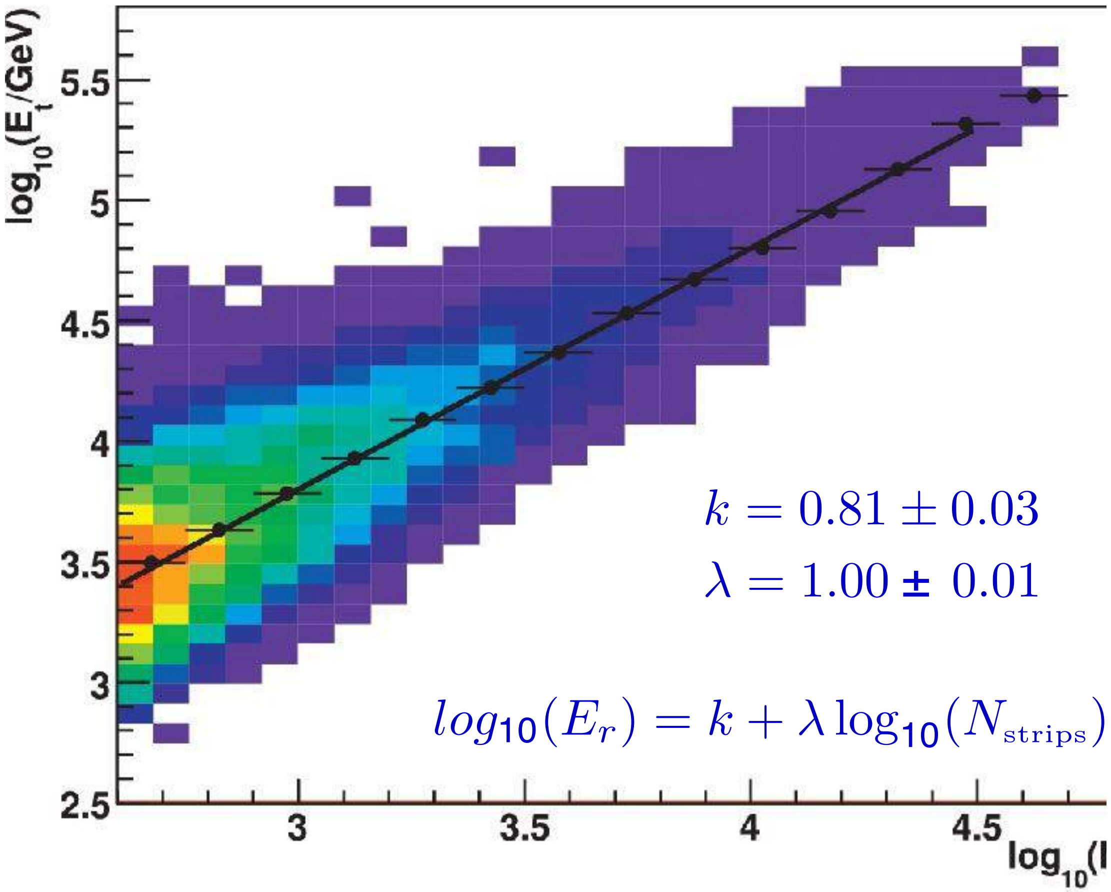
Astr. Part. Phys 90 (2017)

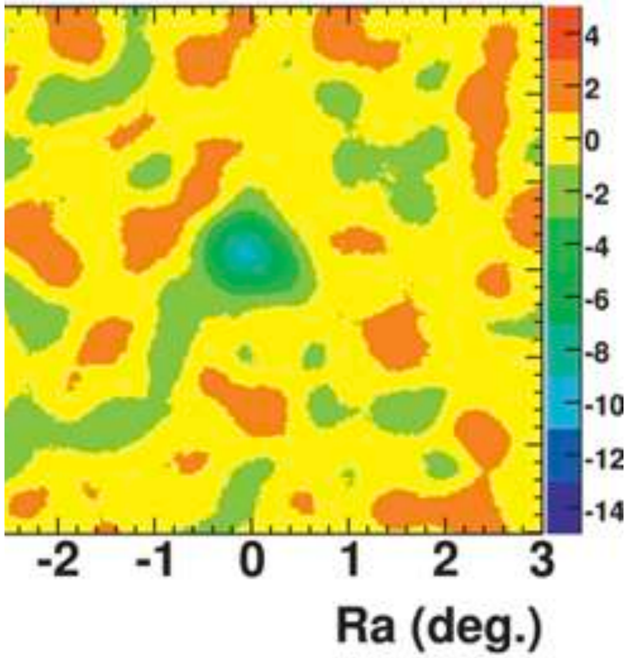


6.5-12 TeV

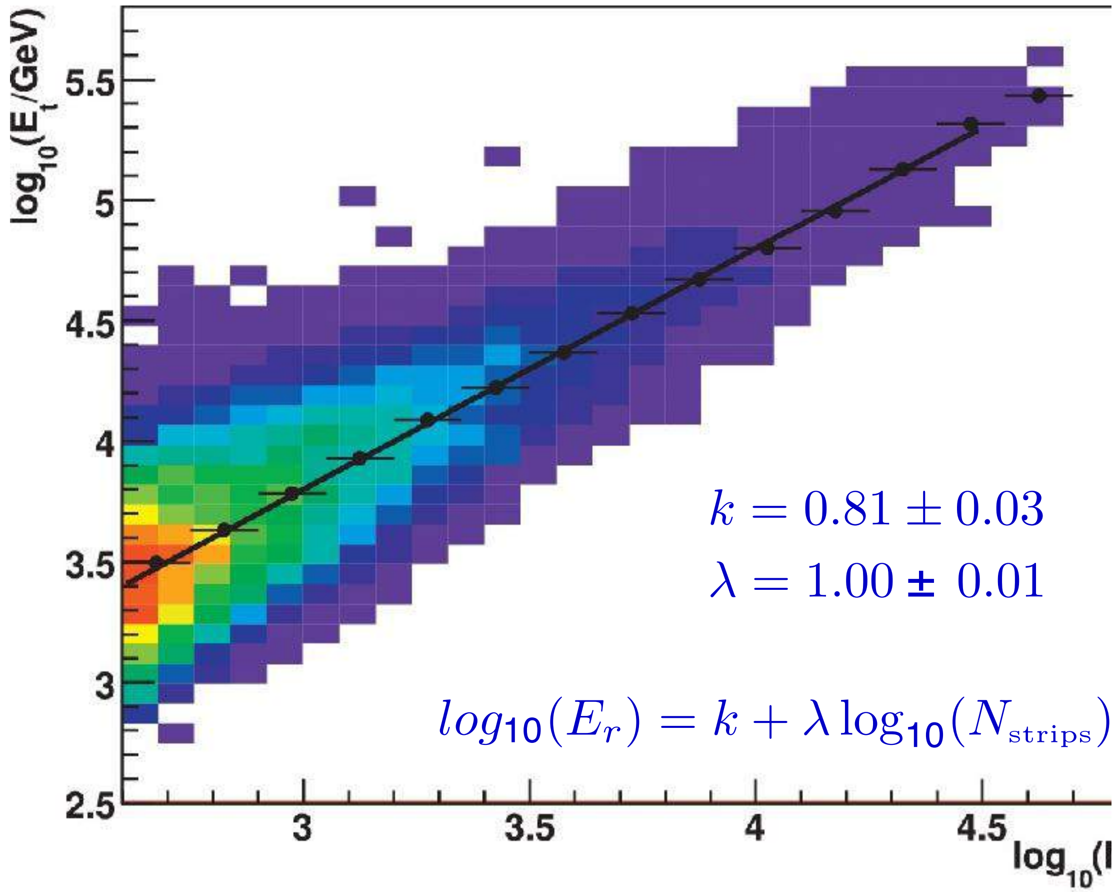


gy calibration with moon-shadows

Absolute-energy-scale calibration of ARGO-YBJ for
in multi-TeV region with the Moon shadow obs
Astr. Part. Phys 90 (2017)

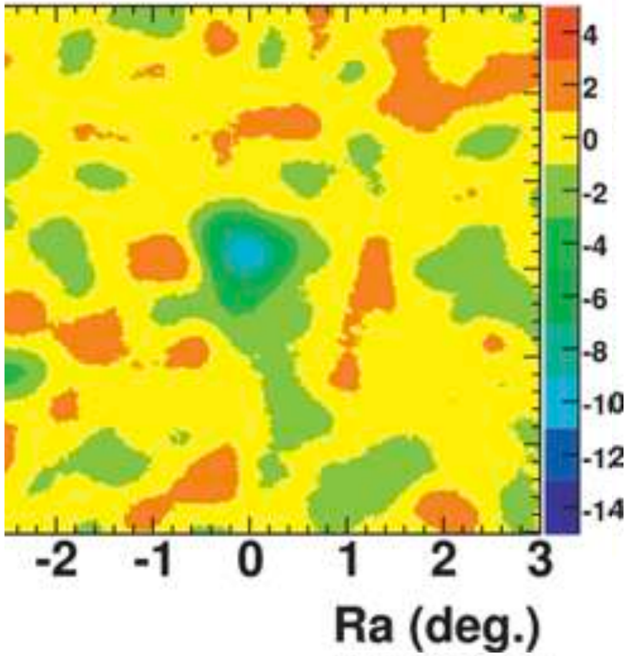


12-20 TeV

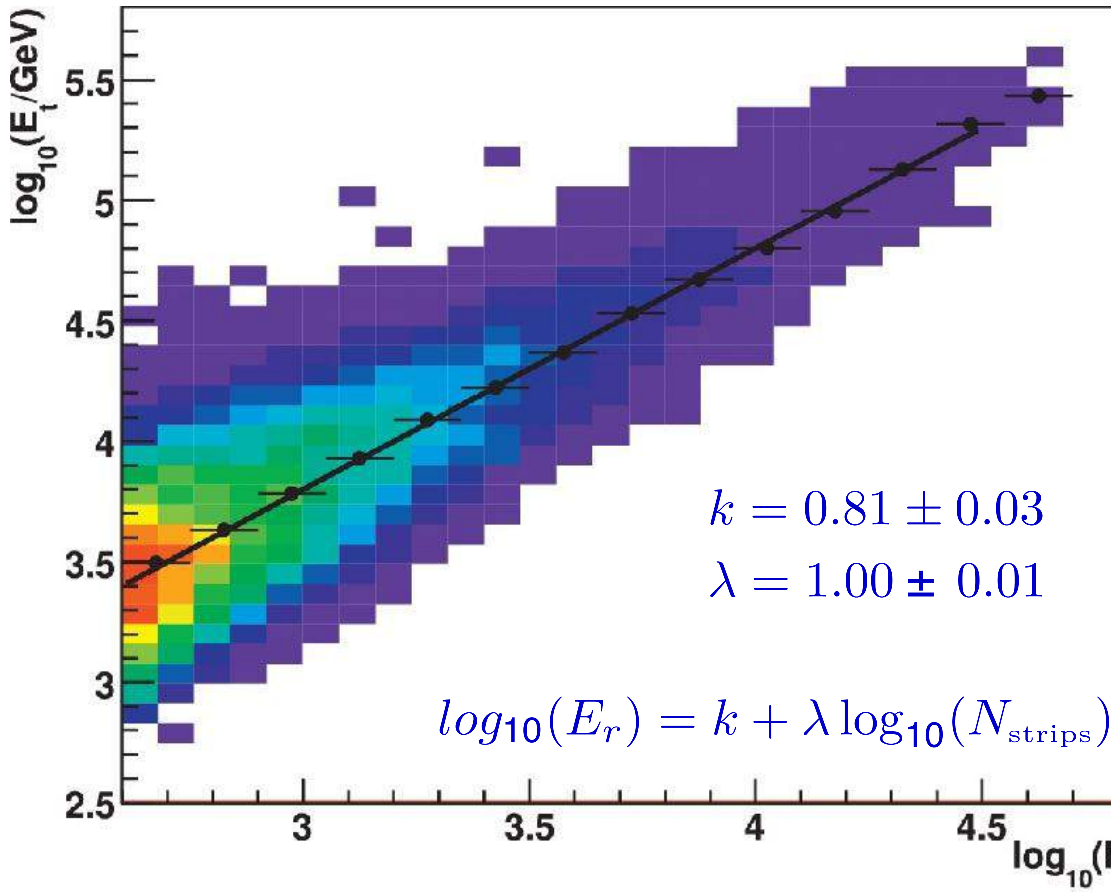


gy calibration with moon-shadows

Absolute-energy-scale calibration of ARGO-YBJ for
in multi-TeV region with the Moon shadow obs
[Astr. Part. Phys 90 (2017)]



>20 TeV

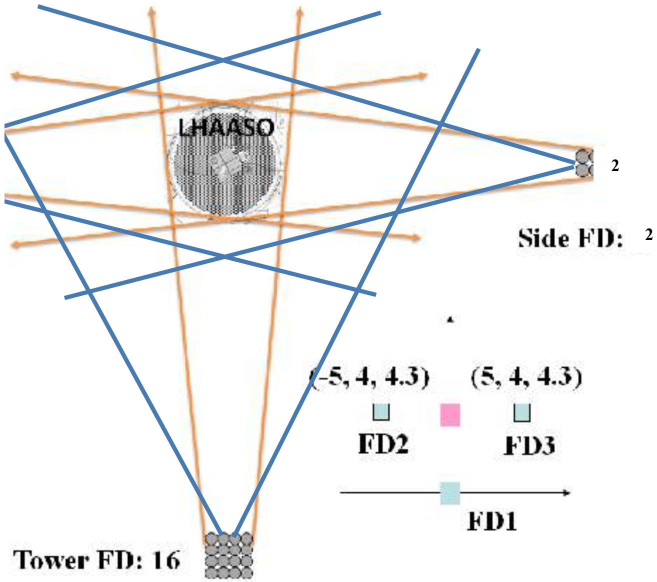


$k = 0.81 \pm 0.03$

$\lambda = 1.00 \pm 0.01$

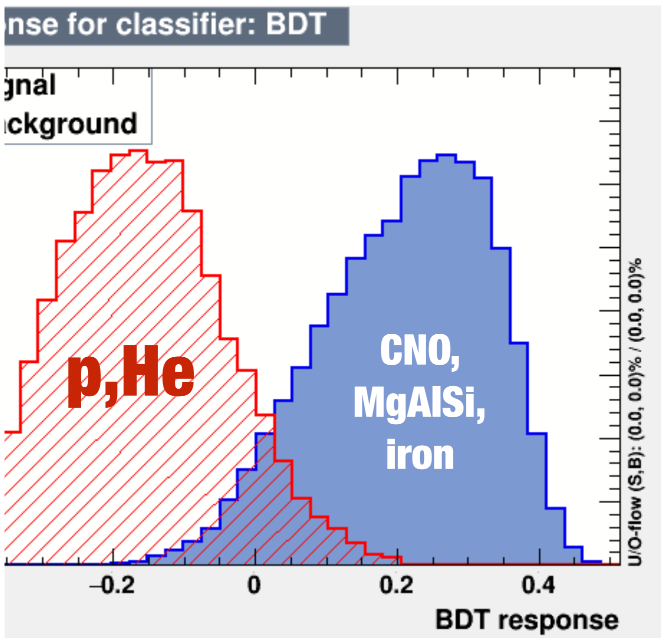
$log_{10}(E_r) = k + \lambda \log_{10}(N_{strips})$

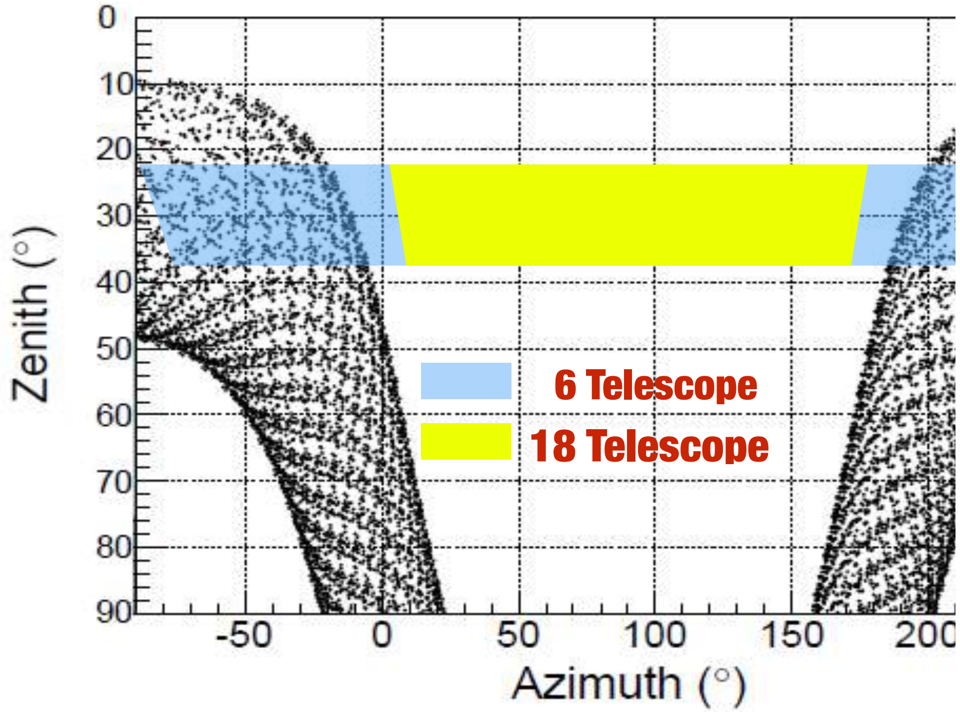
position studies with Hybrid measurements



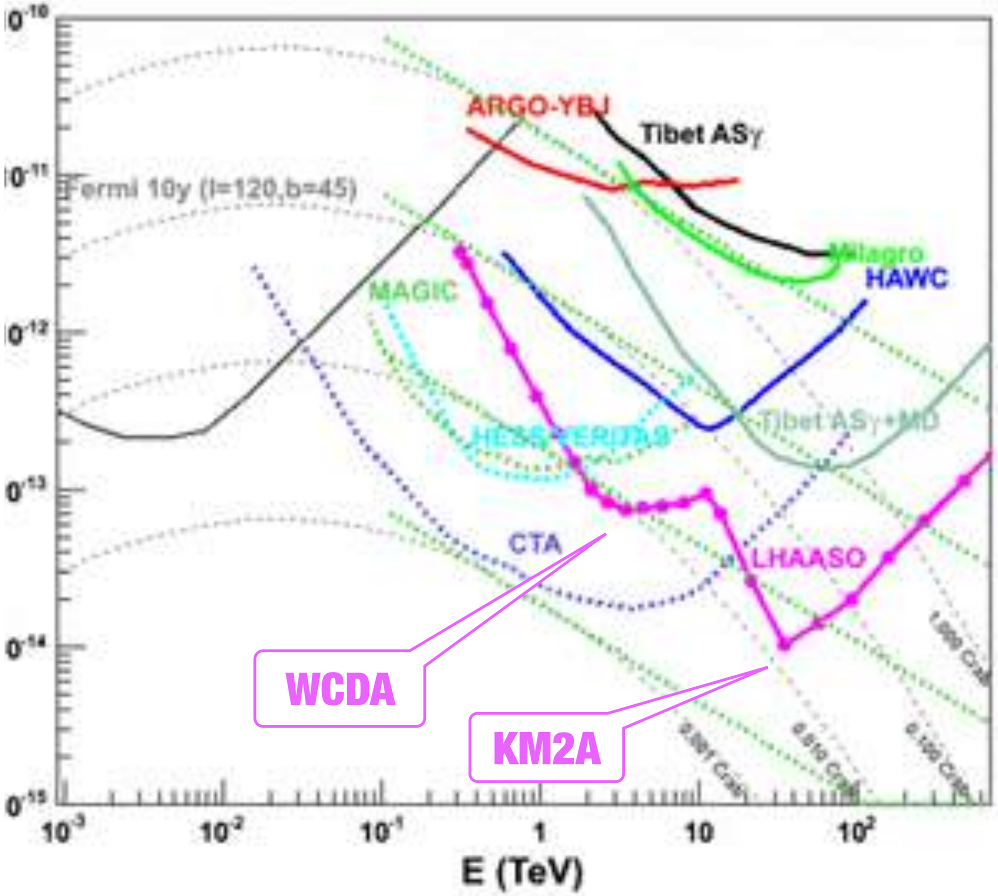
- 0.1-10 PeV in 2019 - Pure proton and pure Helium spectra
  - 6 C-Tel's (60 in elevation) + 1st pool
- 1- 100 PeV in 2021 - Pure iron or heavy nuclei (MgAlSi+Fe) spect
  - 18 C-Tel's (45 in elevation)+ Scin.+ MD array
- 100 PeV in 2023 - 2nd knee
  - 20 F-tel's + MD array

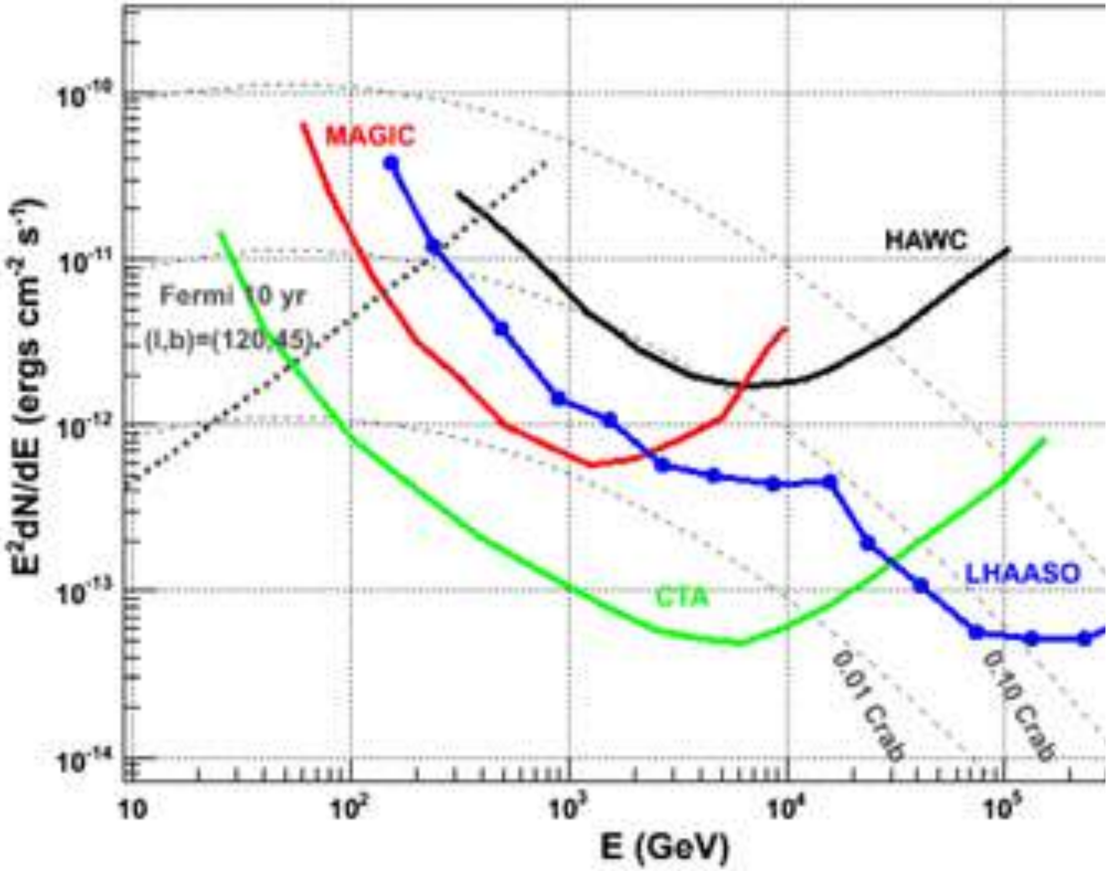
MVA with BDT to achieve separation





LHAASO Integral Sensitivity





Integral *Differential*

LHAASO Timeline

15 TDR

16 approval & release of funds

17 Start of construction

18-2020 construction

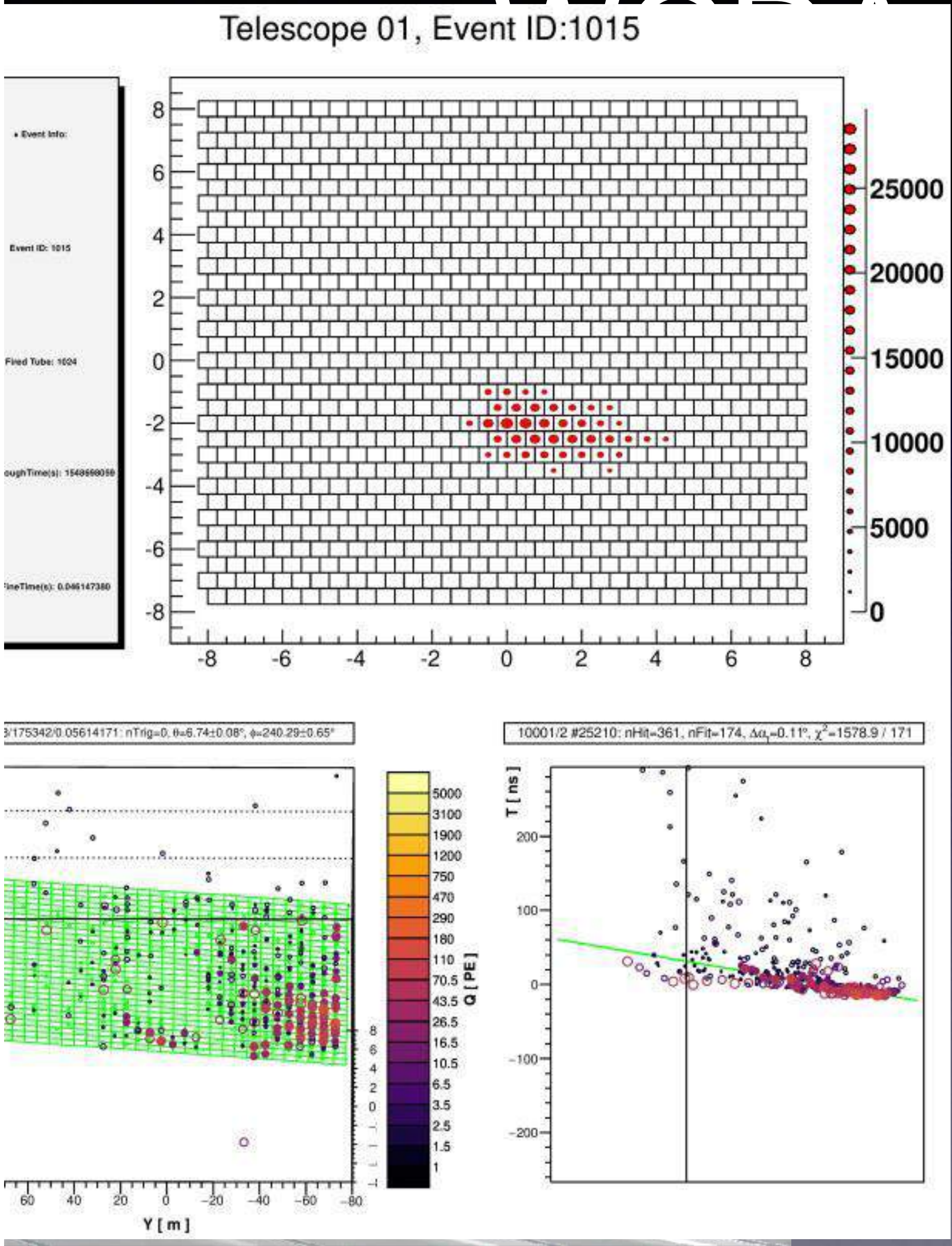
21 start or operation

February 2019 25% ready

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

WCDA - Status

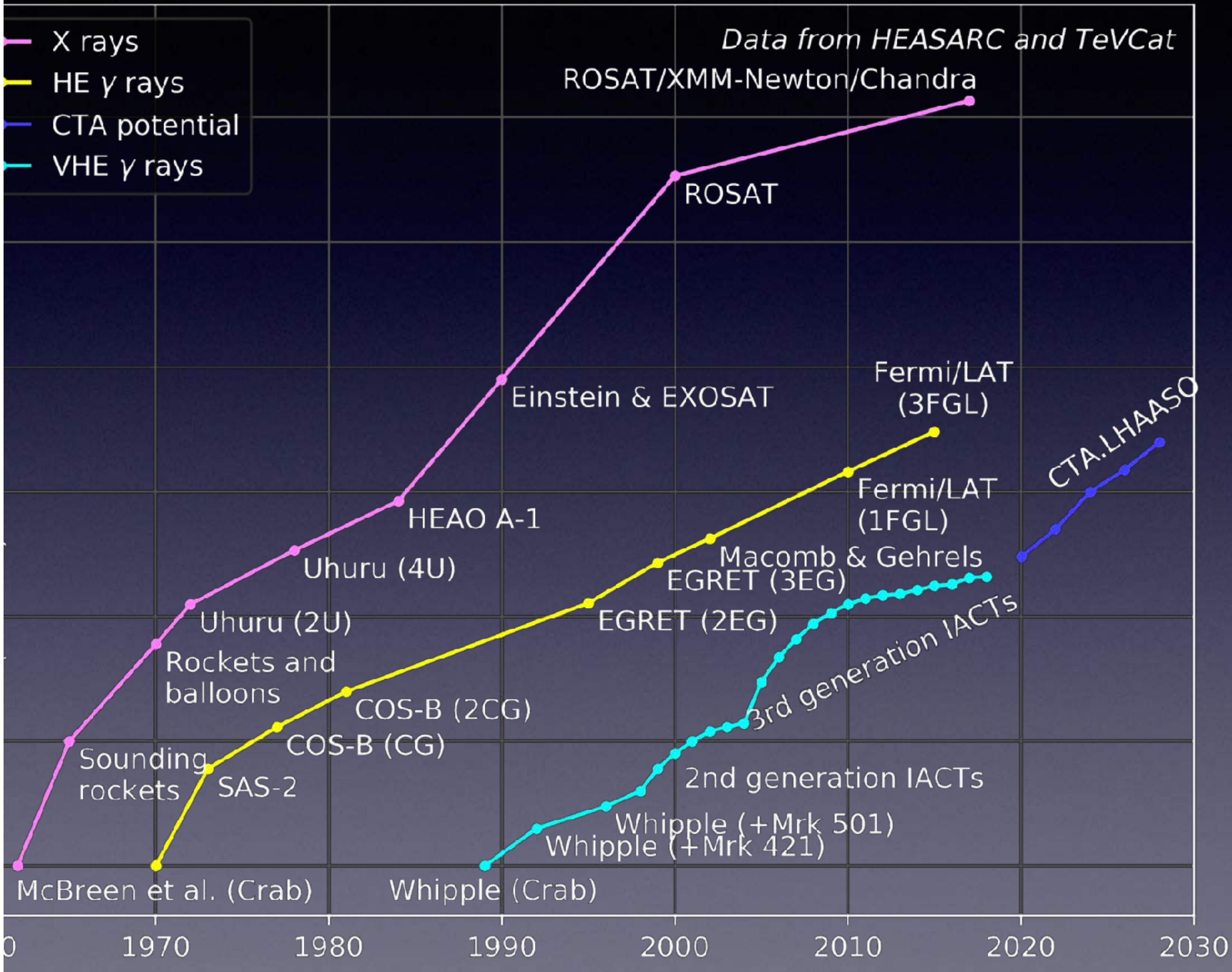
- Status


Telescope 01, Event ID:1015
25000
20000
15000
10000
5000
0
10001/2 #25210: nHit=361, nFit=174, Δα=0.11°, χ²=1578.9 / 171
T [ns]
Q [PE]
Y [m]


Apr-20


May-20

Conclusion



3FGL 3034 sources > 100 Me
95% extragalactic!
21% BL Lacs
16% FSRQ
19% unclassified blazars +
22% unassociated high lat
Still lots of association work
(CTA, HAWC, LHAASO, SPA

My personal Kifune P
based on Fegan mac