Progress on a wide FOV atmospheric Cherenkov telescope based on a refractive water-lens for future gamma-ray astronomy

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Yi Zhang, Cheng Liu, Hui Cai, … (IHEP)

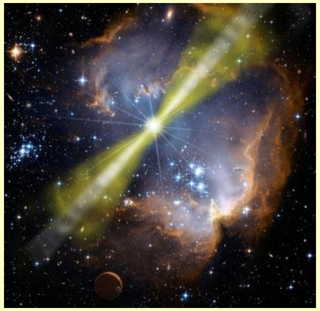
EMEI, SICHUAN, 2018/03/22

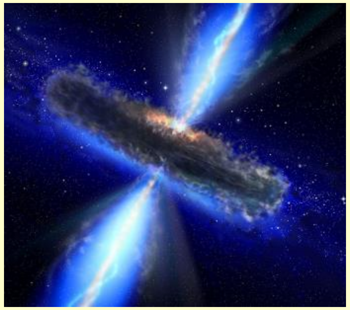
Outline

- **Introduction**
- **Concept of Water-Lens Telescope**
- **First Observation of CRs with the Prototype**
- **Statues and Future Plans**
- **Discussion and Conclusion**

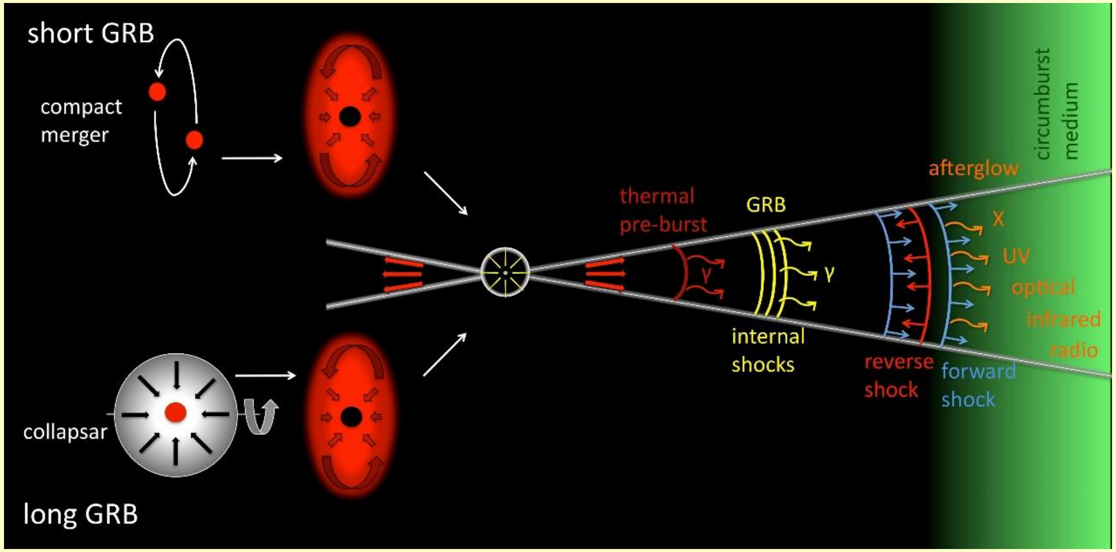
Motivation

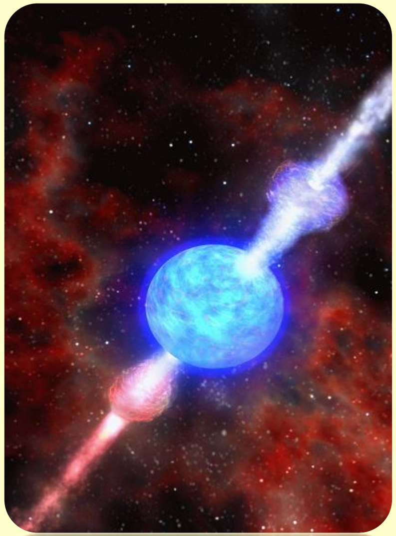
A wide field of view and large dimensional Atmospheric Cherenkov Telescope array at high altitude site for observation of *sporadic* γ-ray sources, i.e, VHE emission of GRBs, possible VHE electromagnetic counterparts of Gravitational Waves, VHE emission of AGNs.





Why Study GRBs at Very High Energy (GeV-subTeV) ?

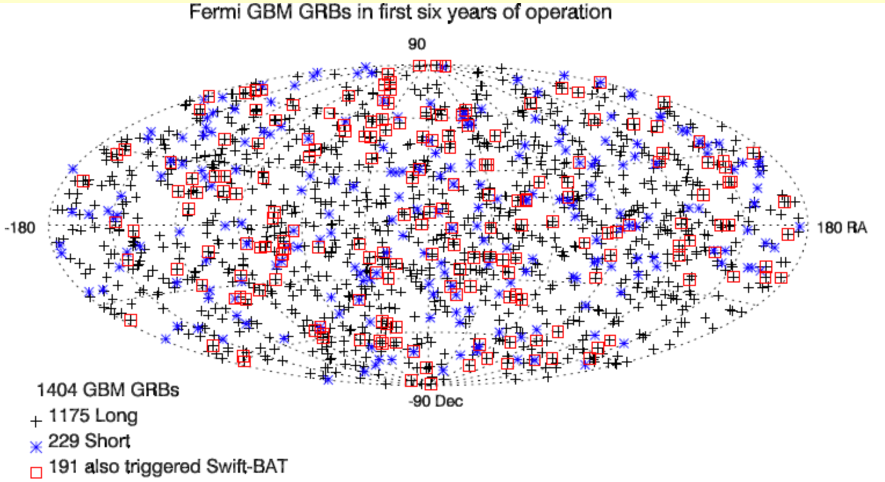




Gamma-ray bursts: the most violent explosions in the universe

- **Acceleration mechanisms , energetics, and therefore constrain the progenitors and jet feeding mechanism**
- **Understanding progenitor then leads to an understanding of cosmology & stellar evolution required to support progenitor population**
- **Extragalactic background light induced absorption (EBL absorption) of high energy photons**
- **Limits on Lorentz Invariance Violation**

VHE emission of GRBs in Fermi era



APJS, 2016, 223:28 (18pp), 2016

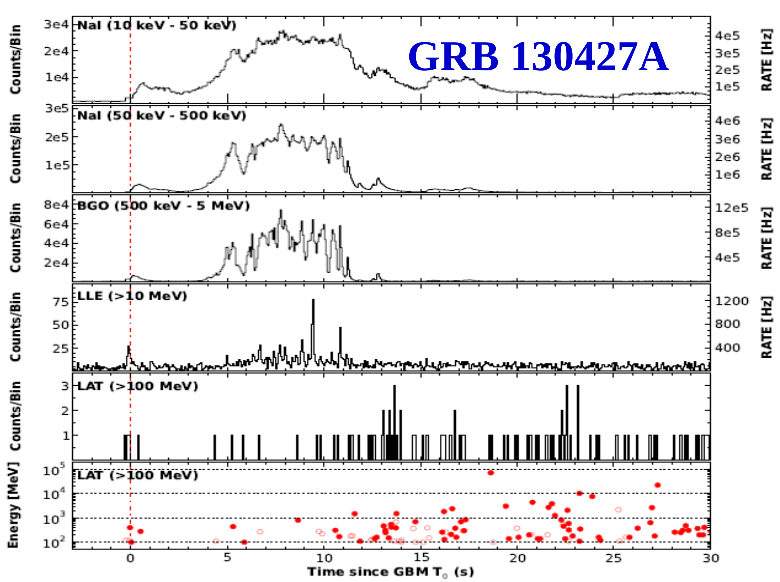
Table 1
Trigger Statistics of the Years 1 & 2, Years 3 & 4 Catalogs, and Years 5 & 6

	GRBs	SGRs	TGFs	SFs	CPs	Other	Sum	ARRs	LAT GRBs
Year 1 and 2	492[a]	171	79	31	68[b]	65[b]	906[c]	40	22
Year 3 and 4	462	18	183	363	141	53	1220	46	21[d]
Year 5 and 6	451[a]	9	207	400	96	61	1224	33	29[d]
Year 1 to 6	1405	198	469	794	305	179	3350	119[e]	72

LAT: 30 MeV–300GeV

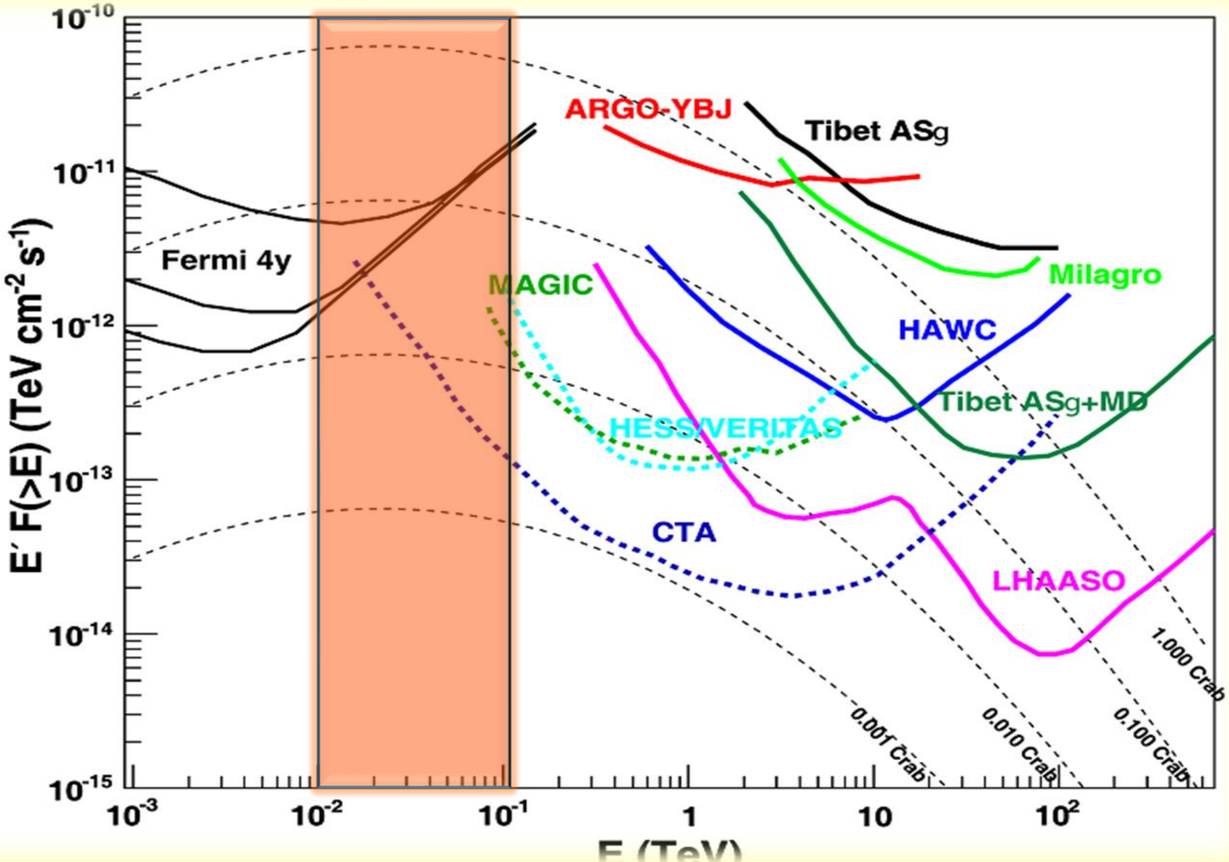
GRBs have energies up to at least 100GeV.

GRB Name	Photon E_{max}	Redshift
GRB080916C	13GeV	4.35
GRB090510	31GeV	0.903
GRB090902B	33GeV	1.822
GRB090926A	19.6GeV	2.1
GRB130427A	95GeV	0.145
GRB 940217	18GeV	/



Science, 2014, 343(6166), p.42(6) ; p.38(4) ; p.51(4);p.48 （4）

Status of VHE γ-ray



S.Z. Chen, *SCIENTIA SINICA Physica, Mechanica & Astronomica*, 45,119503, 2015

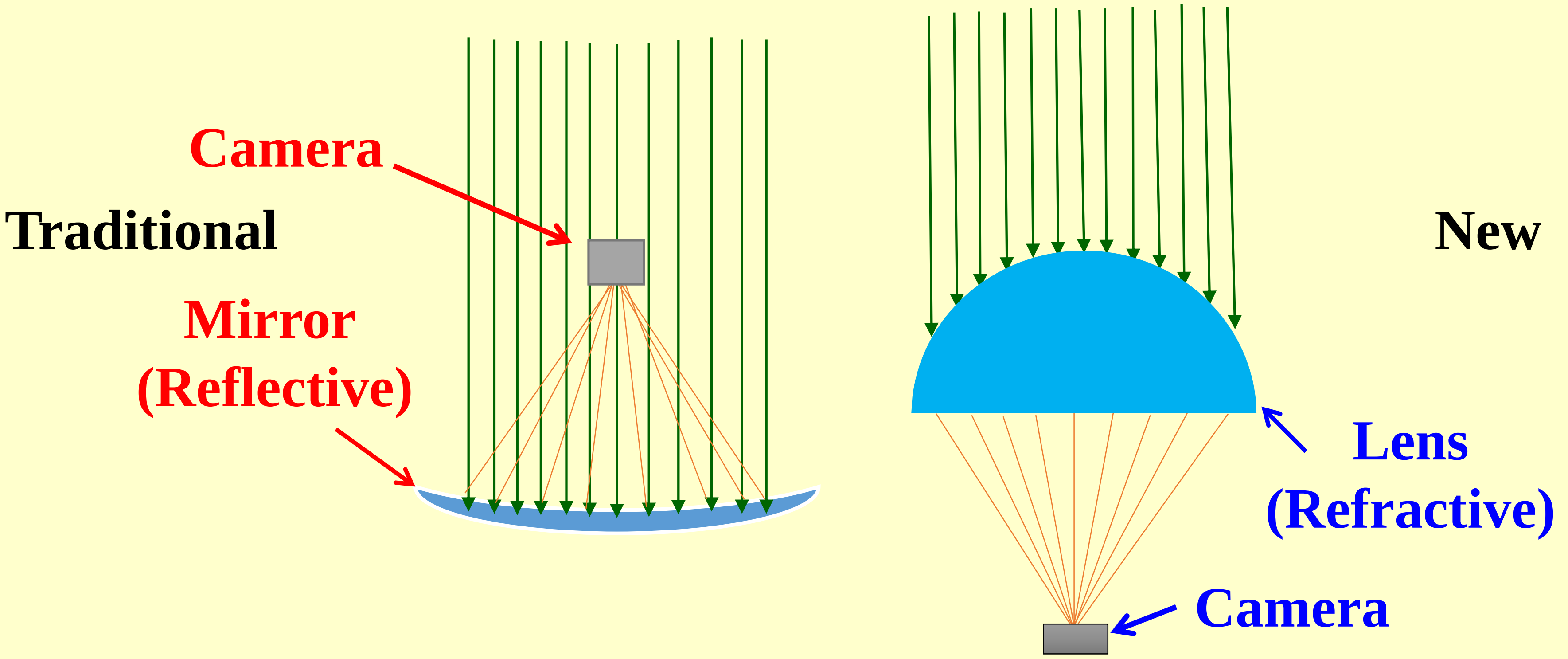
The low sensitivity at sub-100 GeV is the weakness of the current γ-ray detecting techniques.

To detect very high energy emission of *sporadic* γ-ray sources by future ground-based γ-ray experiment, larger FoV and lower energy threshold are the two most important goals to achieve.

Sensitivities of VHE gamma ray detectors. The three curves of Fermi indicate the sensitivity of 4 years observation for different positions (l=0^o, b=0^o), (l=0^o, b=30^o), (l=0^o, b=90^o) . The performance for HESS, MAGIC, VERITAS, CTA is based on 50 hours of data taking; for Tibet ASγ (ASγ+MD presented here is for final layout that include 12 MDs and a full filled array), Milagro, ARGO-YBJ, HAWC, LHAASO, it is based on one year of data.

Wide FoV Cherenkov Telescope
Refractive Optics

Luisa Arruda, Report of PASC Winter School, Sesimbra, 12/2008



Novel technique using lenses: a lens can work as an efficient light collector!

- ☐ **large FoV;**
- ☐ **large effective area;**
- ☐ **good transmittance;**
- ☐ **no shadows.**

Wide FoV Cherenkov Telescope

Reflective Optics

WFCTA/CRTNT

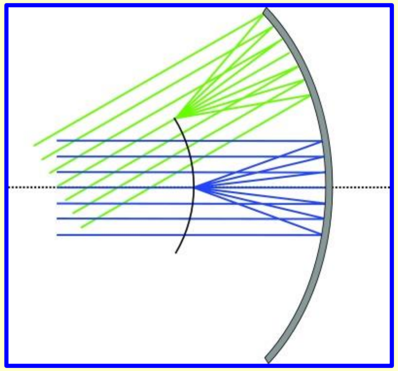
S. S. Zhang, et.al , *NIMA* 629 (2011) 57–65

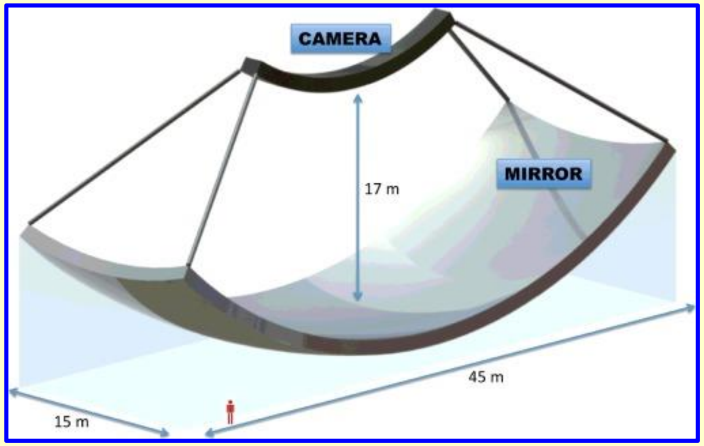
- A $5m^2$ spherical mirror
- FOV of $14^o \times 16^o$ with 0.5^o pixels;
- to measure the energy spectrum and the composition of cosmic rays (CR) in the energy range from 30 TeV to several EeV.

Meridian Atmospheric CHErenkov TElescope (MACHETE)

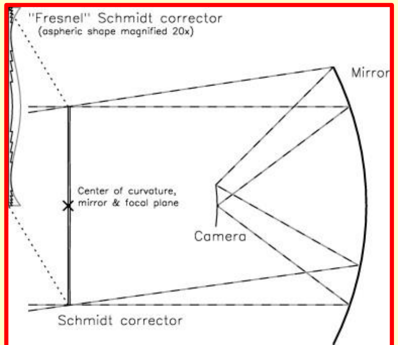
J. Cortina et.al., *APP* 72 (2016) 46–54

- Each of the two telescopes would have a camera with a FOV of 5×60 sq deg oriented along the meridian. About half of the sky drifts through this FOV in a year.
- A spherical shape of 34 m radius .
- Optical PSF of 0.06° for an ideal mirror.
- 15,000 photodetectors.





Mirror: $45m\times14m=620m^2$
Camera: $1.5m\times18m=27m^2$



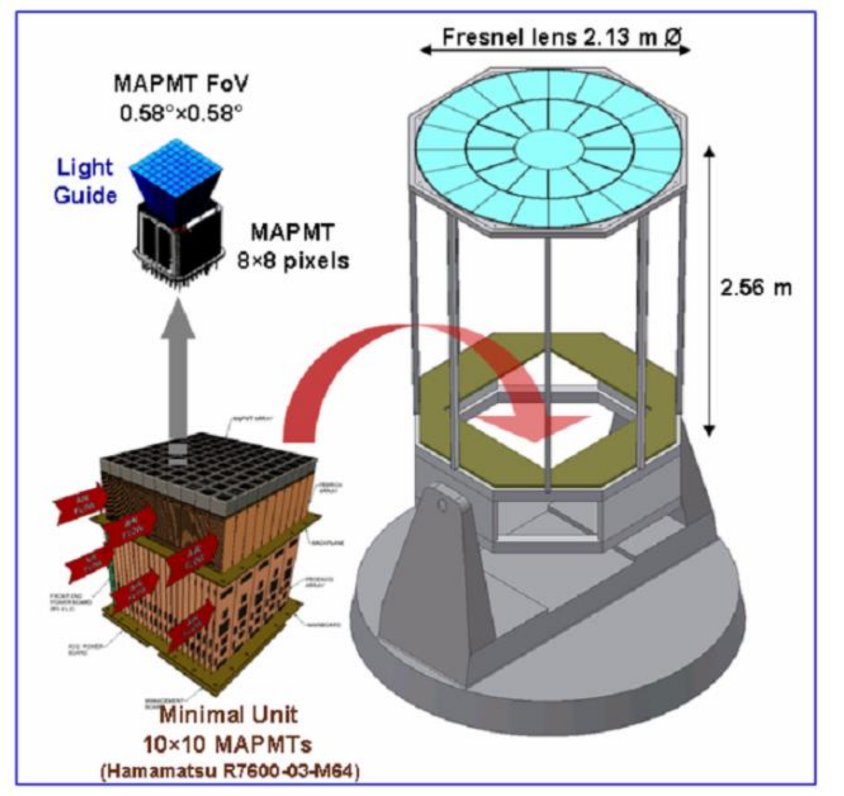
Schmidt-type IACT

R. Mirzoyan et.al *APP* 31 (2009) 1–5

Wide FoV Cherenkov Telescope
Refractive Optics

GAW: Gamma Air Watch

The optics of GAW, composed by a large dimensional single-sided Fresnel lens, will allow to achieve large field of view. G. Cusumano *ICRC2011*:ID1352



Large dimensional Fresnel lens is very expensive.

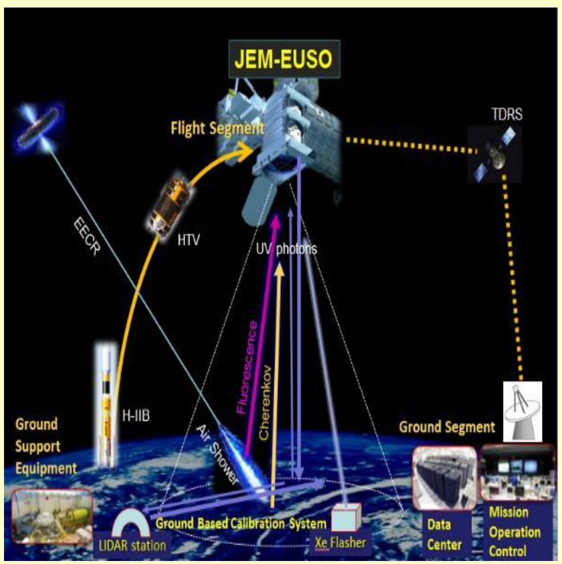
Wide FoV Cherenkov Telescope
Refractive Optics: EUSO

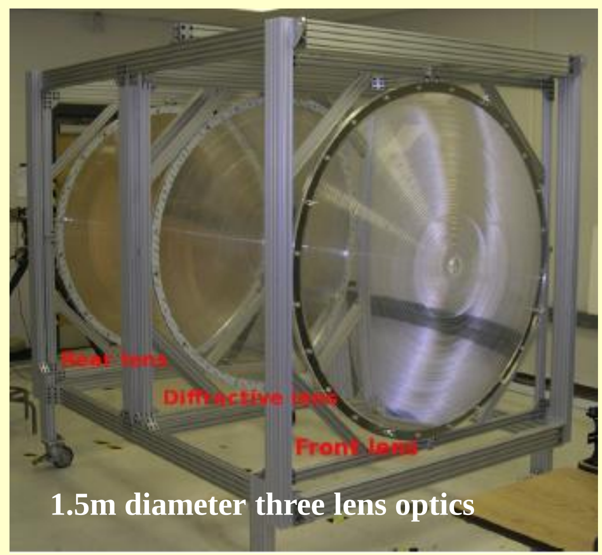
JEM-EUSO is a Fresnel-optics refractive telescope devoted to the observation of Ultra High Energy Cosmic Rays (UHECR).

Casolino M et al., (JEM-EUSO Collaboration) 2014 *Exp. Atron*.

- **Lens diameter 2650mm**
- **Field of View(FoV) ±30°**

The prototype lens also used by FAST have detected some candidates UHECRs in time coincidence with the TA FD. **T. Fujii, et.al *APP* 74 (2016) 64–72**





1.5m diameter three lens optics

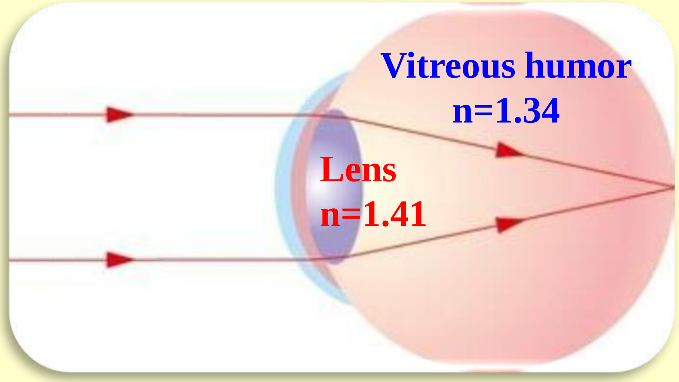
Large dimensional Fresnel lens is very expensive.

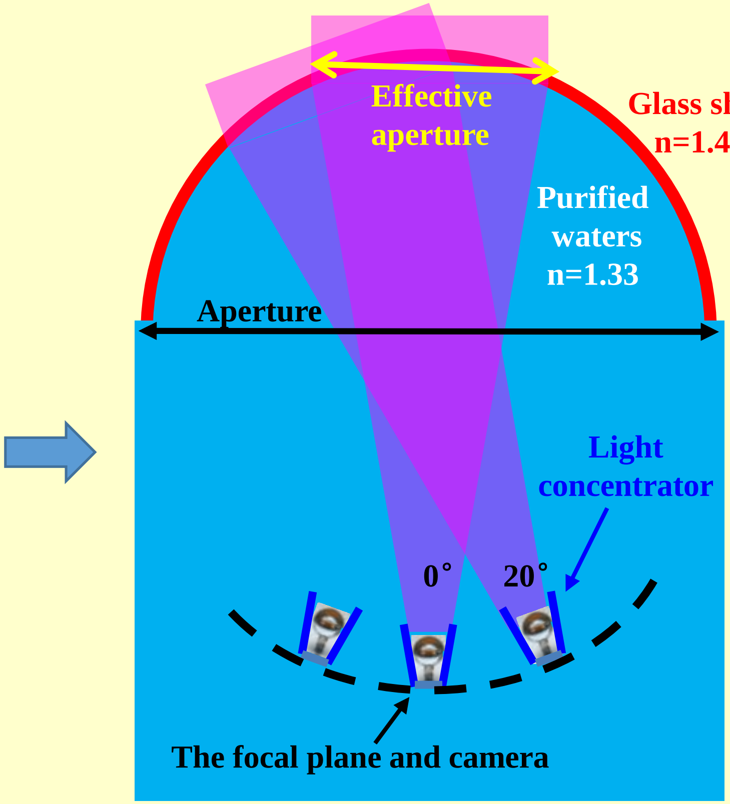
EUSO-TA
EUSO-Balloon
EUSO-SPB
EUSO-SPB2
Mini-EUSO
K-EUSO
TUS
JEM-EUSO

Conceptual design for the water-lens telescope array

- **Our concept is inspired by the structure of human eye.**
- **High transmittance of purified water for ultraviolet photons**
- **A refractive water-lens telescope with acrylic shell as a light collector for observing Cherenkov light induced by CRs and high energy γ-ray, especially aiming for detecting the high energy emission of *sporadic* γ-ray sources.**

Human eye

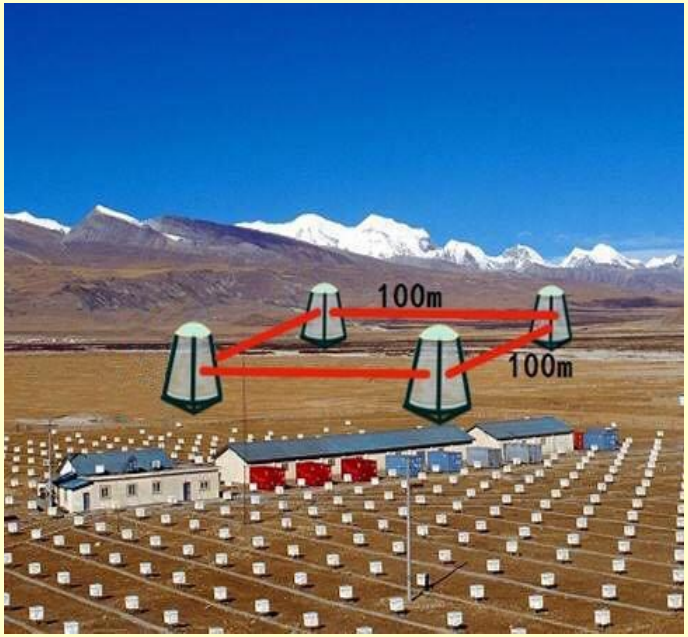




Large dimensional water-lens is relatively cheap.

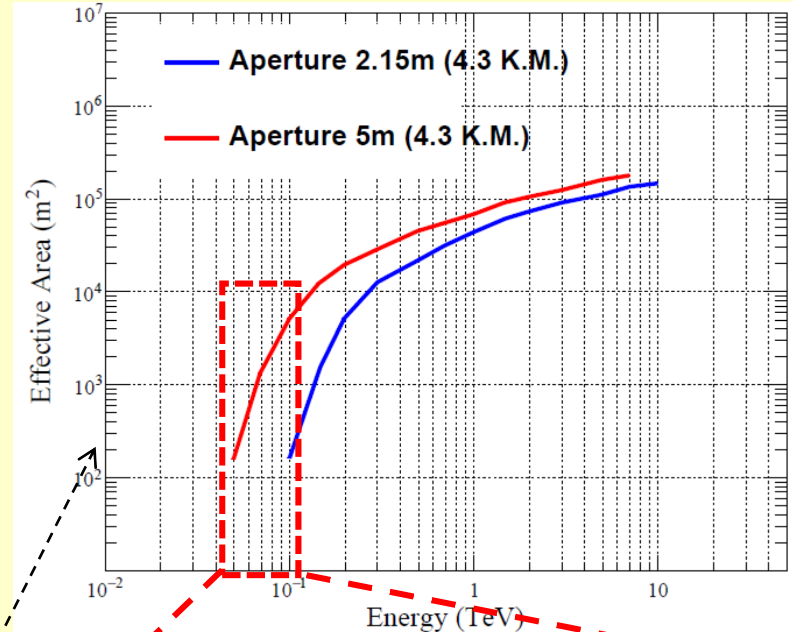
- **Preliminary simulation result: Effective Area**

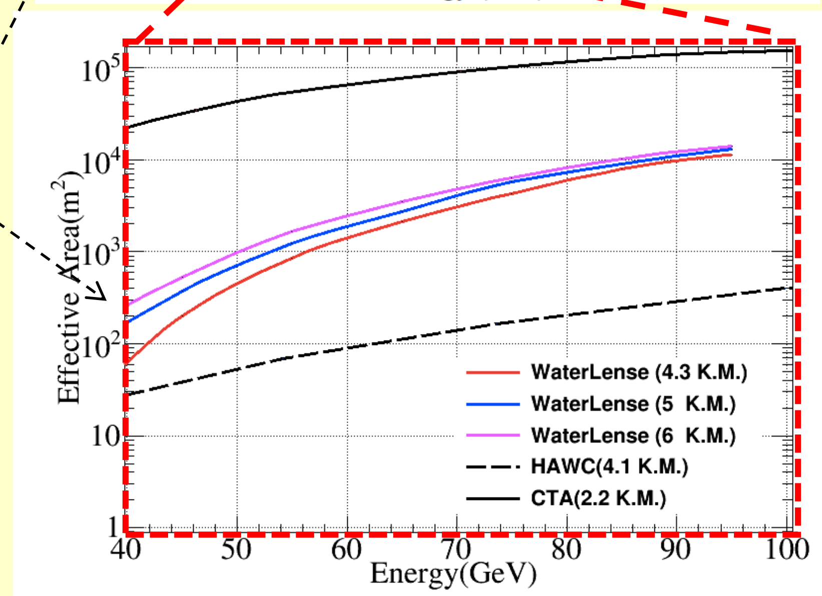
Very preliminary （By Caihui <ihep>）



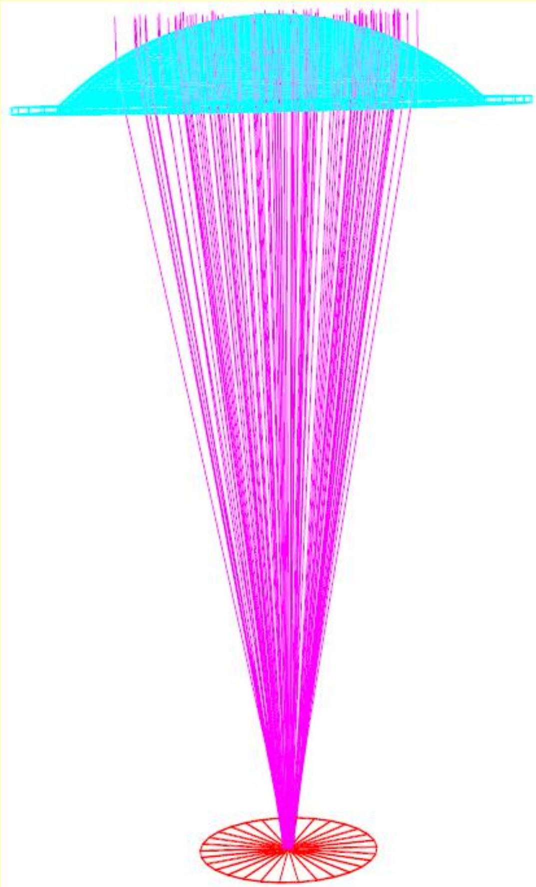
Aperture： 6.9m
Effective aperture:5m
Focal length： 12m
Point spread function (PSF) r_{80}: 80mm (0.38°)
Field of View： 40°×40°
Array: 4 Telescopes

	CTA(LSTs)	Water-lens telescope
Dimension	24m	5m（effective aperture）
Telescope number	4	4
Effective area(m^2)@60GeV	$\sim 10^4 m^2$	$\sim 10^3 m^2$
Field of View	tens of square degrees	thousand of square degrees





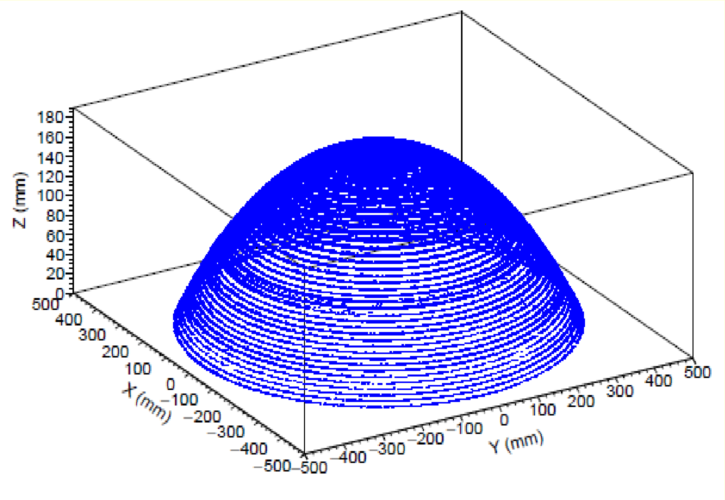
• Water-lens prototype



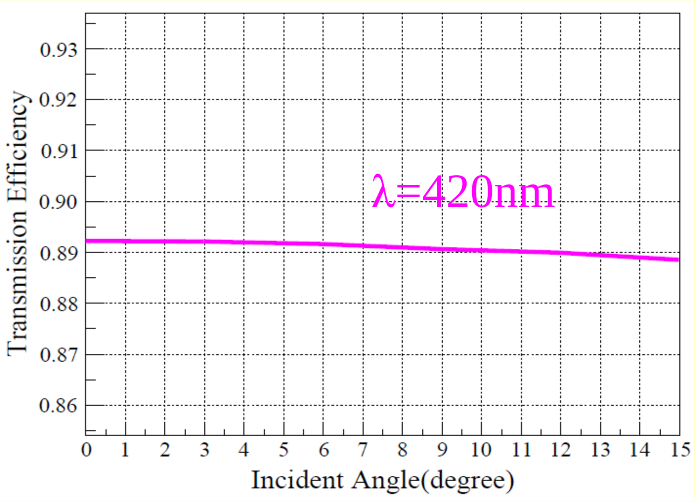
Ø=0.9m

As a pathfinder, we designed and manufactured a water lens prototype with a thin spherical cap. We have successfully observed Cherenkov light induced by high energy CRs in coincidence with a scintillator EAS array in Yangbajing Observatory.

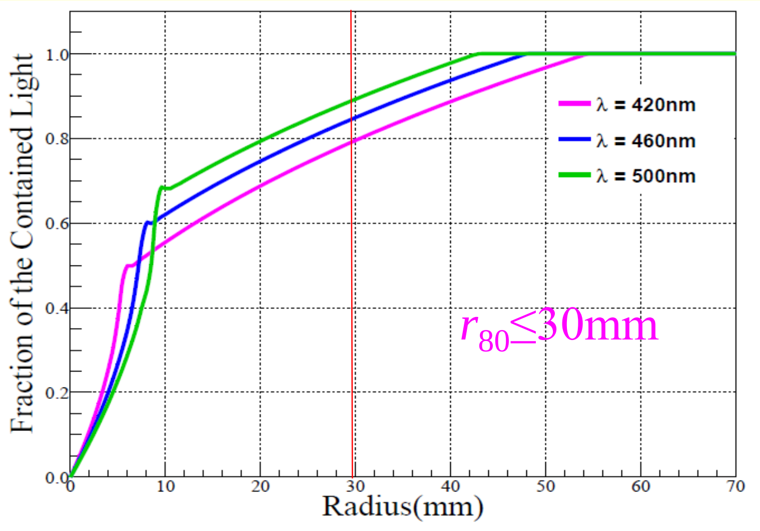
• The optical property of water-lens prototype



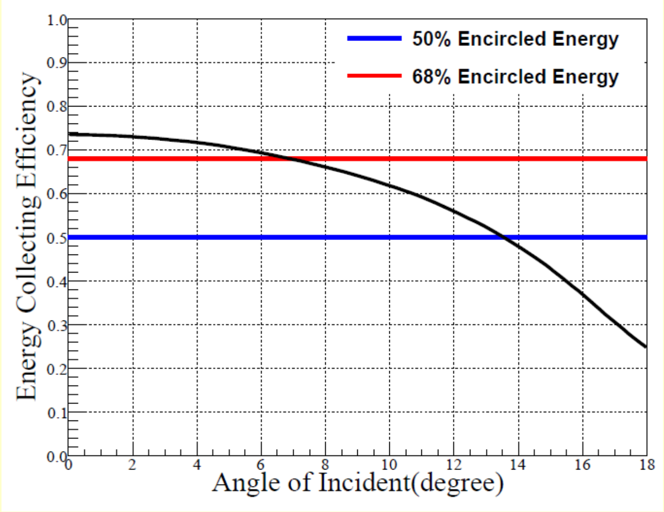
The **surface accuracy** of lens is **±1mm** which has been assessed by industrial Computerized Tomography (CT).



Between the incident angle of 0^o and 15^o, the **transmittance** is approximately uniform around **89%.**



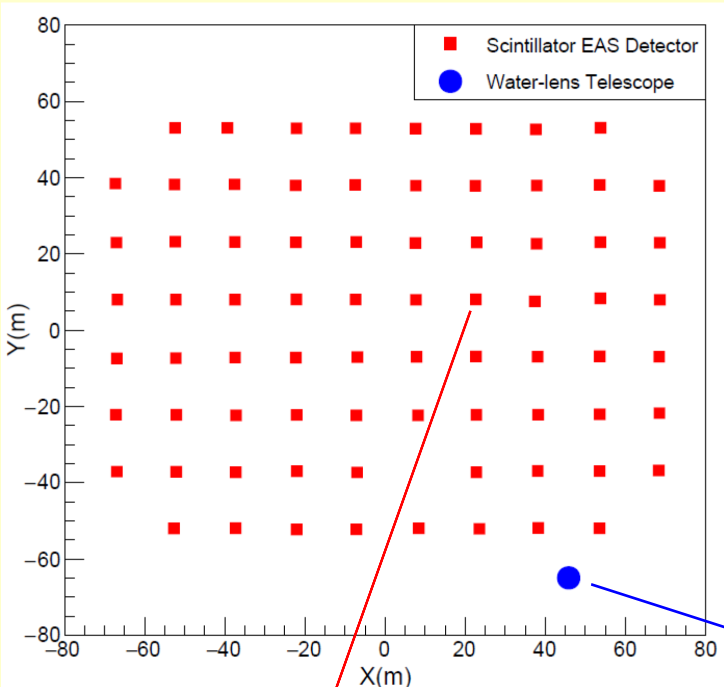
For the focal length of 168 cm, r_{80} **=30mm** corresponds to ~1^o, i.e, the focal plate scale of **2.9 cm deg-1**.



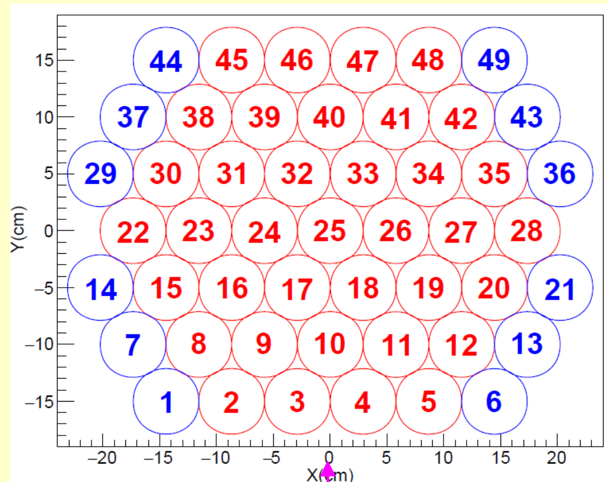
The **FOV** of **$14^o \times 14^o$** and $27^o \times 27^o$ will have **68%** and 50% encircled energy respectively

• Off-line coincidence with the scintillator EAS array

Experiment conducted at Yangbajing Observatory in November 2016

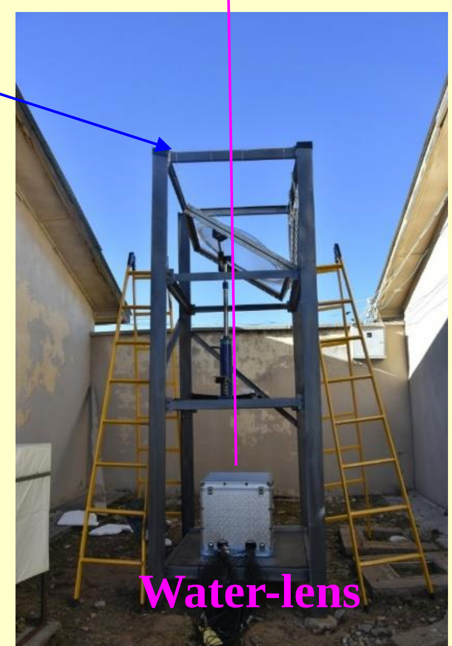


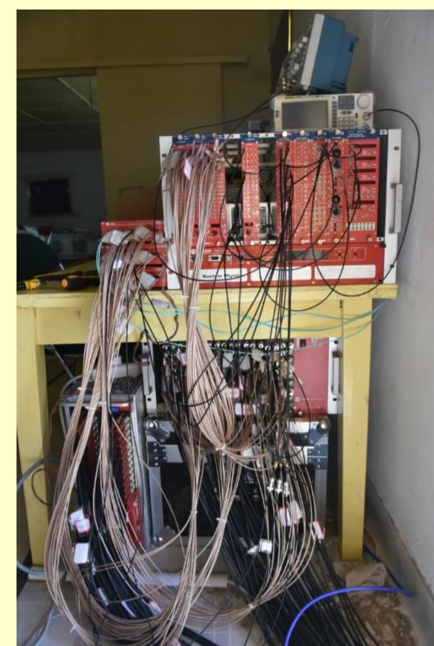
Layout of the coincidence expeiment



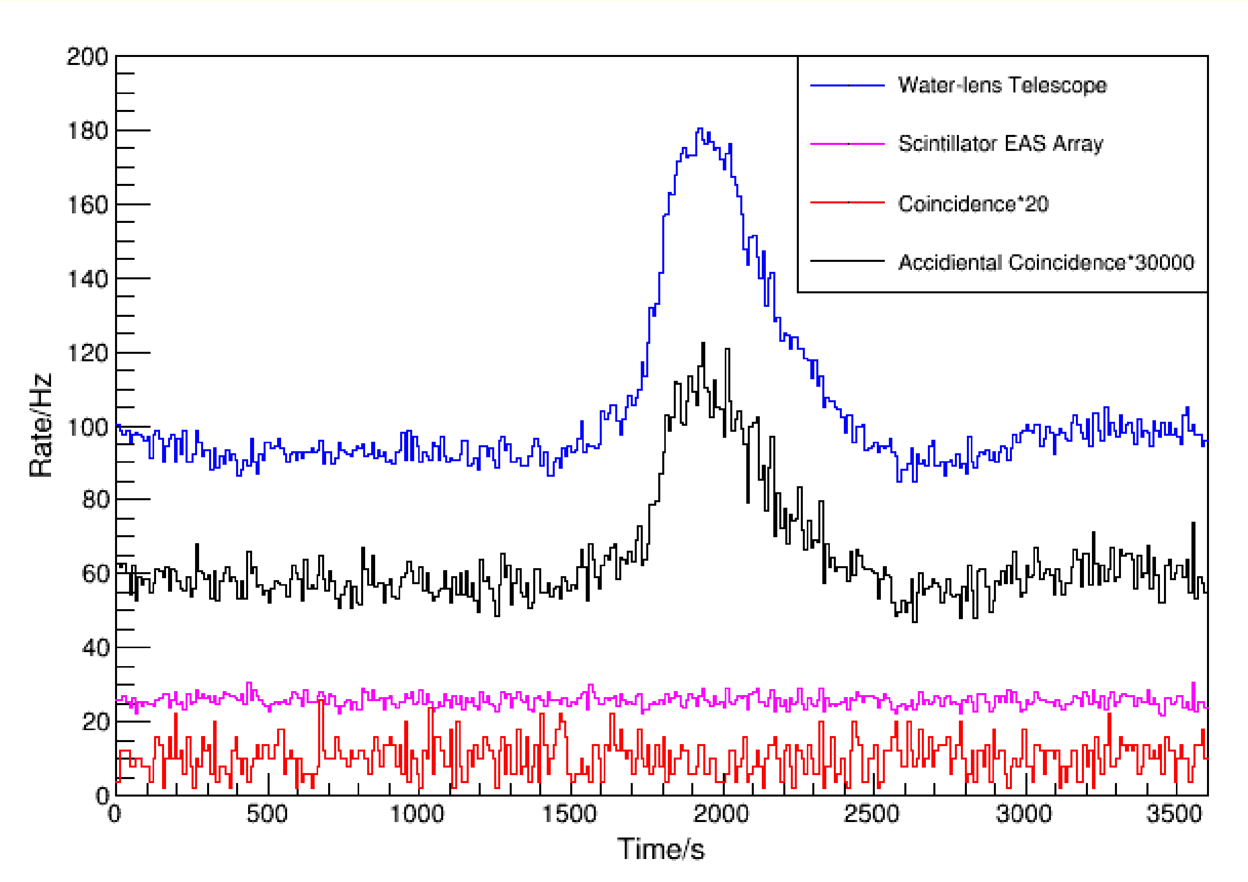
Camera

R7725 PMT: 51mm (1.74°)
center hexagonal (37pixels) +outer guard ring (12 pixels)
The full aperture of the camera is 15° × 13°.





- **First observation of CRs**



- **Water-lens**
  - **Events:1.79×10^7**
  - **N_1=157.7Hz.**
- **EAS array:**
  - **Events:2.95×10^6**
  - **N_2=26.04Hz**
- **Coincident event**
  - **Coincident time window 400ns.**
  - **Events:5.18×10^4**
  - **N=0.46Hz.**
- **Accidental coincident rate**
  - **$R=2N_1N_2\tau$=0.003Hz.**

Therefore the accidental coincident rate can be ignored, which indicates that the coincident events are real Cherenkov light induced by CRs.

• Typical CRs events

EAS Array

$E = 77.6\, TeV$

$(\sum \rho = 87.8\, n/m^2)$

$dr = 68m$

Hillas parameters

$size = 184\,(p.e)$

$max1 = 42(p.e)$

$max2 = 38(p.e)$

$length = 1.4(^o)$

$width = 1.2(^o)$

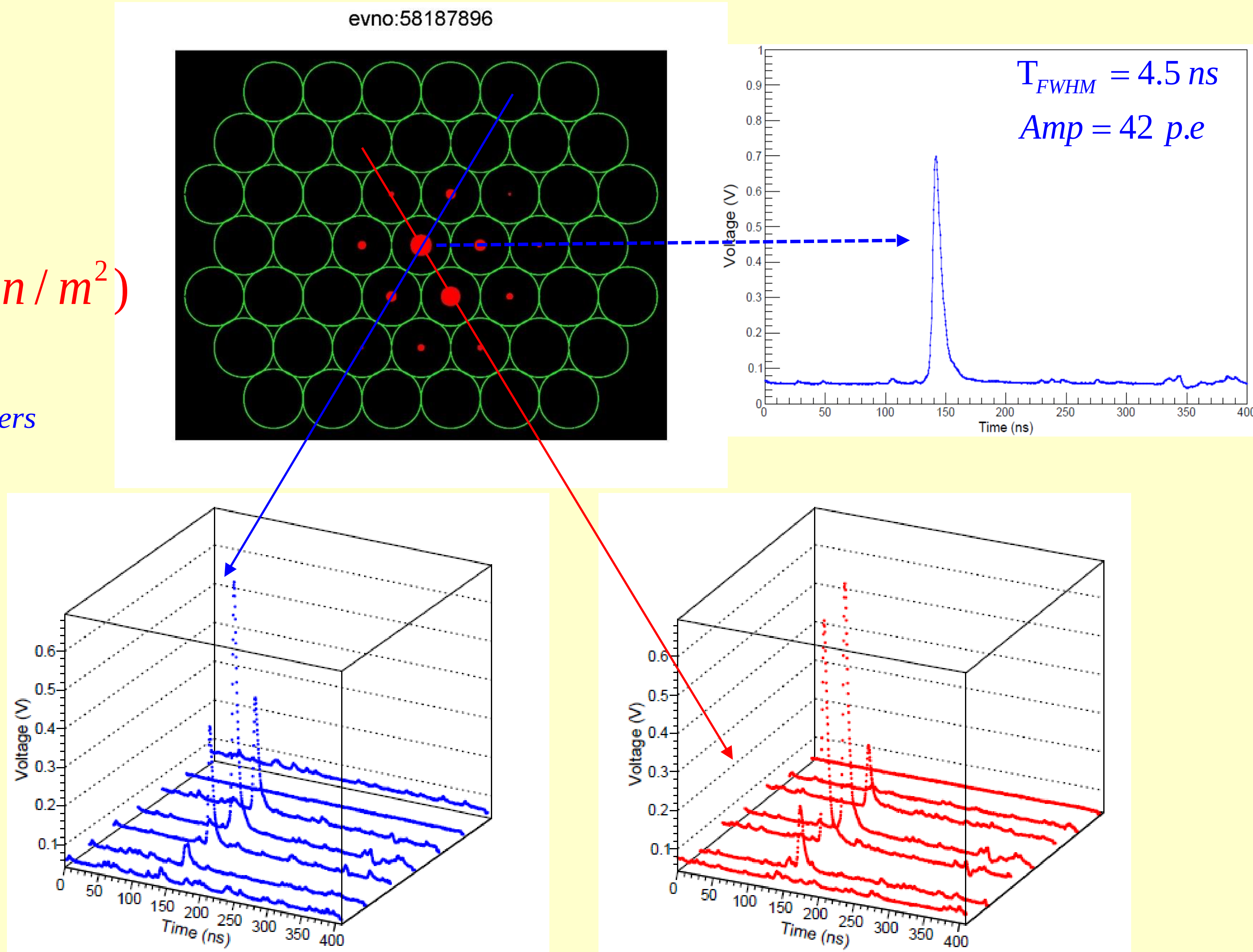
$distance = 2.6(^o)$

$azwidth = 1.3(^o)$

$miss = 1.1(^o)$

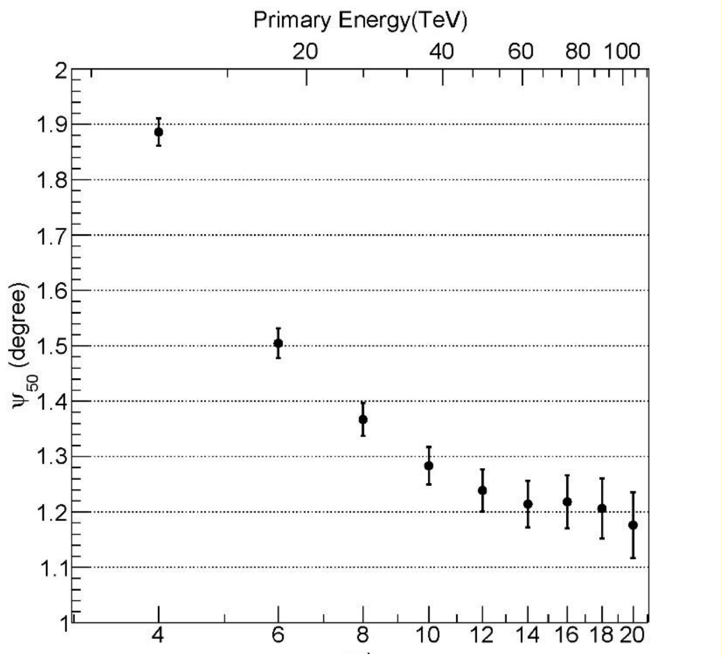
$disp = 0.6(^o)$

$alpha = 25.2(^o)$

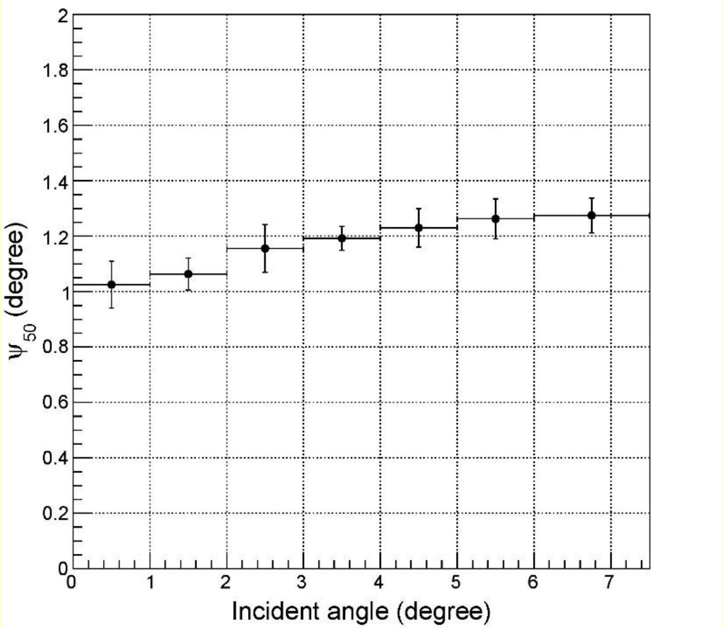


The intersection angle between the reconstructed direction of the EAS array and the water-lens is 0.5º.

- # Estimation of angular resolution



When *nch*≥12, the ψ_{50} will be stable and reach ~1.2^o. The angular resolution of the EAS array can be estimated from a Monte Carlo simulation, the ψ_{EAS50} is ~0.8^o for the data set (*nch*≥12). In this case, the average angular resolution of the water-lens telescope ψ_{LENS50} is estimated as ~0.9^o



The ψ_{50} as a function of the incident angle of the primary air shower for the data set of *nch*≥12 . For the on-axial lights, we get the best ψ_{50} at ~1.0^o. For the off-axial lights, ψ_{50} gets worse with increases in the incident angle. For light with an incident angle of 7^o,the ψ_{50} reaches ~1.25^o. There are two main reasons for the deterioration: planar surface(camera); cap shape (not ideal hemisphere).

Statues and Future Plans

Step1

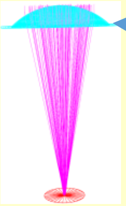
- 0.9m lens + EAS Array
- CRs (done)

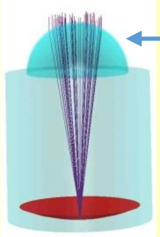
Step2

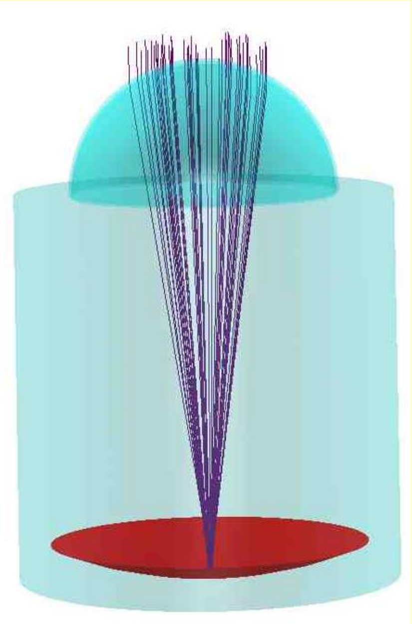
- 2m lens (being manufactured)
- Crab

Step3

- 5m（Effective aperture） (2×2) lens
- VHE emission of sporadic γ-ray sources (e.g, GRBs)







Discussion and conclusion

- IACT that based on refractive optics may provide a innovative way for the ground-based γ ray astronomy by achieving a very large FoV.
- The prototype telescope has successfully observed Cherenkov light that has induced by CRs .
- The prototype telescope can achieve a $15^{o} \times 13^{o}$ FoV and a $\sim 0.9^{o}$ angular resolution which is suitable for taking certain Cherenkov images for air showers.
- A larger dimensional water-lens with wide FoV at high altitude site would be used to lower the energy threshold for γ ray astronomy, especially for detecting VHE emission of GRBs, AGNs, and possible VHE electromagnetic counterparts of Gravitational Waves.

The end

Thank you!

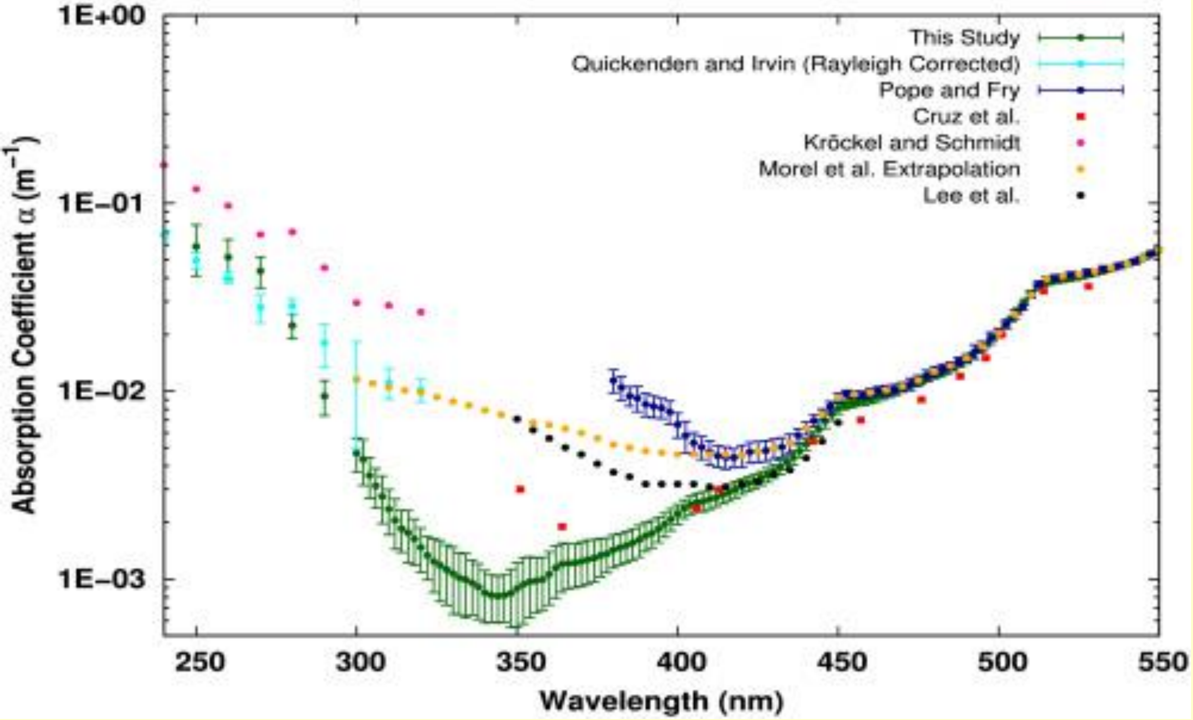
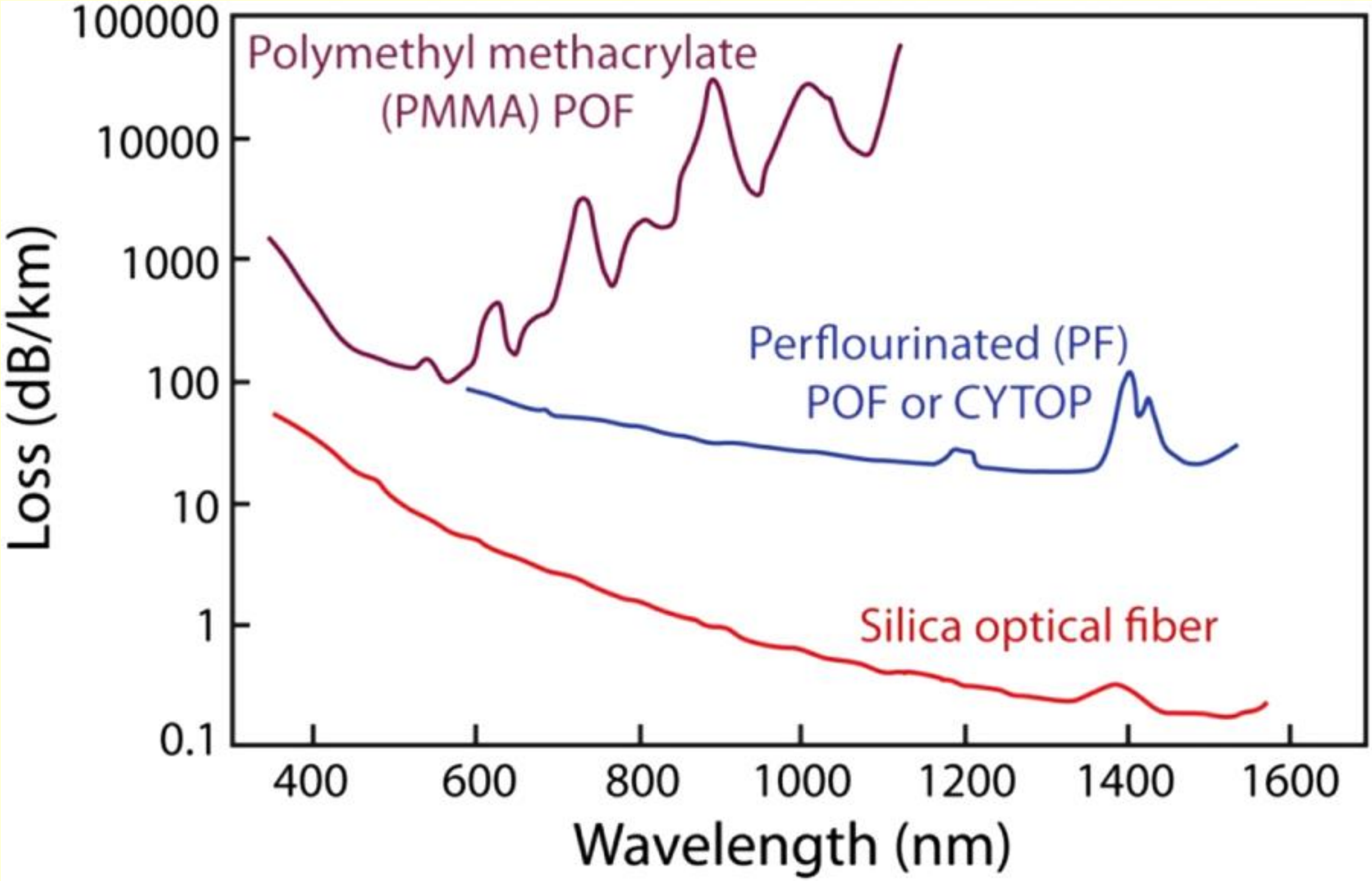


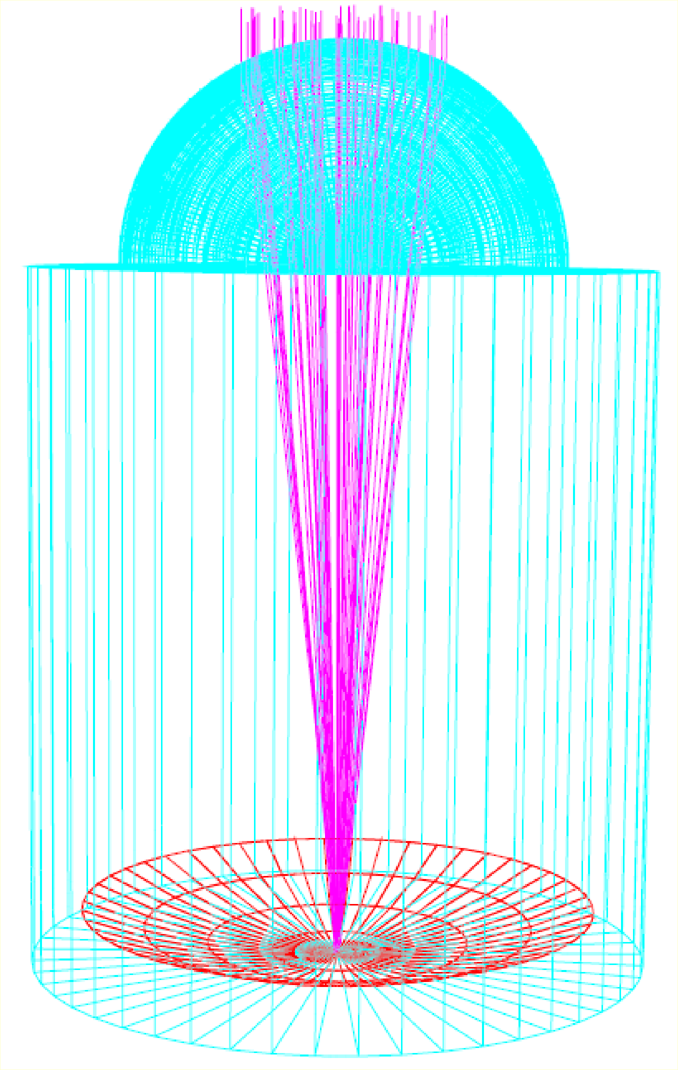
表 3.2: 不同波长光波在高纯水中的衰减长度 (吸收系数取自文献 [87])

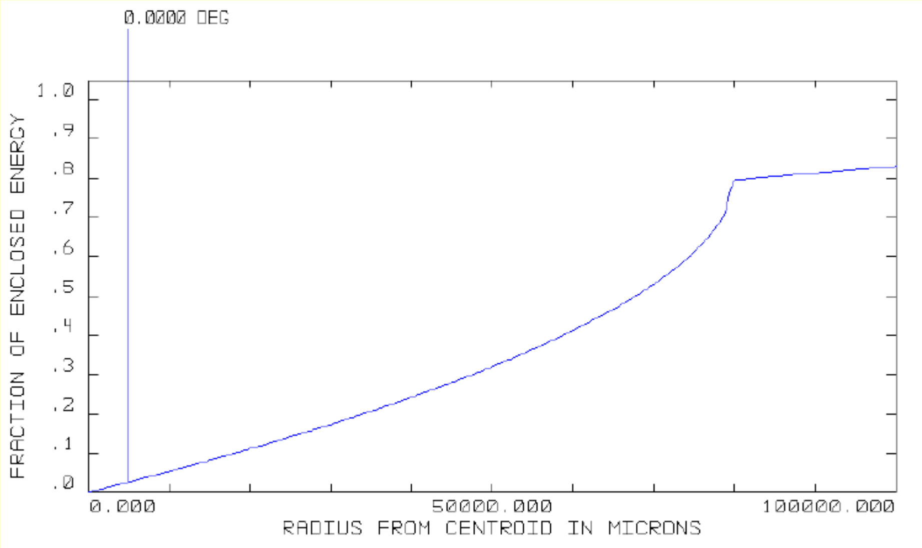
波长 λ(单位：nm)	吸收系数 (单位：m^{-1})	衰减长度 (单位：m)
300	4.67×10^{-3}	213.6
340	0.85×10^{-3}	1176.0
380	1.43×10^{-3}	698.8
420	3.12×10^{-3}	320.0
460	9.09×10^{-3}	109.5
500	2.07×10^{-2}	47.8

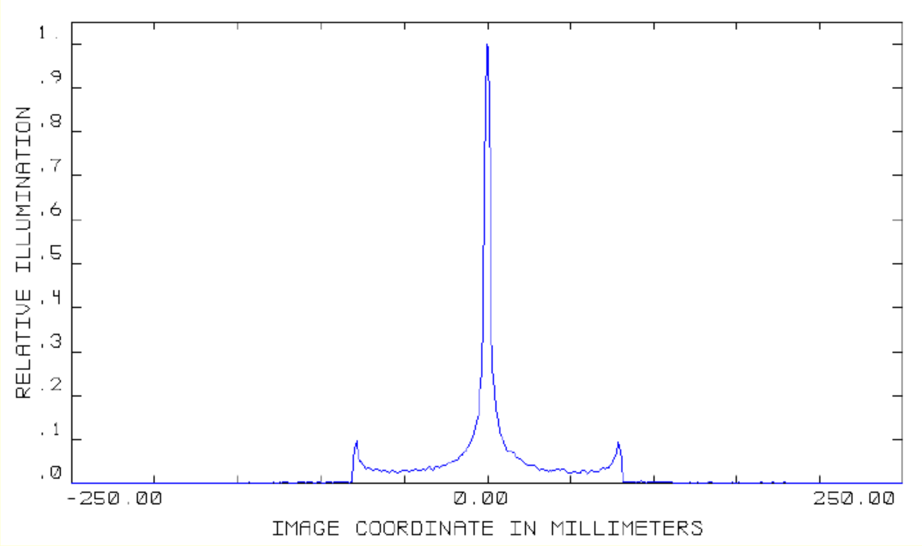
PMMA对光波的吸收



Polymethyl methacrylate (PMMA) POF
Perflourinated (PF) POF or CYTOP
Silica optical fiber
Loss (dB/km)
100000
10000
1000
100
10
1
0.1
400
600
800
1000
1200
1400
1600
Wavelength (nm)







r_{80} equals to 80mm, which corresponds to 0.38 degree for the focal length f=12m.

~10000 PMT **$40^o \times 40^o$**

Exp Astron (2013) 35:413–457
DOI 10.1007/s10686-012-9316-z

ORIGINAL ARTICLE

IACT observations of gamma-ray bursts: prospects for the Cherenkov Telescope Array

Rudy C. Gilmore · Aurelien Bouvier · Valerie Connaughton · Adam Goldstein · Nepomuk Otte · Joel R. Primack · David A. Williams

2.3.1 Effective area

Our assumptions about the effective area of CTA are based on Configuration E, which assumes a central cluster of four 24-meter class large-size telescopes (LSTs) that provide sensitivity to the lowest energy gamma-rays, and an additional 23 medium-size telescopes of the 12-meter class (MSTs) providing sensitivity at higher energies, $\gtrsim$100 GeV. Sensitivity at energies above 1

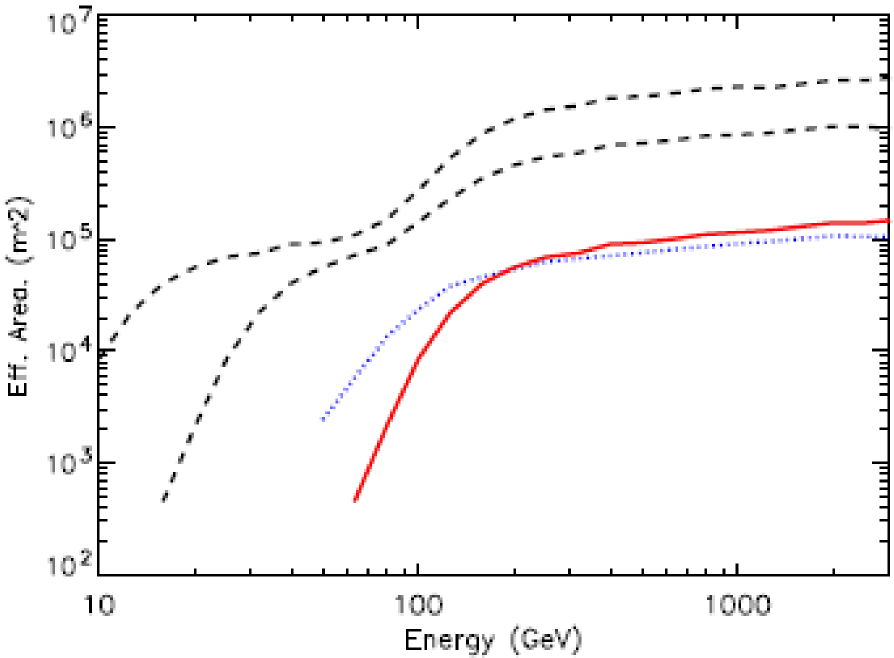


Fig. 6 The effective area functions used in this work. *Solid red* is the VERITAS effective area with standard cuts, and the *dotted blue line* is the MAGIC [14] implementation with standard cuts, shown here for comparison. The *two dotted black* curves are the effective area functions used in this work, denoted CTA realistic (*lower*) and CTA optimistic (*upper*)

Astroparticle Physics 35 (2012) 641–650

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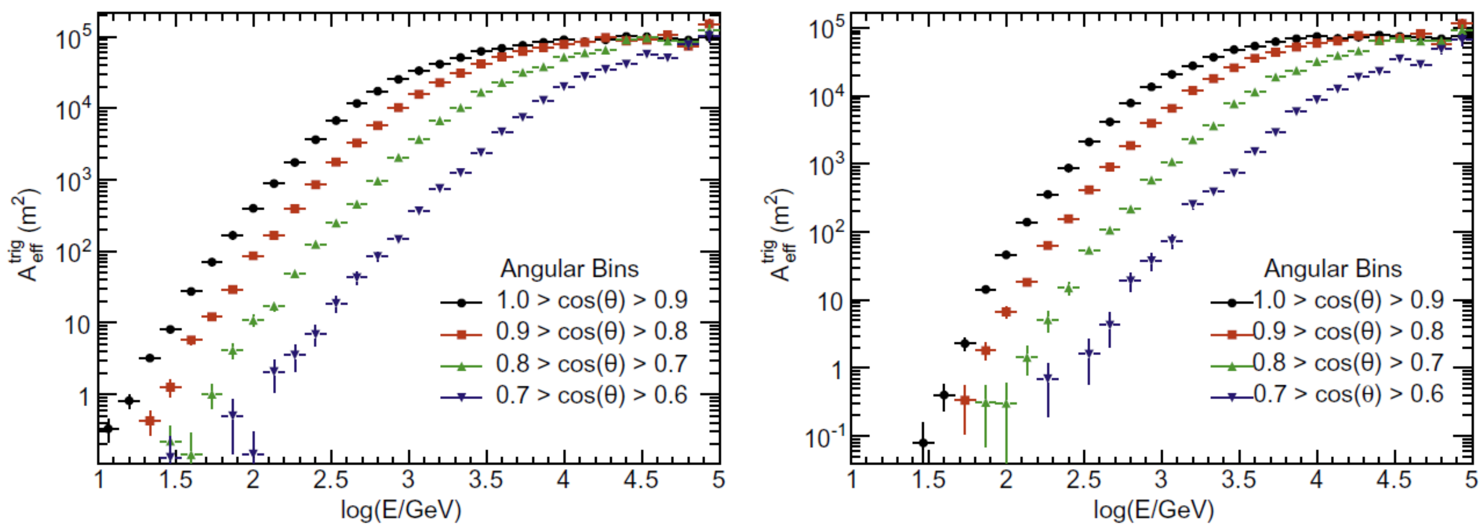
ASTROPARTICLE PHYSICS



(a) Effective area of the HAWC for $nHit > 30$. (b) Effective area of the HAWC for $nHit > 70$.

Fig. 2. Effective area of HAWC using the main DAQ system. Both panels show the effective area A_{eff}^{trig} of HAWC in the triggered mode as a function of γ-ray energy for 4 ranges of zenith angle. A trigger rate of ≈17 kHz (*nHit* > 30) is assumed in the left panel. A trigger rate of ≈5 kHz (*nHit* > 70) is assumed in the right panel. Showers reconstructed with >1.1° error are excluded for the left panel and >0.8° for the right panel. No gamma-hadron separation cut is applied. For the energies relevant to GRB searches, i.e. below ≈300 GeV, applying a gamma-hadron separation results in a global reduction of the effective area by a factor of 0.85 (left) and 0.75 (right).