5th Workshop for Air Shower Detection at High Altitudes

Design Highlights of the LHAASO Project

Huihai He, IHEP, CAS
on behalf of the LHAASO collaboration
2014-5-27

Outline

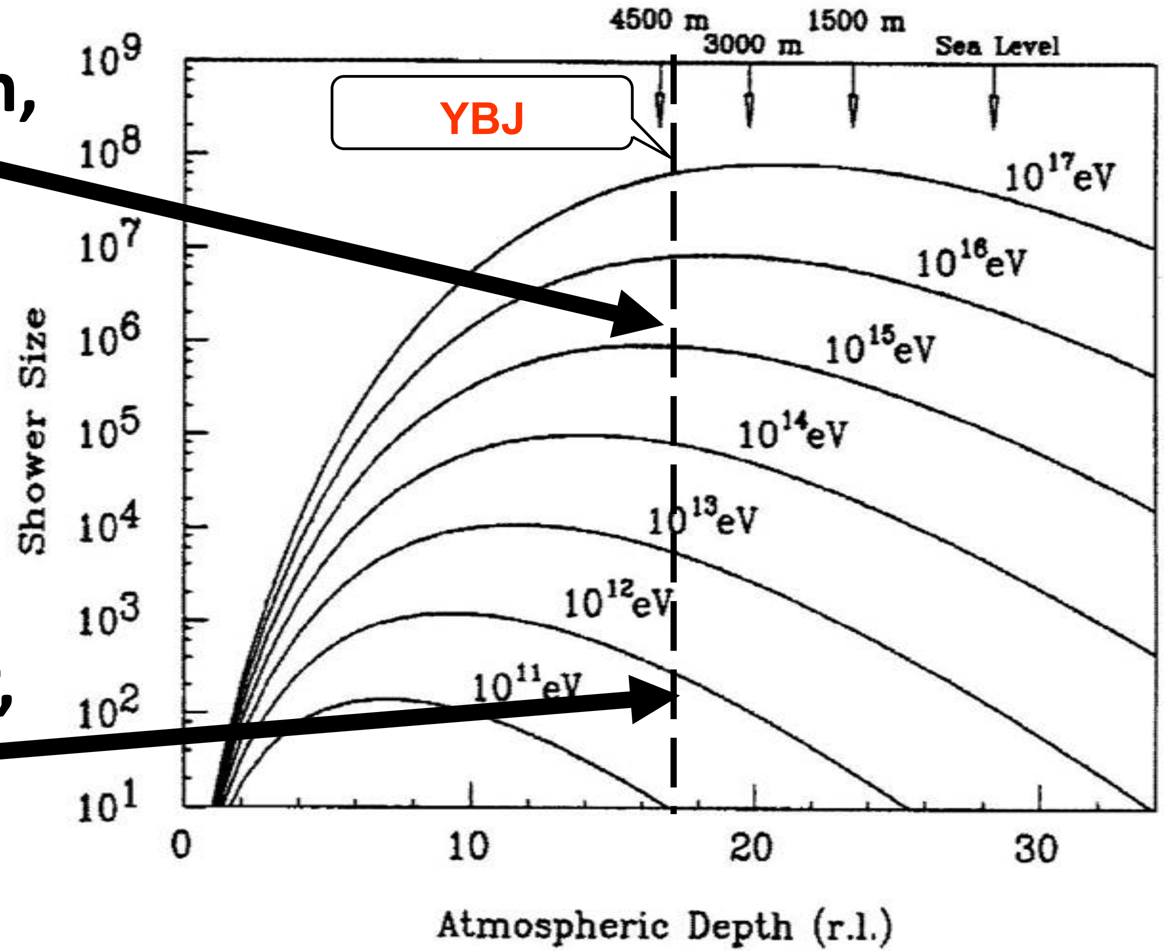
- Introduction
- LHAASO detectors
- LHAASO electronics
- “Trigger-less” DAQ

Major scientific goals

- GAMMA RAY ASTRONOMY
  - Searching for GCR sources by measuring SED above 30TeV
  - Survey in the Northern hemisphere for gamma ray sources above 100GeV
- COSMIC RAY PHYSICS
  - Energy spectrum for individual compositions below 1EeV
- …

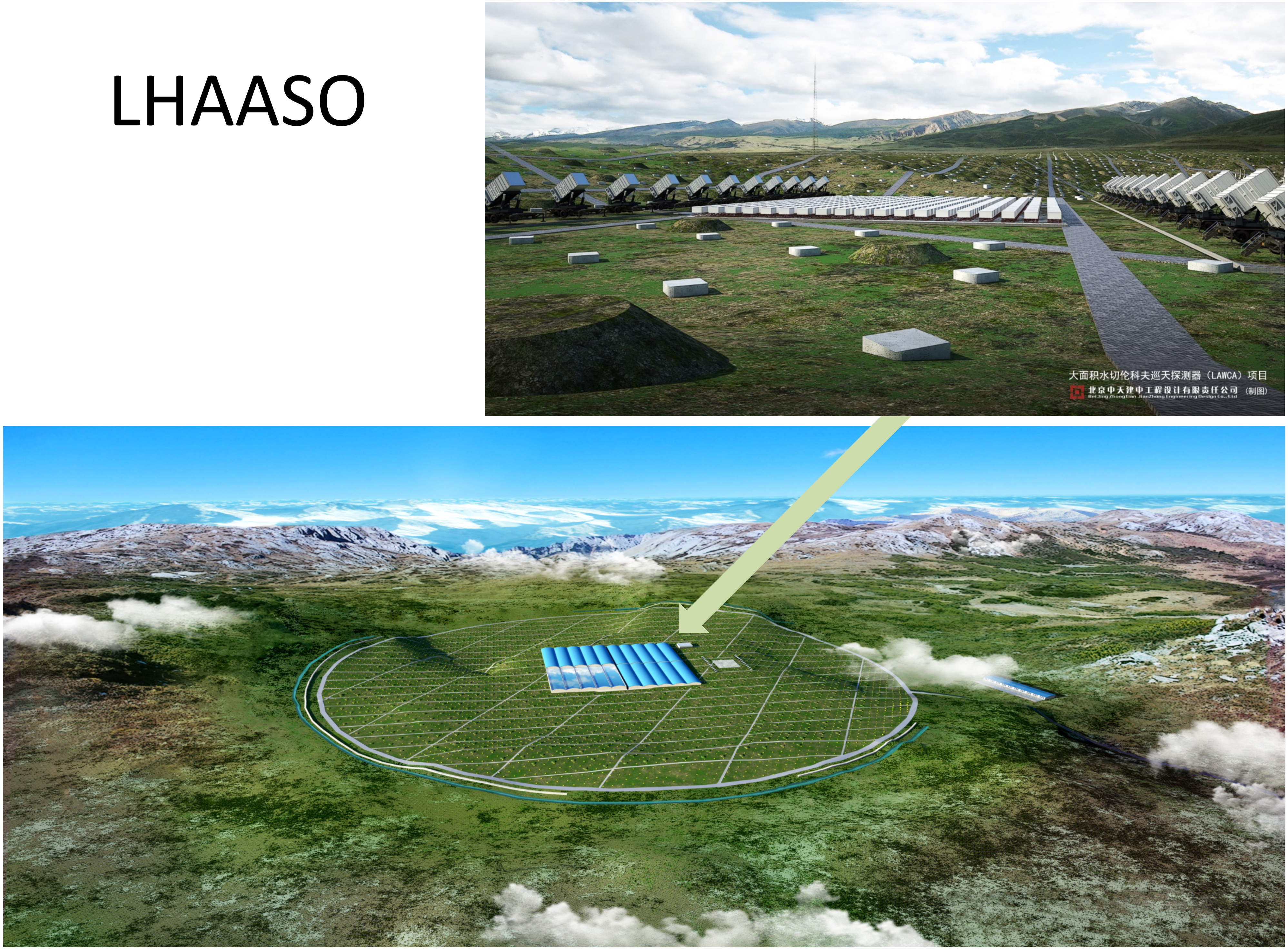
Measurement of air showers at high altitude

- **HE: near Xmax →lower fluctuation, better σ_E**

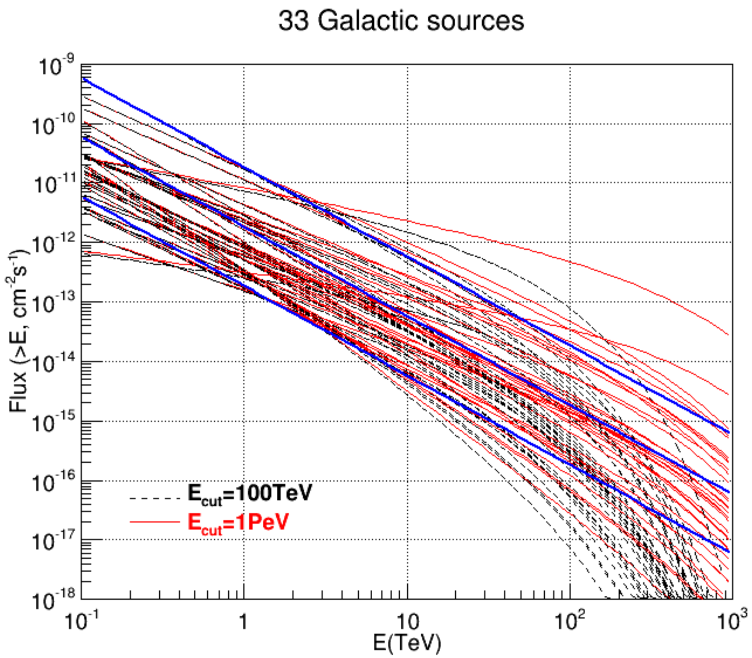


- **Lower E_{th} →deeper, more sources**

LHAASO


大面积水切伦科夫巡天探测器（LAWCA）项目
北京中天建中工程设计有限责任公司 （制图）
BeiJing ZhongTian JianZhong Engineering Design Co., Ltd

KM2A: *Gamma ray astronomy beyond 30TeV*



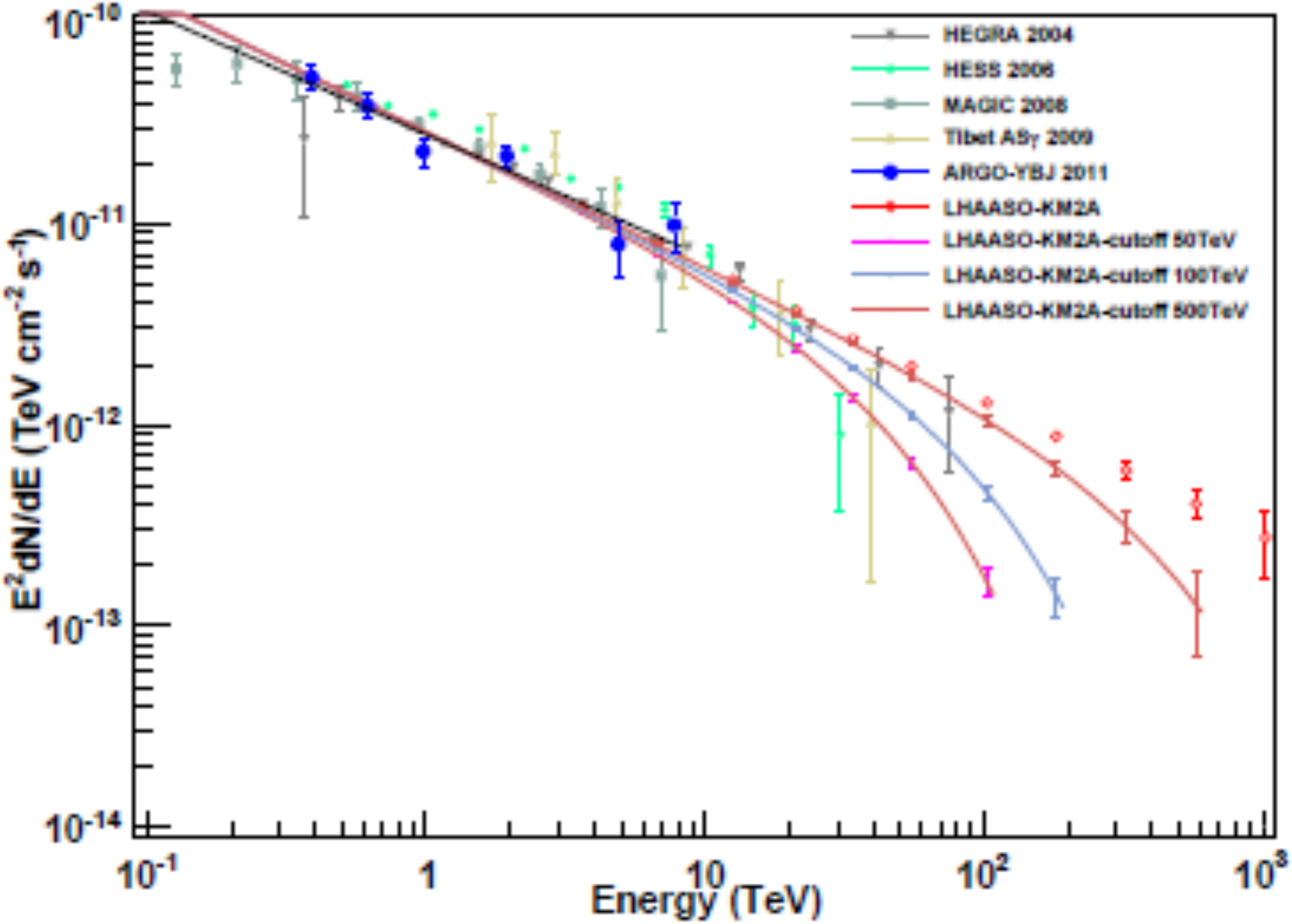
- 1km² array
- ED coverage 0.5%
  - ~5000m²
- MD coverage 5%
  - ~50000m²

- **Sensitivity: 1%I_{Crab}@100TeV**
  - **1000/year/km²÷100=10/year/km²**

Background free, >2000 km²hr/year (CTA: 100 km²hr/year)

γ/p discrimination power:10^{-4}-10^{-5} (IACT、HAWC: 10^{-2})

- **Wide field of view**
- **Energy resolution: 20%@100TeV**

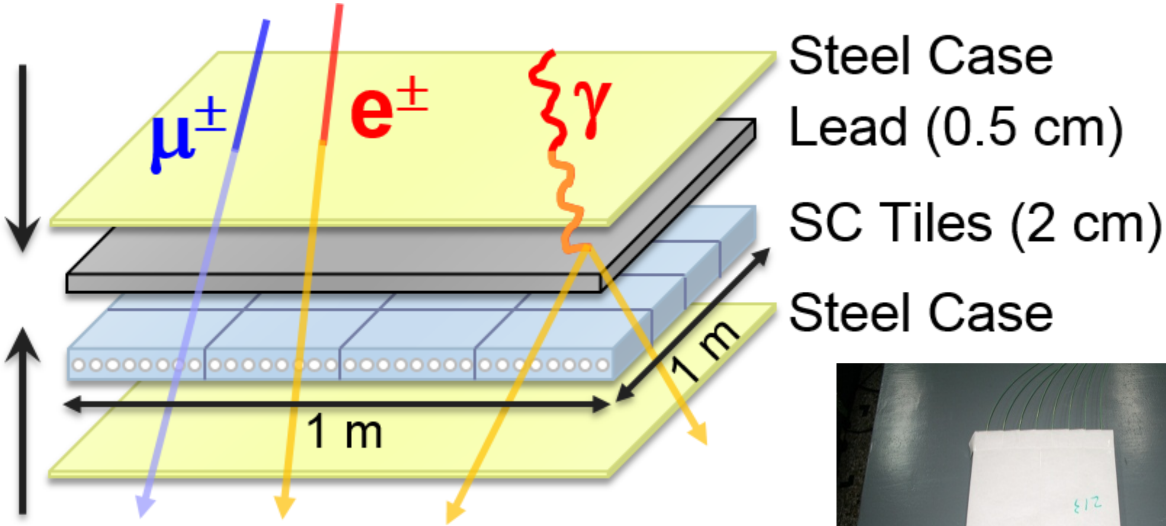


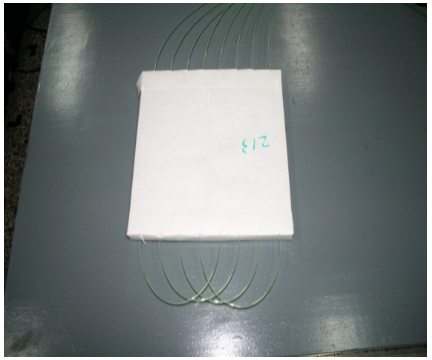
HEGRA 2004
HESS 2006
MAGIC 2008
Tibet ASγ 2009
ARGO-YBJ 2011
LHAASO-KM2A
LHAASO-KM2A-cutoff 50TeV
LHAASO-KM2A-cutoff 100TeV
LHAASO-KM2A-cutoff 500TeV
E²dN/dE (TeV cm⁻² s⁻¹)
Energy (TeV)
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
10⁻¹
1
10
10²
10³

ED Specifications

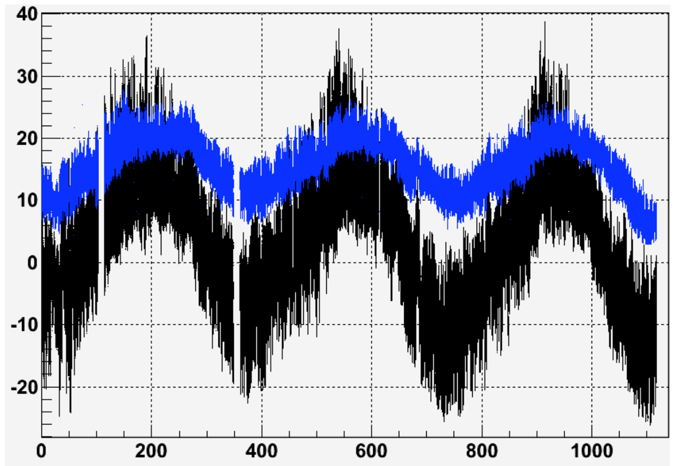
Item	Value
Effective area	1 m^2
Thickness of tiles	2 cm
Number of WLS fibers	32/tile×4 tile
Detection efficiency (> 5 MeV)	>95%
Dynamic range	1-10,000 particles
Time resolution	<2 ns
Particle counting resolution	25% @ 1 particle 5% @ 10,000 particles
Aging (<20%)	>10 years
Spacing	15 m
Total number of detectors	5635

Electromagnetic Particle Detector (ED)





- **Uniformity for 5635 units: < 10%**
- **Stability with ±30°C: <5%**
- **Aging in 10 years: <20%**

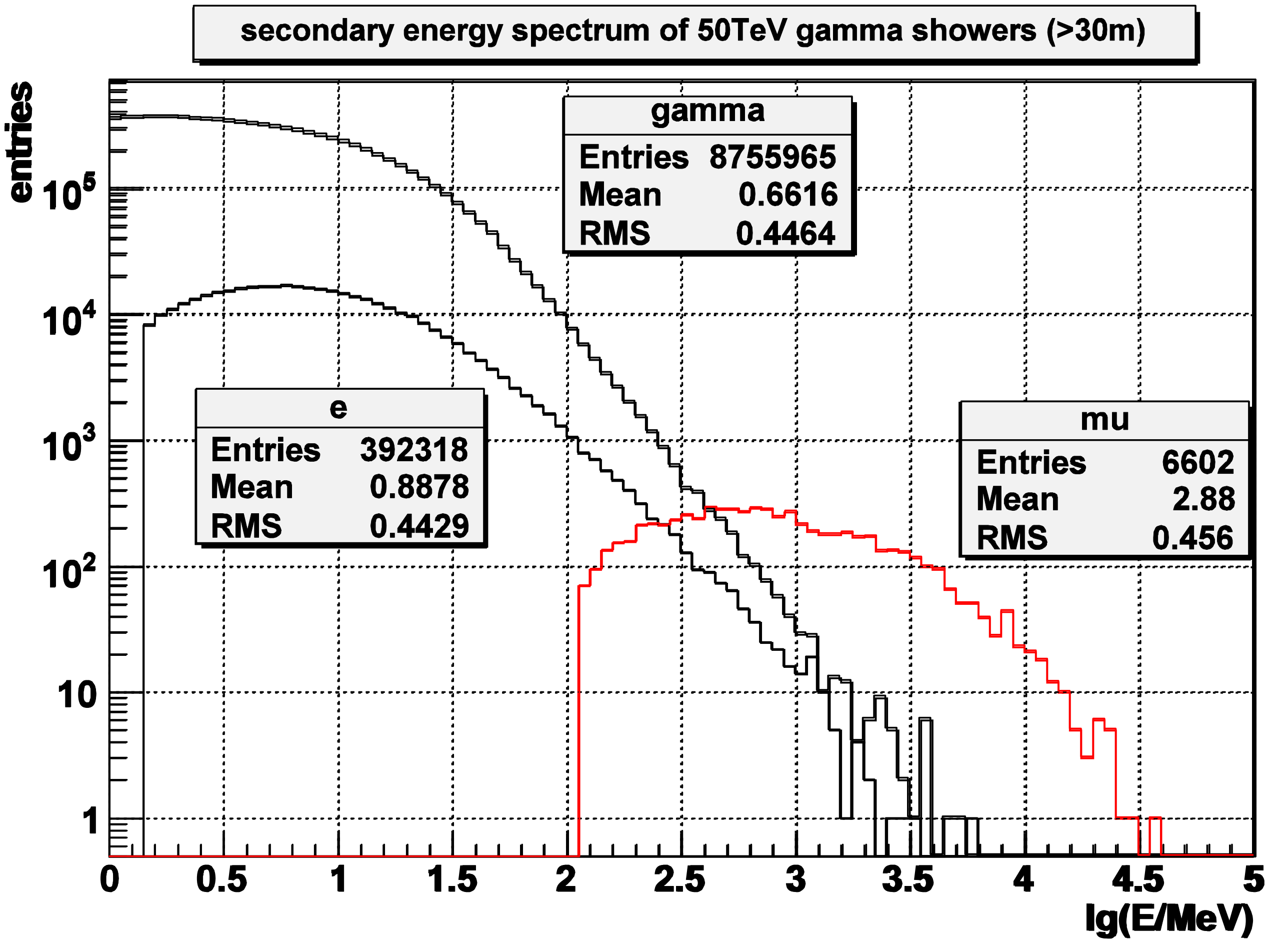


MD Specifications

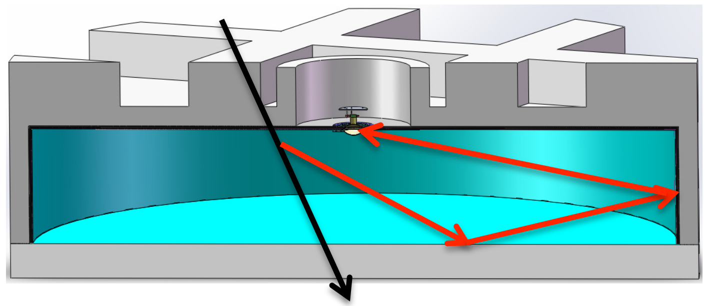
Item	Value
Area	36 m^2
Water Depth	1.2 m
Molasses overburden	2.5 m
Water transparency (att. len.)	> 30 m (400 nm)
Reflection coefficient	>95%
Dynamic range	1-10,000 particles
Time resolution	<10 ns
Particle counting resolution	25% @ 1 particle 5% @ 10,000 particles
Aging (<20%)	>10 years

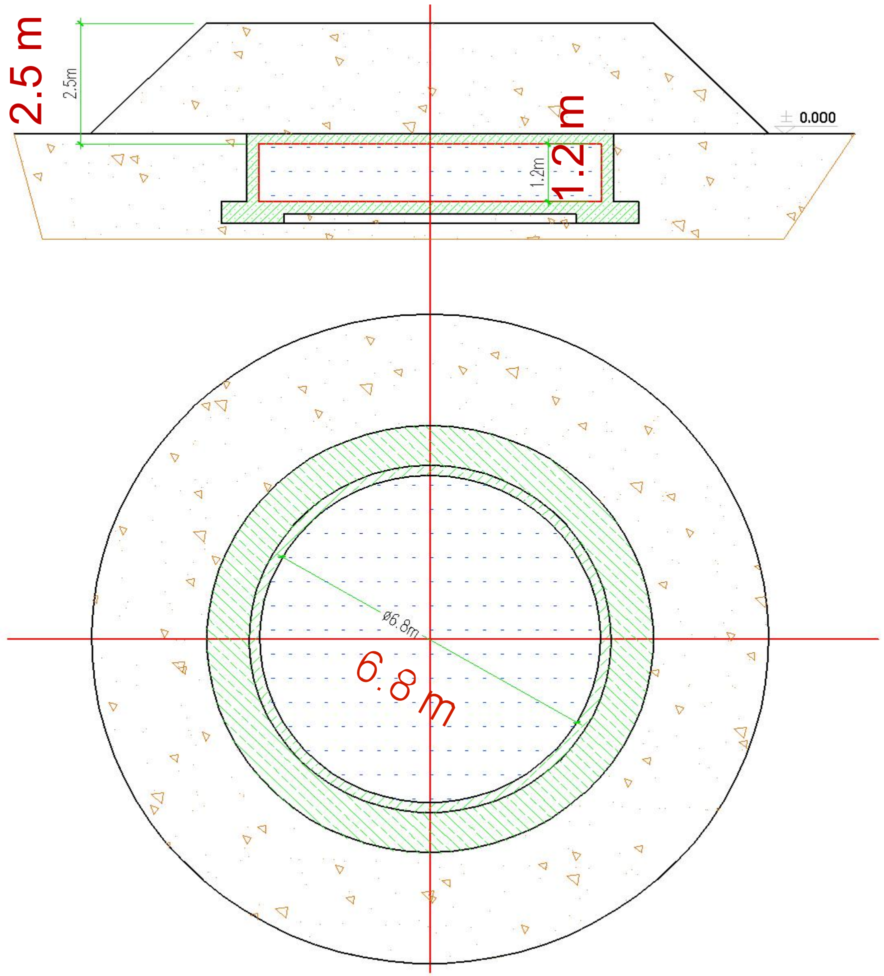
A large area (pure) muon detector

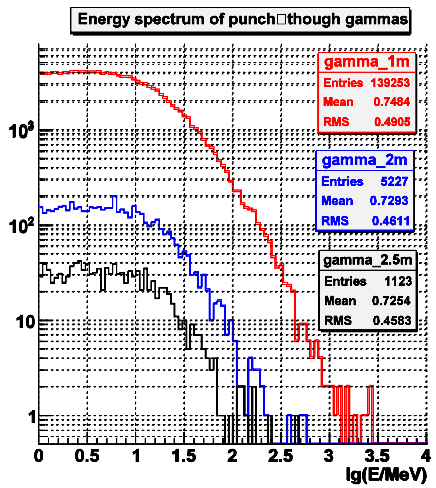
- Muon detection efficiency
- $N_\gamma:N_e:N_\mu$~1:5%:0.1%, (>1GeV, N_μ>> N_γ)

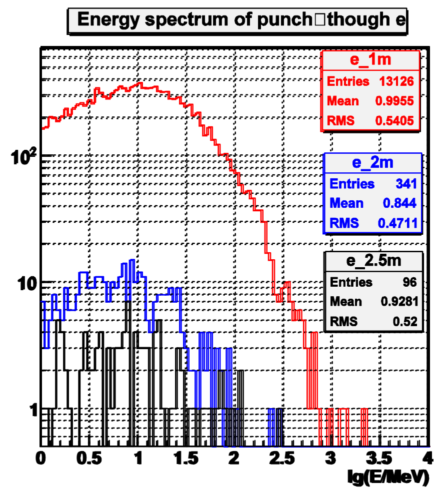


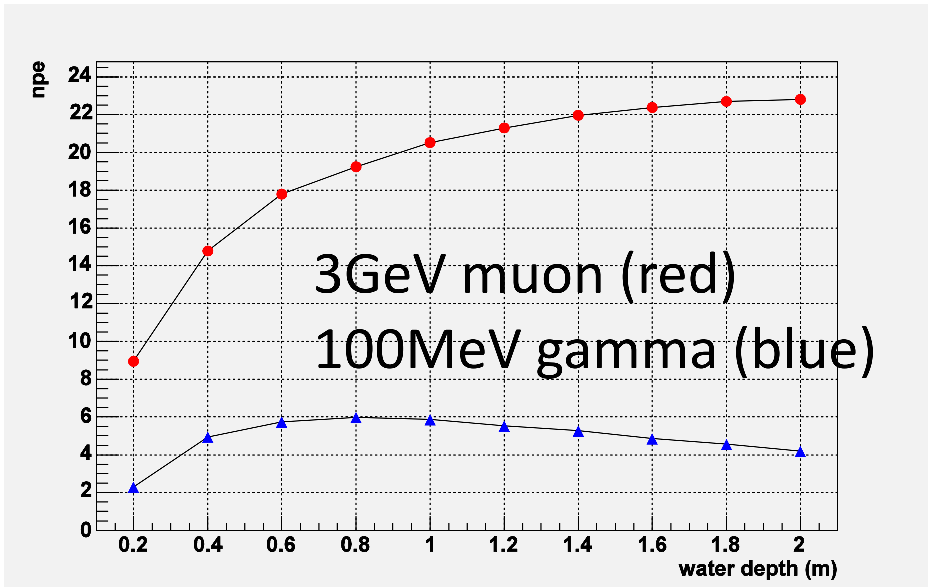
Muon Detector (MD)

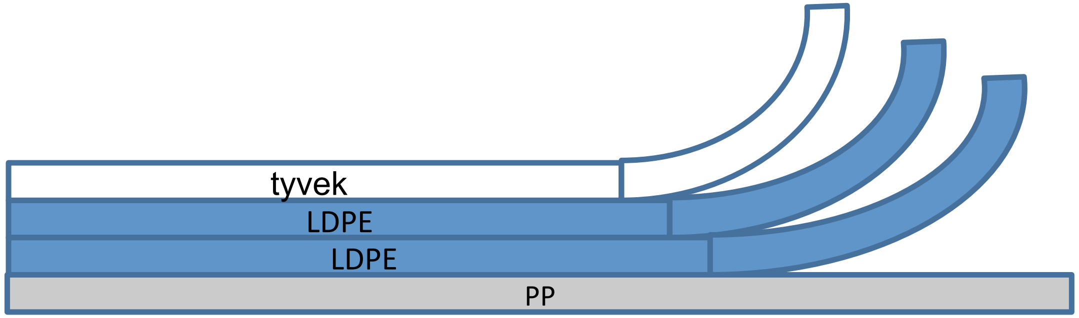


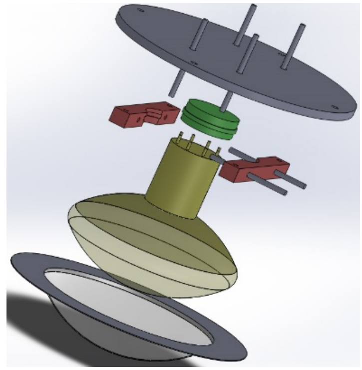


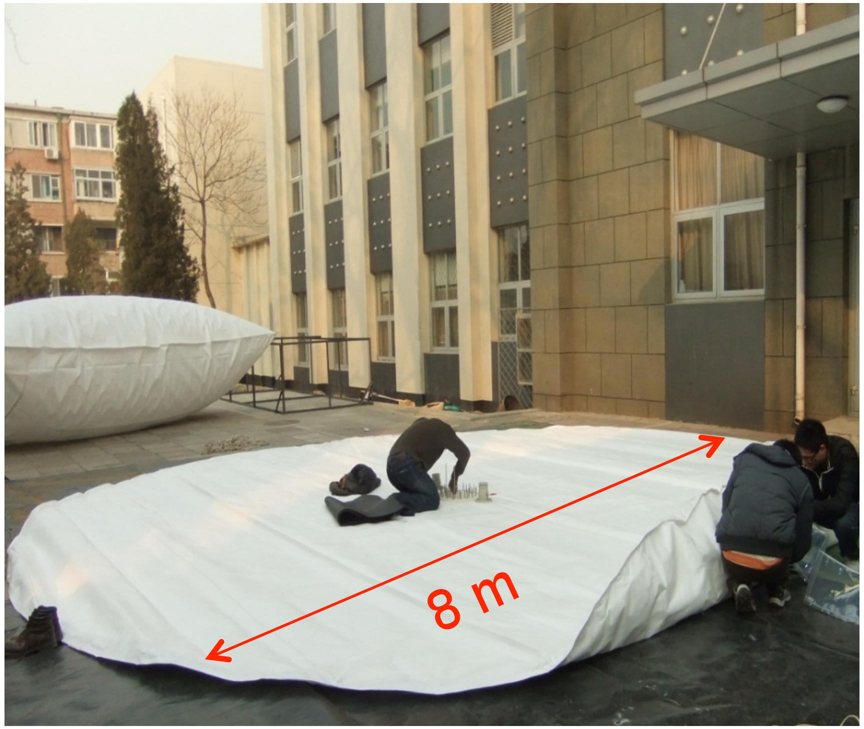




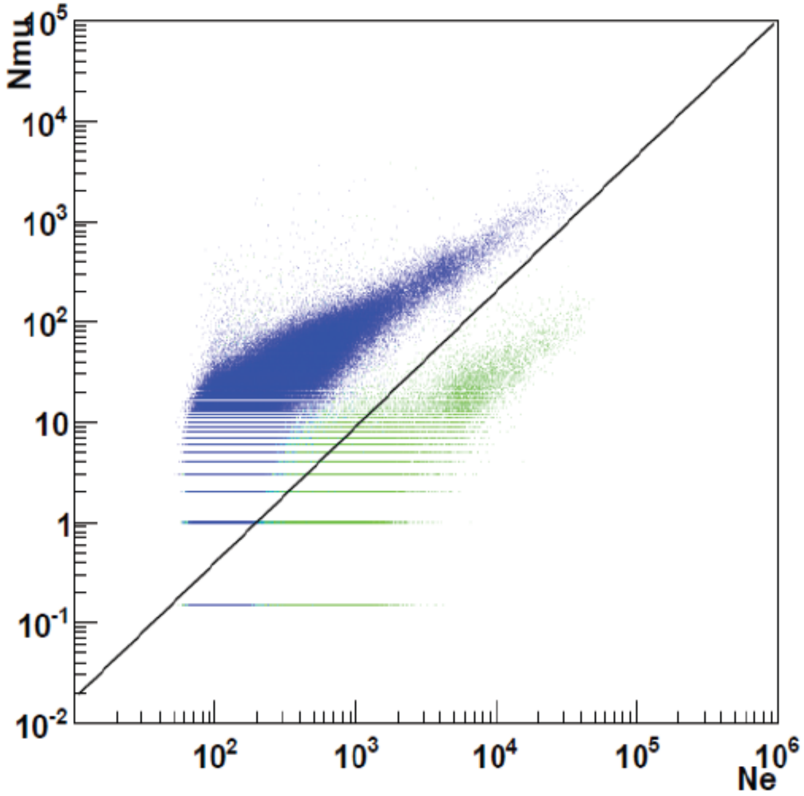



tyvek
LDPE
LDPE
PP



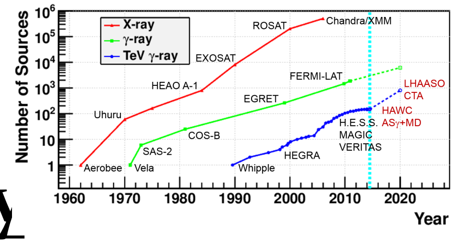

8 m

Gamma/proton Discrimination - KM2A

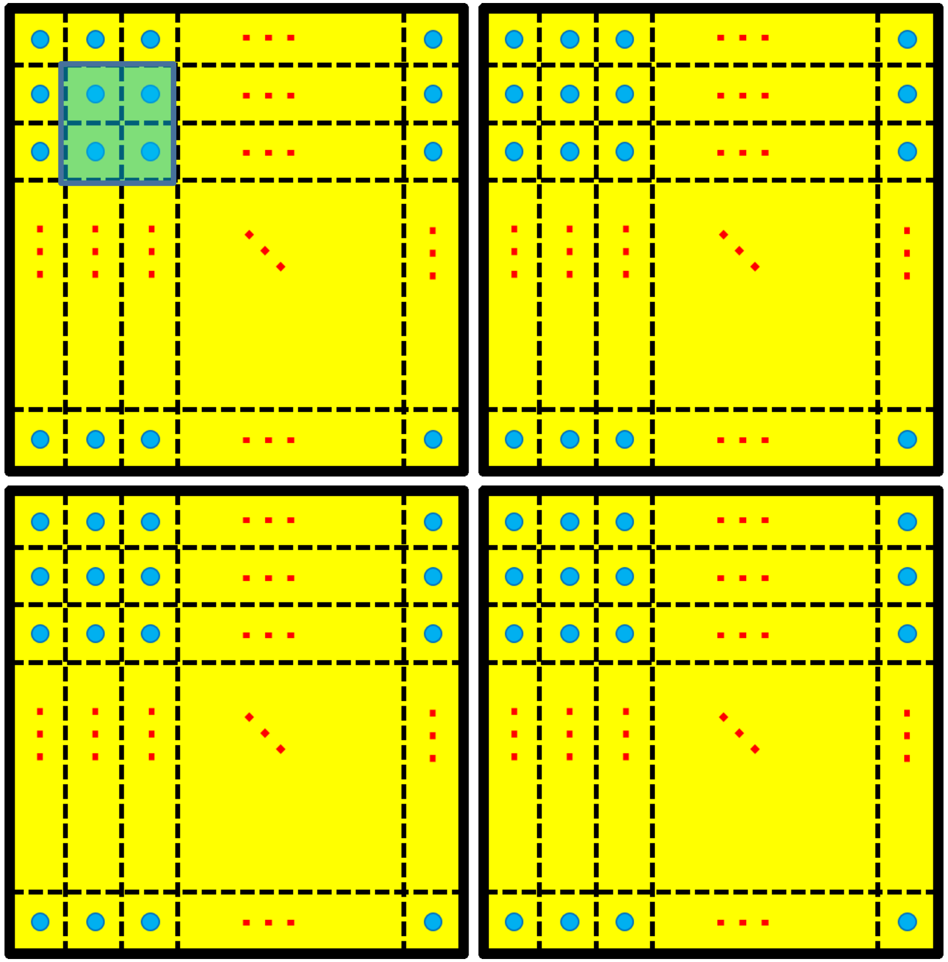


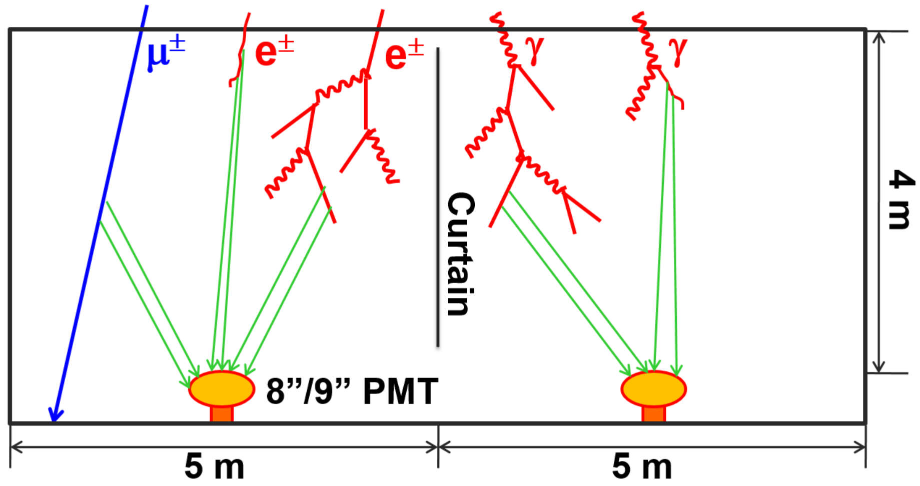
nHit	$\log_{10}$(E) GeV	Q-factor
20-30	3.60	2.67
30-45	3.87	5.62
45-65	4.12	11.9
65-90	4.35	20.7
90-120	4.55	46.4
120-180	4.76	86.6
180-260	5.03	backgroud free
260-360	5.28	backgroud free
360-500	5.53	backgroud free
500-700	5.82	backgroud free
700-1000	6.11	backgroud free

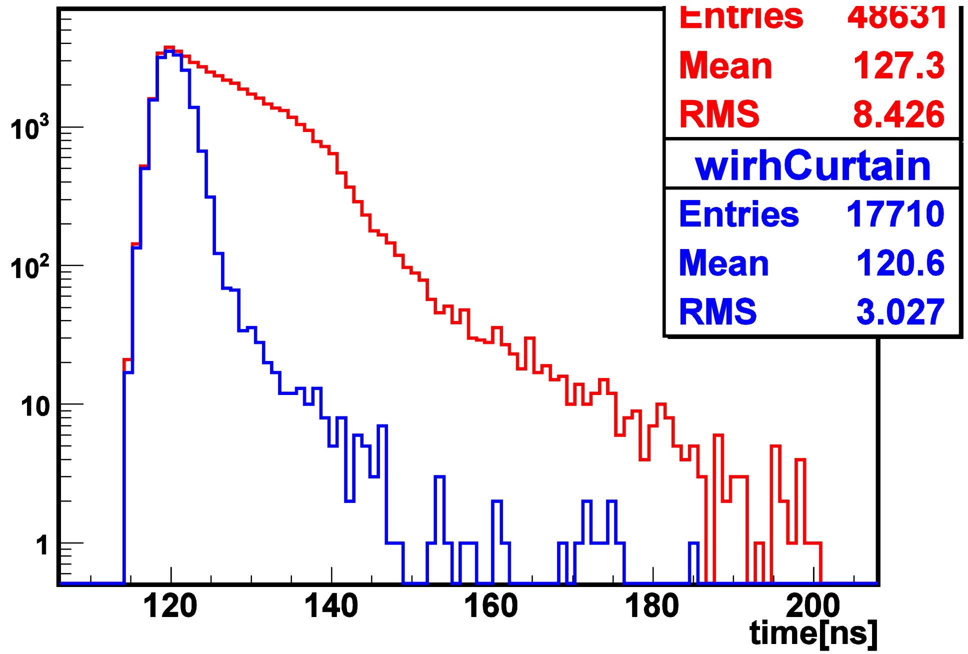
WCDA: Survey of the VHE gamma ray sky



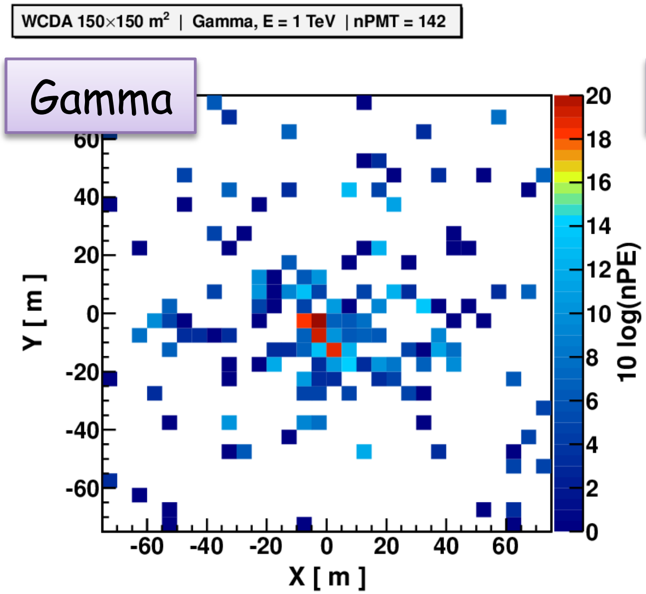
- <1% I_{Crab} → 300m*300m

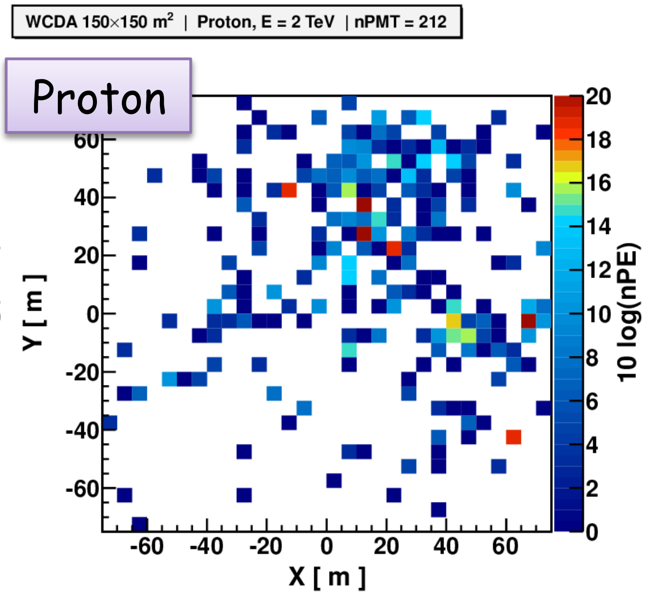


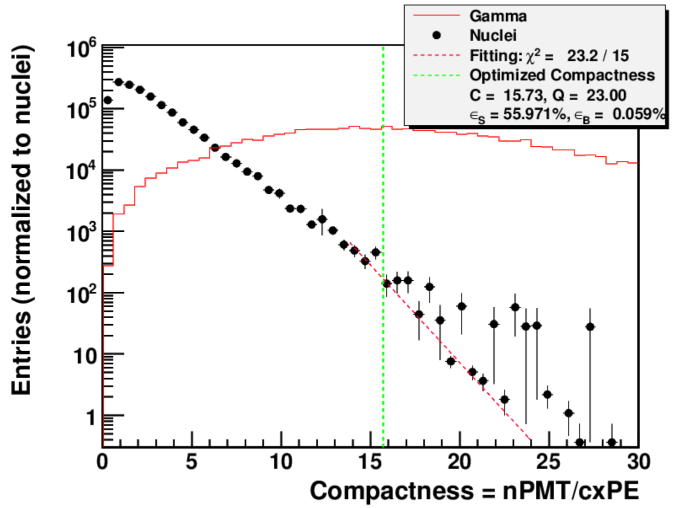


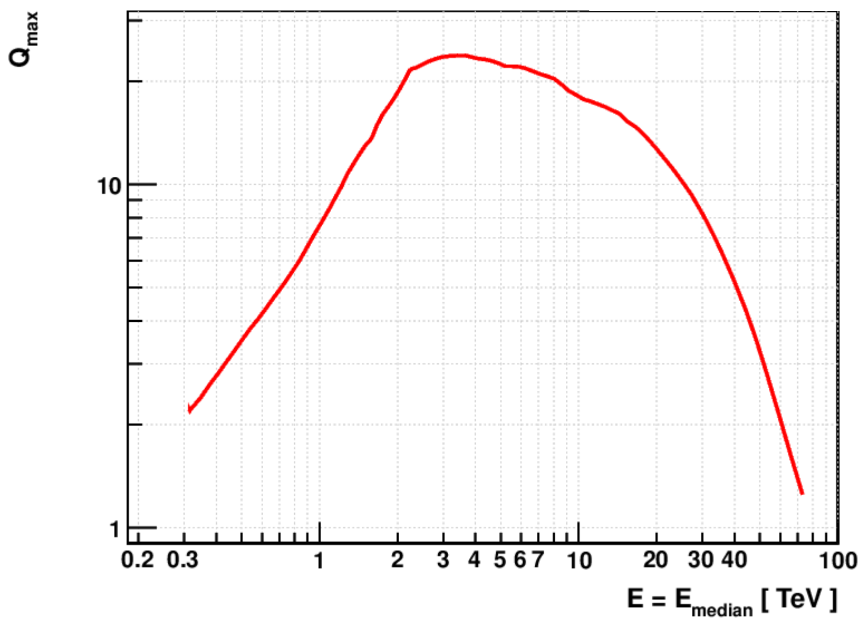


Gamma/proton Discrimination - WCDA







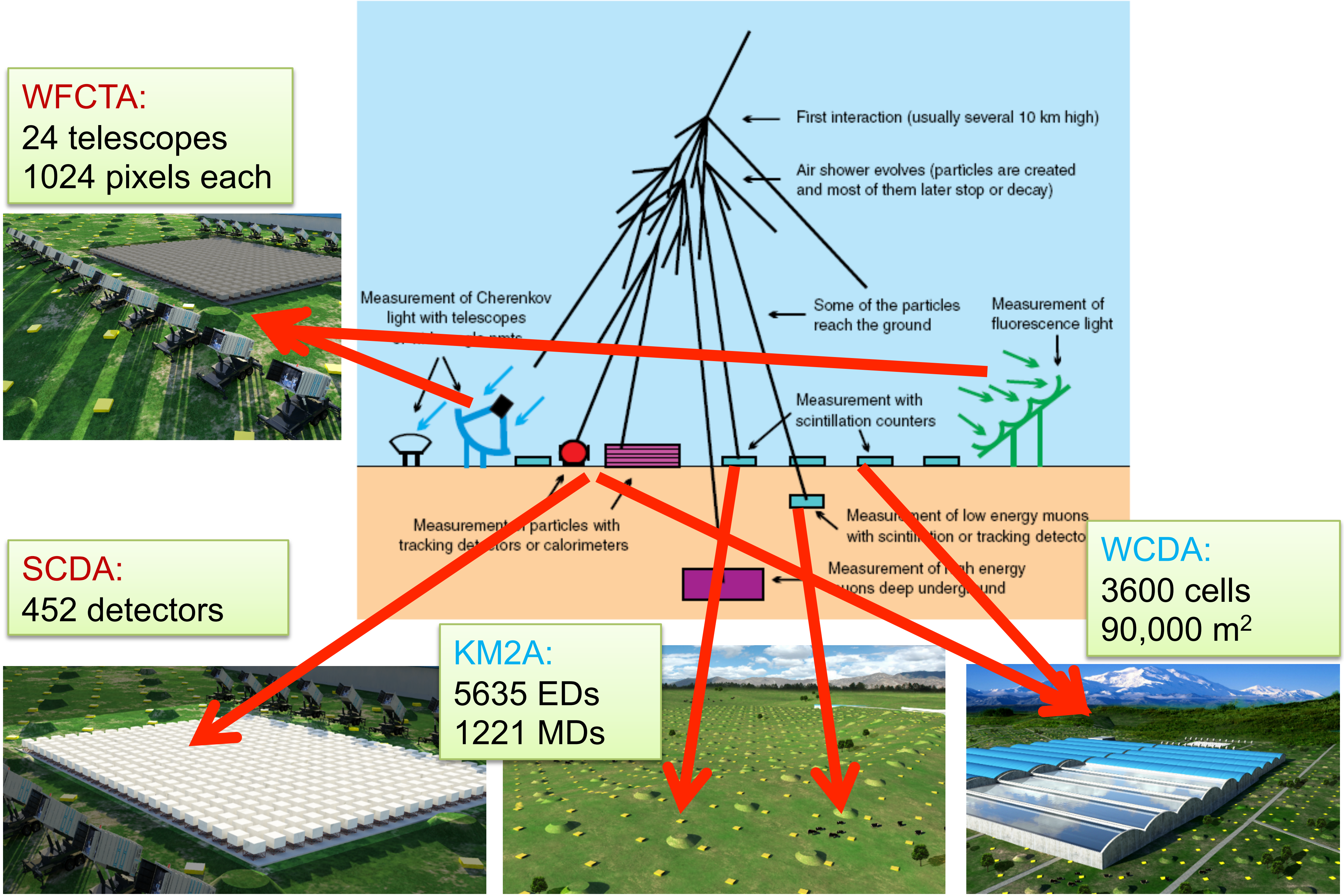


- Brightest "sub-core":
  - Signal of the brightest PMT outside the shower core region (e.g., 45 m);
- "Compactness" can be employed to reject cosmic ray background efficiently.

WCDA Specifications

Item	Value
Cell area	25 m^2
Effective water depth	4 m
Water transparency	> 20 m (400 nm)
Precision of time measurement	0.5 ns
Dynamic range	1-4000 PEs
Time resolution	<2 ns
Charge resolution	40% @ 1 PE 5% @ 4000 PEs
Accuracy of charge calibration	<2%
Accuracy of time calibration	<0.2 ns
Total area	90,000 m^2
Total cells	3600

Hybrid Detection of Extensive Air Showers by LHAASO



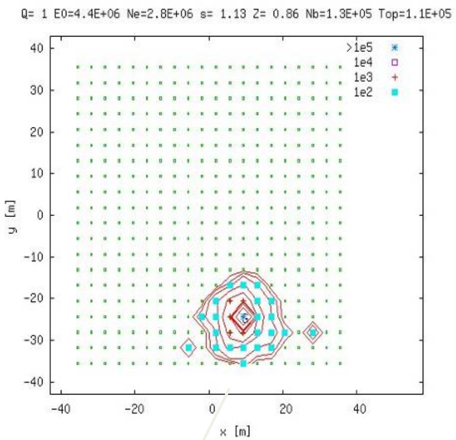
LHAASO observables of showers

	Ground-based EAS arrays	Air Cherenkov/Fluorescence Telescopes	
Direction	Space-time	Image (stereo)	Image (stereo)
Core	Lateral distribution	Stereo imaging	Stereo imaging
Energy	Lateral distribution	Cerenkov light, geometry	Longitudinal development
Composition	Lateral distribution, muons ($\pi^{\pm}$), particles near the core (π^{0})	Image, Xmax	Xmax

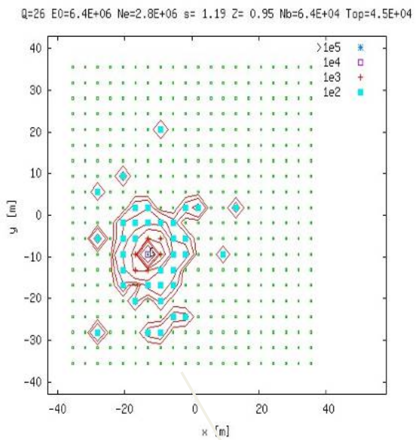
Resolution for light and heavy compositions

μ -content, Xmax and HE (>30TeV) shower particles

Proton



Iron

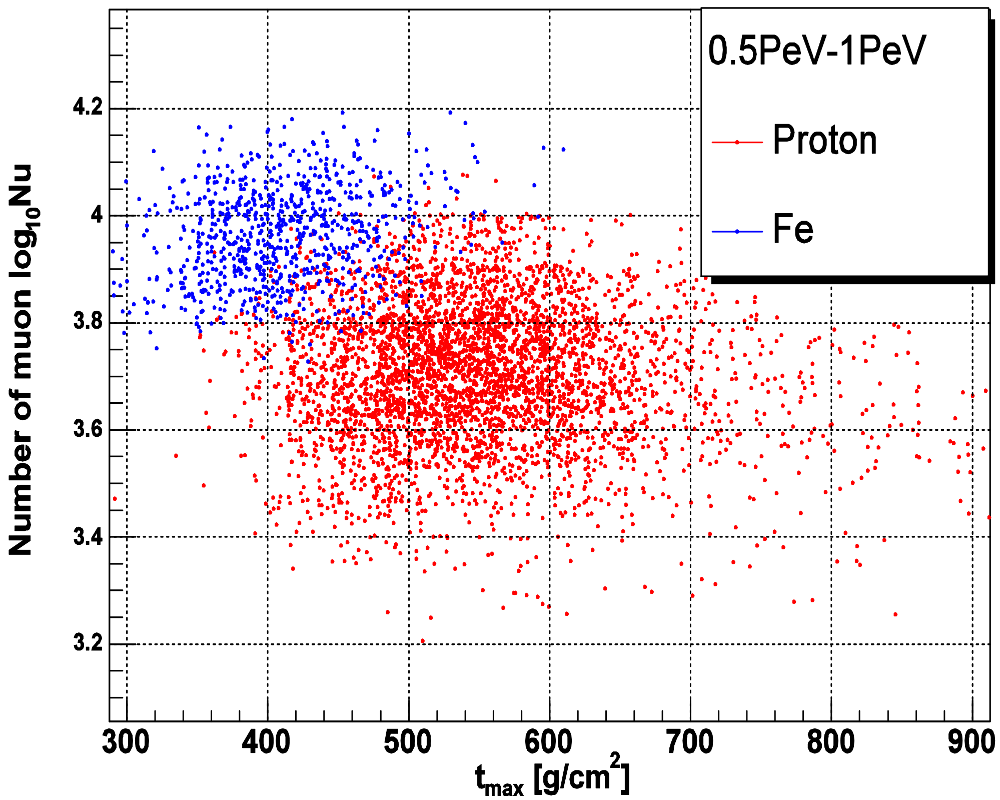


For Proton and Helium:

- 1.5 m spacing
- Nb>100 , any 5 (> 30 GeV)

For Iron:

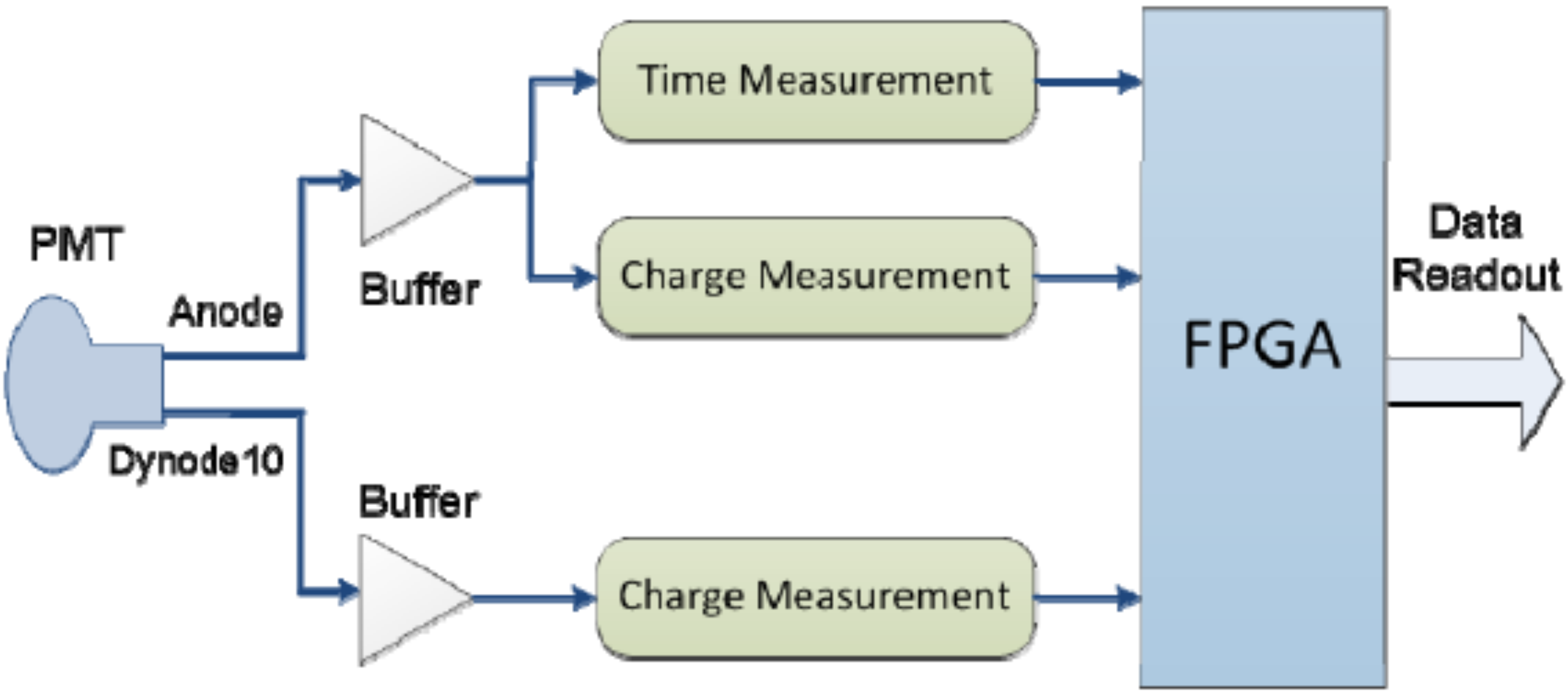
- 3.75m spacing
- Nb>100 , any 21 (> 30 GeV)



LHAASO detector signals

- LHAASO measures the density, energy and direction of shower secondary particles which emit UV photons through
  - Air (Cherenkov and Fluorescence for WFCTA)
  - Water (Cherenkov for WCDA and KM2A-MD)
  - Scintillating (for KM2A-ED and SCDA)
- PMTs are used to convert the lights to photo-electrons
- All LHAASO detector signals come from PMTs
  - Timing: direction
  - Charge: energy, composition

Basic FEE Design

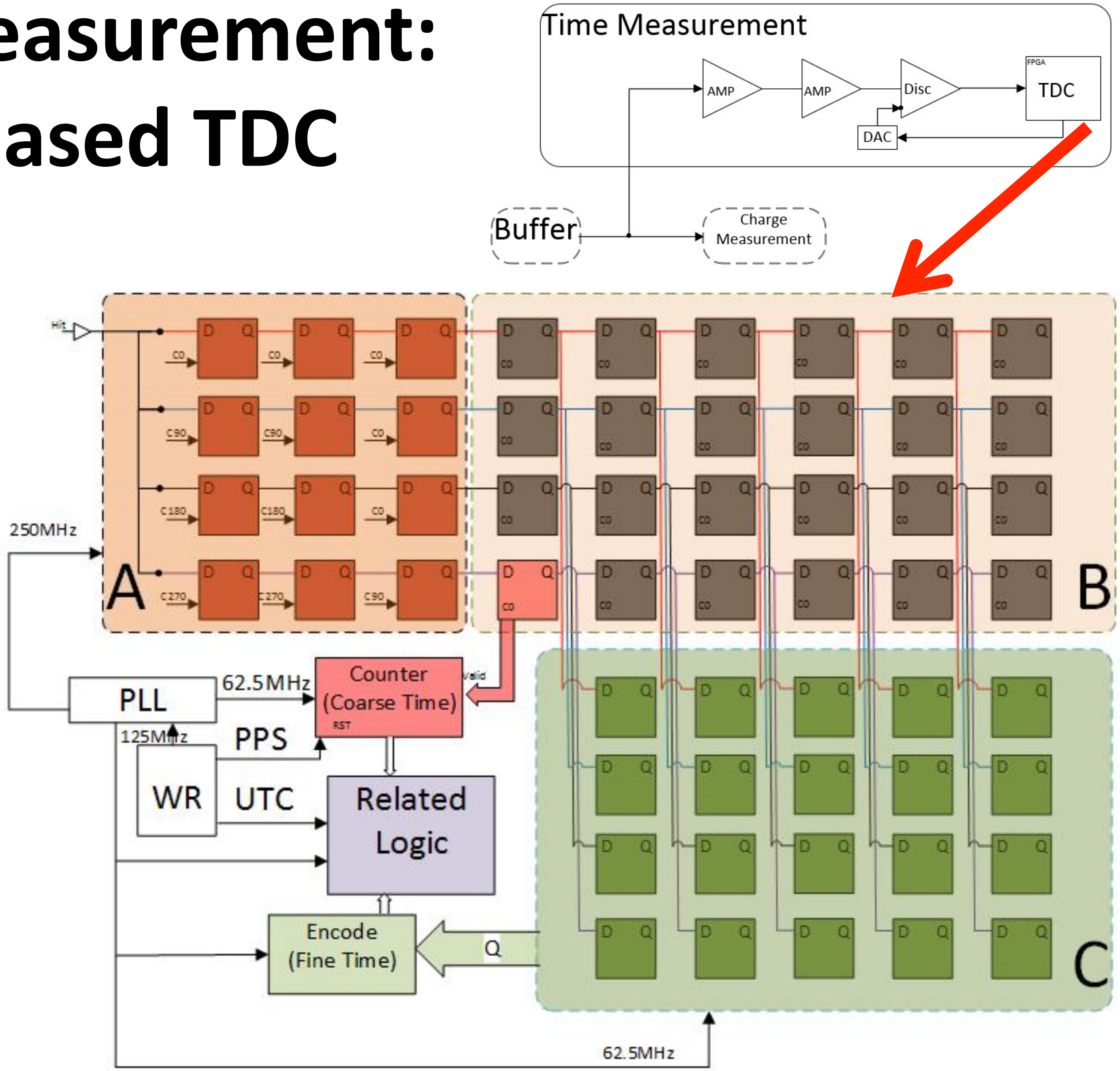


LHAASO Timing Measurement

- **Gamma Ray Astronomy**
  - **Pointing accuracy: <0.1 deg**
    - **Timing accuracy: <0.2ns(WCDA)/0.5ns (KM2A)**
  - **Sensitivity ~ angular resolution**
    - **time jitter: <0.5ns(WCDA)/1ns(KM2A)**
- **Over an area of 1km^2**
- **Under high altitude environment**
  - **Maximum daily temperature variation: 30 deg**
  - **Annual temperature variation: ±30 deg**

For Electronics

Timing Measurement: FPGA-based TDC



LHAASO detector timing

Over 7,000 detector units
Spread around $1km^2$ area

0.5°Angular resolution for shower reconstruct from *timing* of hits TOF

Synchronous timing among detectors

1000m coax cable in 30°C change, Δ delay = 15ns!

Time-stamp Synchronization

Time stamps of >7,000 nodes to be aligned <500ps (rms).

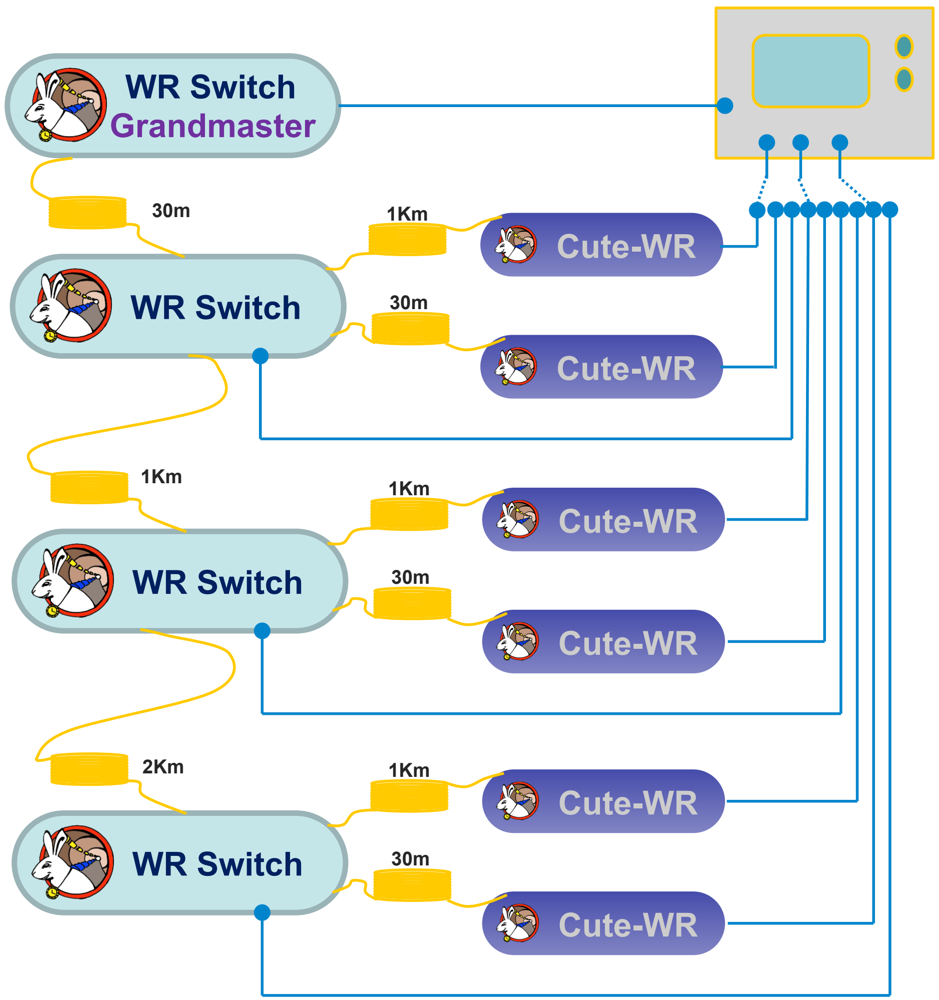
Frequency distribution & phase locking

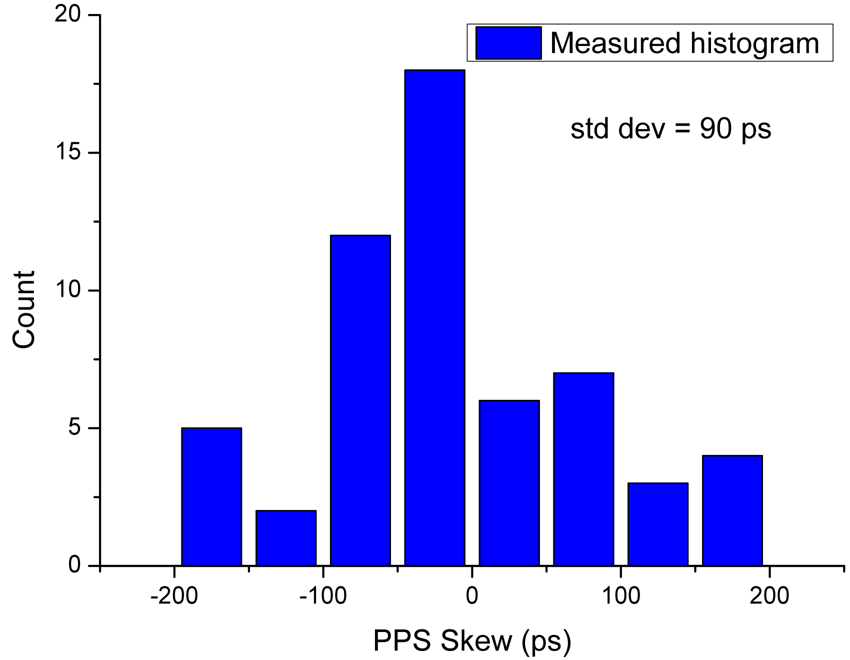
Distribute synchronous ADC clock with <100ps skew.

Traceability & Real-time calibration

Timing delay compensation due to environmental perturbation in hardware in real time.

WR performance



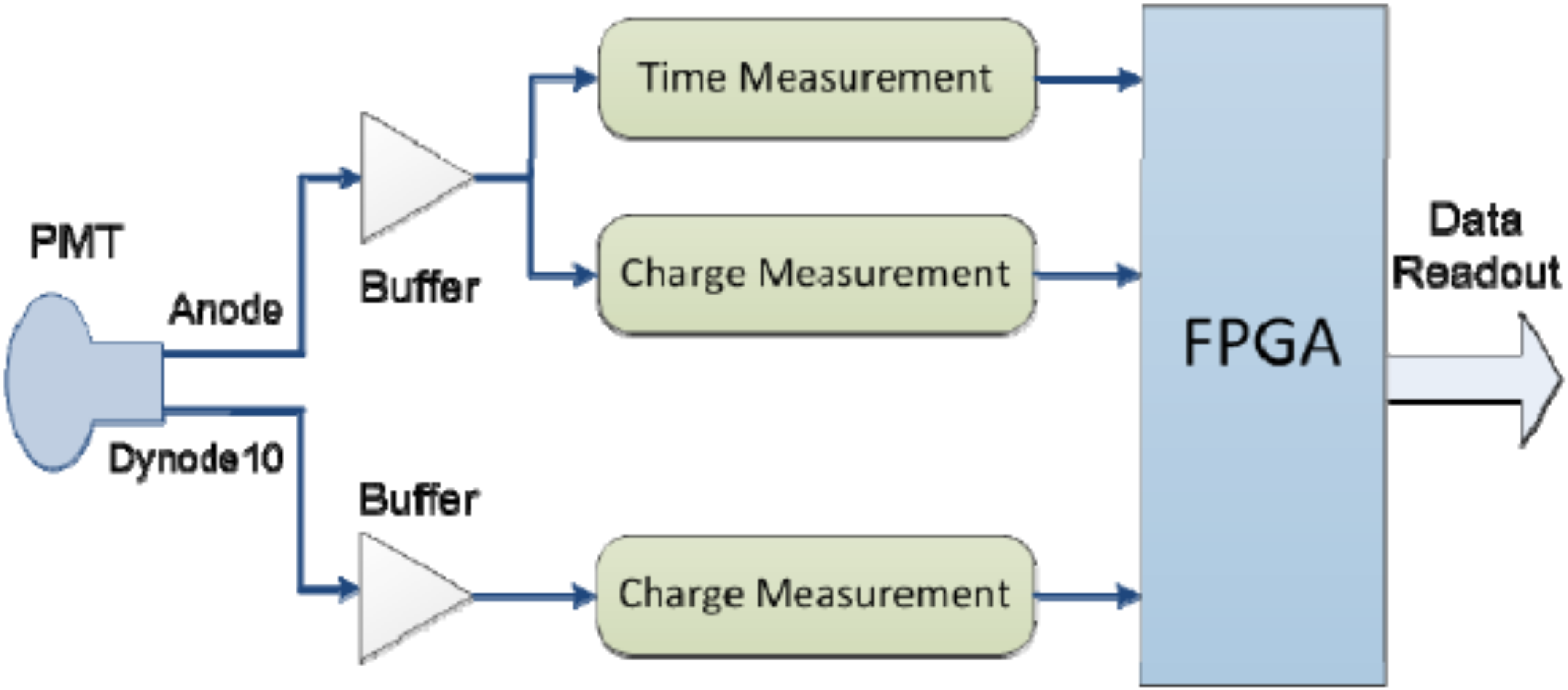


Cascade topology

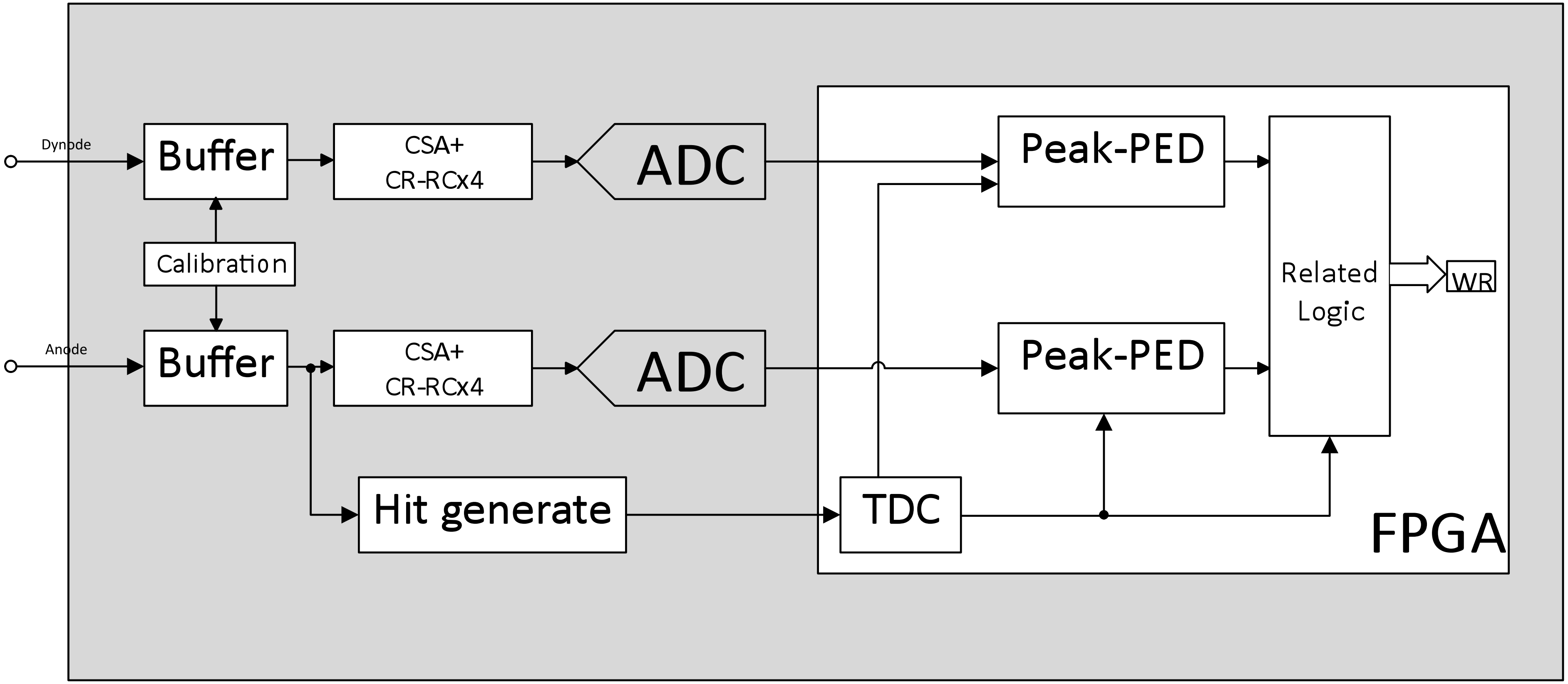
WR CERN: 1ns

Charge Measurement

- Each array covers a wide energy band, requiring a large dynamic range which is achieve by anode+dynode readout of PMTs.



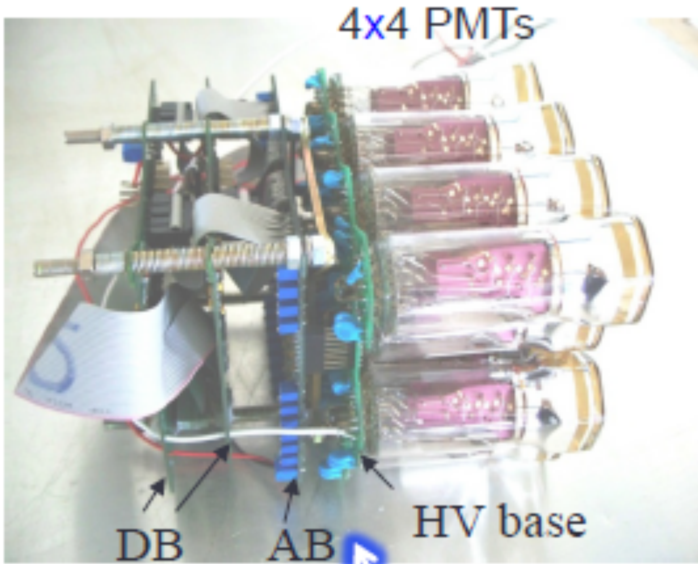
Charge Measurement



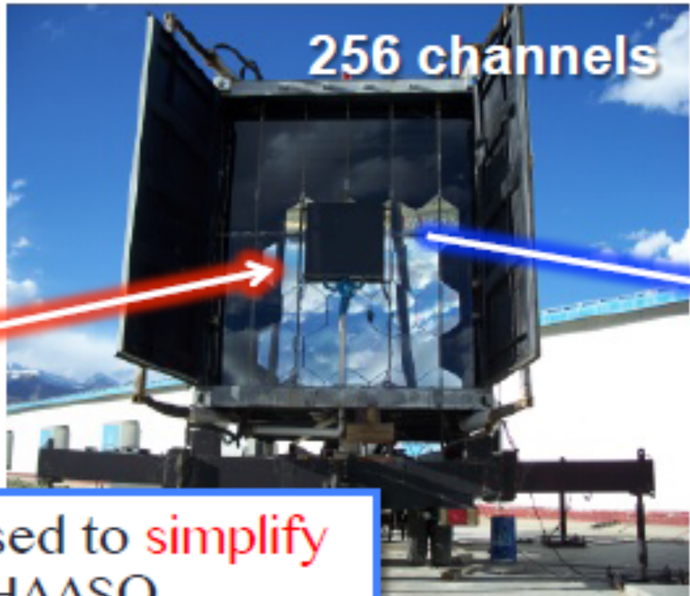
- **(KM2A-ED and WFCTA: 500/50MHz FADC-based waveform digitization)**

Challenges for electronics

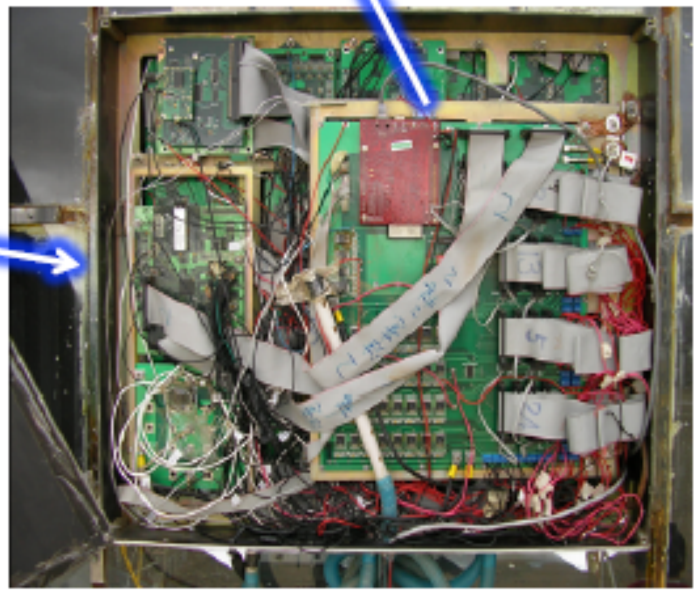
- ✧ High altitude and low air pressure ➔ *decreased heat dissipation*
- ✧ Large number of channels ➔ *increased density, complexity and power consumption*
- ✧ Harsh environment and remote location ➔ *require stability, reliability and maintainability*
- ✧ Design based on IC ➔ *simplified design, decreased power consumption, increased reliability*



- Compact design
- High stability
- High reliability
- Easy to maintain



- **Large number of channels**
  - WFCTA: 1024 channels each
- **Heat dissipation at 4300m**
  - Air density: 60%
  - Active heat dissipation system



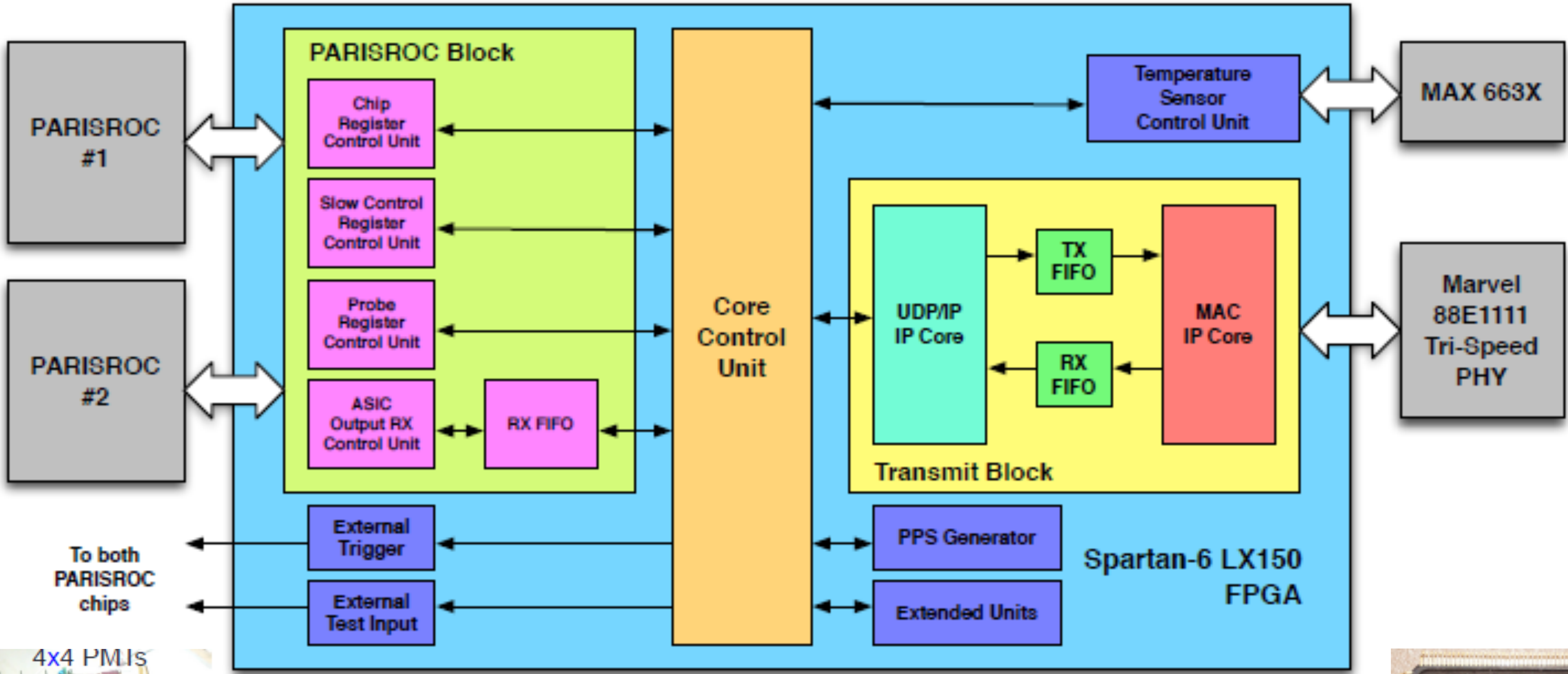
Prototypes in YBJ, Tibet

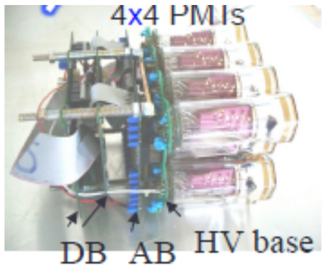
The ASICs can be used to simplify the electronics of LHAASO

Software block & power consumption

Unit	Power Consumption
PARISROC 2 X 2	~ 1.0W
Ethernet Interface	~ 1.1W
FPGA & Peripherals	~ 0.9W
	~ 3.0W (2.98W meas.)

- ✧ Fully described in VHDL and FSM structure
- ✧ Resource occupation: < 10% (XS6LX150)
- ✧ Power consumption: ~ 128 W for 64 clusters without Ethernet Interface (260W budget)

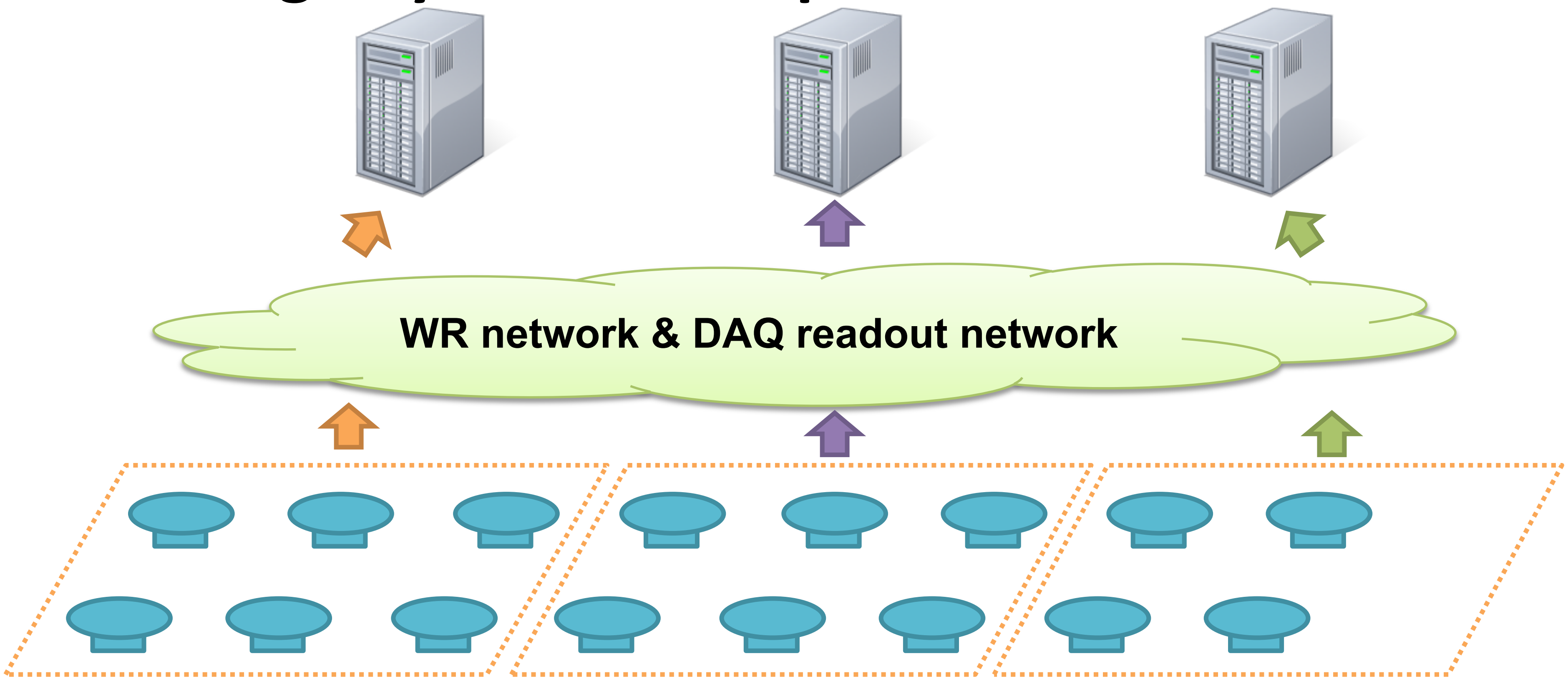




"Triggerless" DAQ

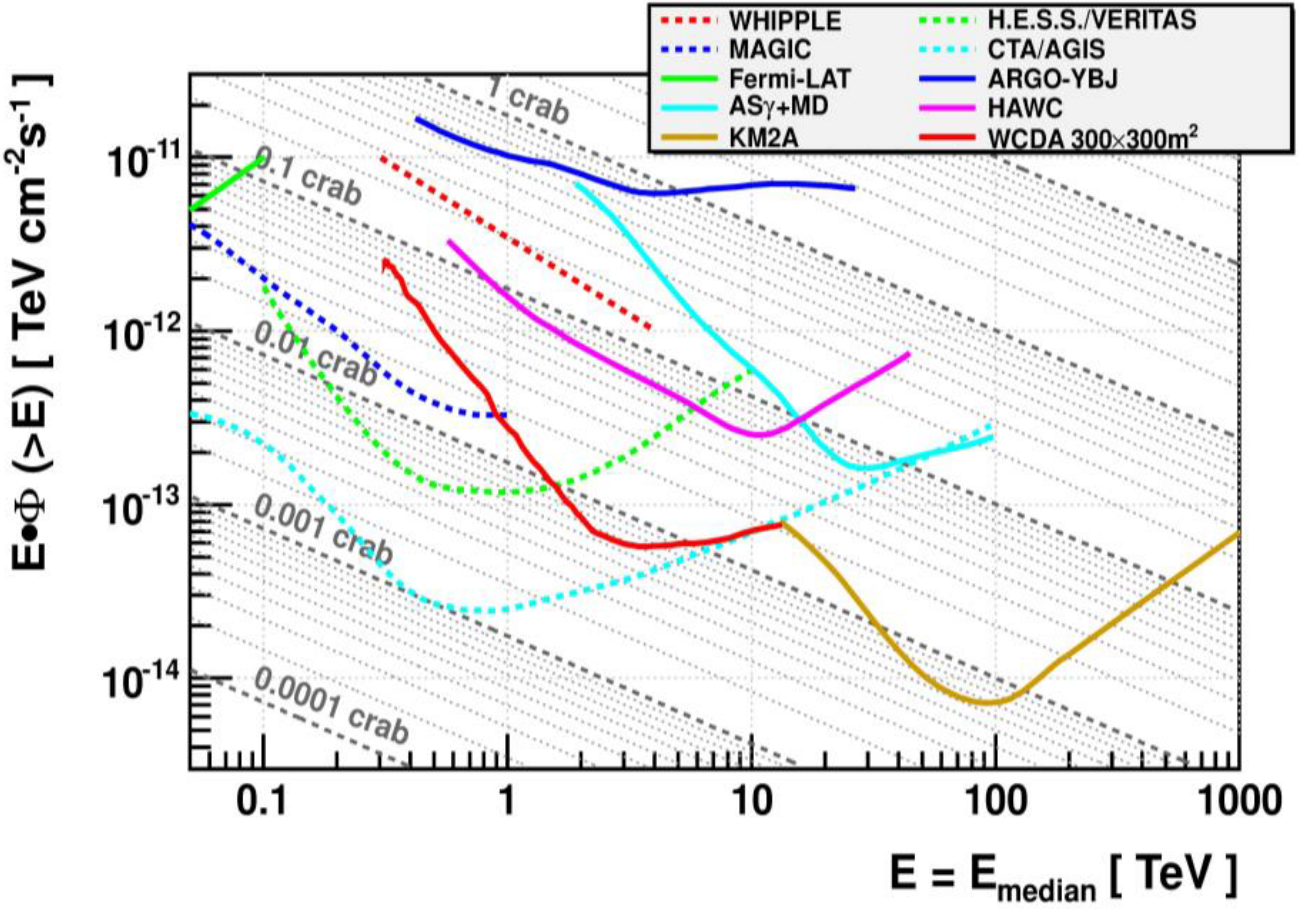
---hybrid measurement of shower

- **Triggering, building, (re-construction) and storage by online computers**



Data Rate

		WCDA	KM2A
	Single rate(Hz)	50k	ED: 1k MD: 12k
	No. of Channels	3600	ED: 5635 MD: 1221
DAQ-in	Hits in trigger(MHz)	180	5.6
	Pre-Trigger(MB/s)	2160	450
DAQ-out	After-Trigger(MB/s)	300~400	~10

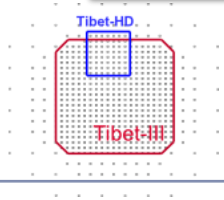

WHIPPLE
MAGIC
Fermi-LAT
ASγ+MD
KM2A
H.E.S.S./VERITAS
CTA/AGIS
ARGO-YBJ
HAWC
WCDA 300×300m²
1 crab
0.1 crab
0.01 crab
0.001 crab
0.0001 crab
E•Φ (>E) [TeV cm⁻²s⁻¹]
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻¹⁴
0.1
1
10
100
1000
E = E_median [TeV]

Instrumentation History

IACTs are typically 10× better in sensitivity, gained from the lower energy threshold (stat.)

Whipple
(0.2 Crab)

1980



Tibet-ASγ
(1.5 Crab)

Crab detected! 1989

HEGRA, CANGAROO, CAT … 0.04 Crab

2001

Milagro
(0.9 Crab)

H.E.S.S.
(0.008 Crab)

2004

VERITAS
(0.008 Crab)

2007

ARGO-YBJ
(0.6 Crab)

MAGIC
(0.02 Crab)

2009

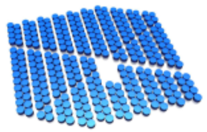
~150 Sources observed

2014

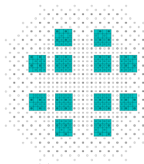
10 years delay!

~10 Sources

2015

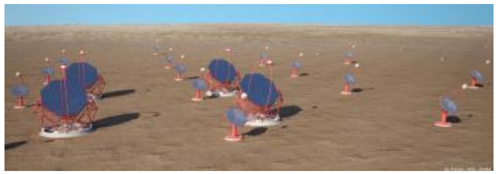


HAWC
0.06 Crab

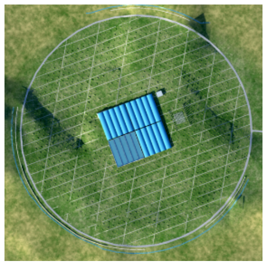


ASγ+MD
0.06 Crab

CTA
(0.001 Crab)



2018
?



LHAASO
(0.01 Crab)