VHE Particle Astronomy with All-sky Survey High Resolution Air-shower telescope (ASHRA)

ASURA (阿修羅)

- A god of Indian myth.
- A statue of National treasure at Kofuku temple in Nara.
- He has 3 faces and 6 arms.

ASHRA Collaboration

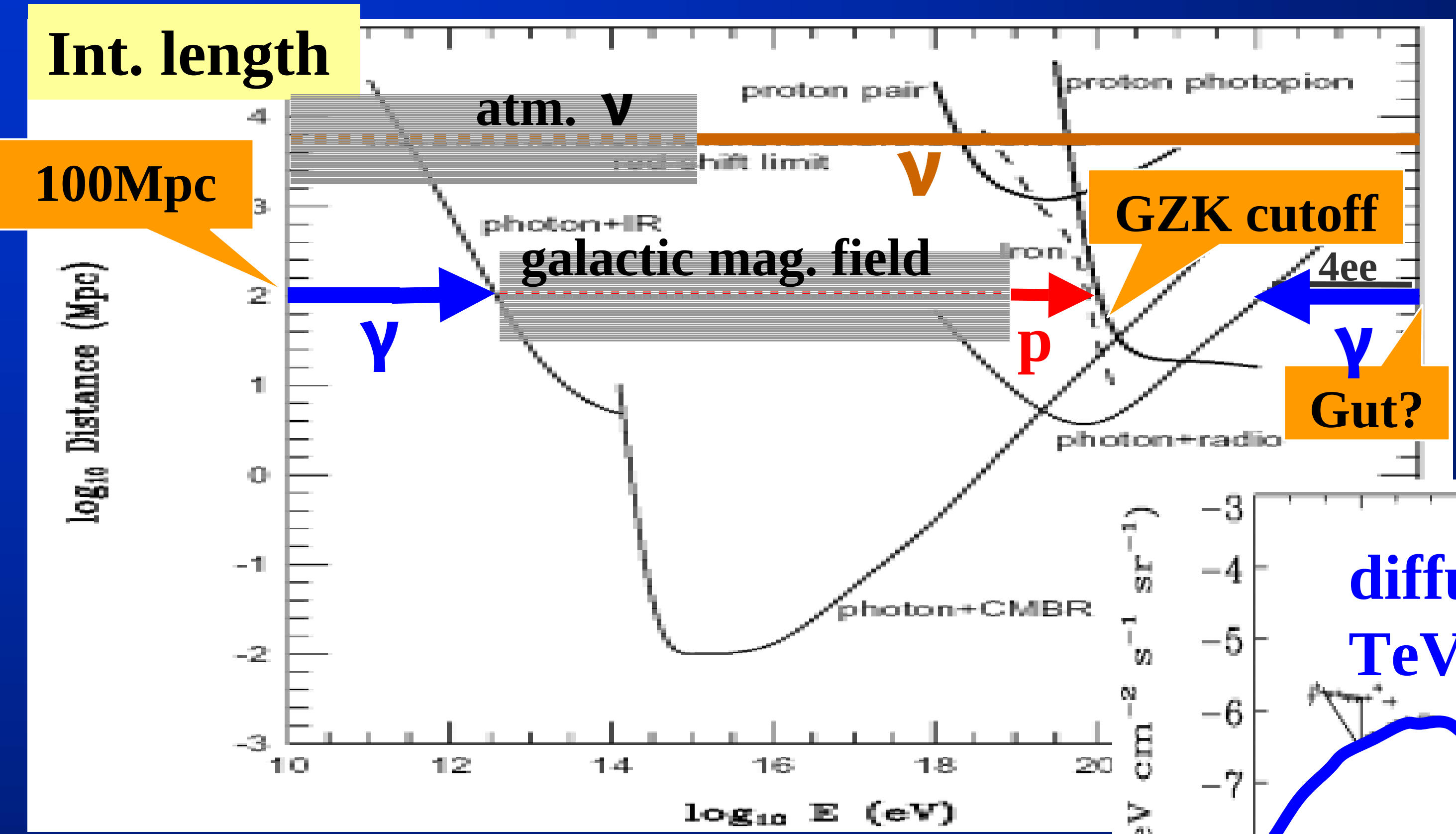
Makoto Sasaki

ICRR, Univ.Tokyo

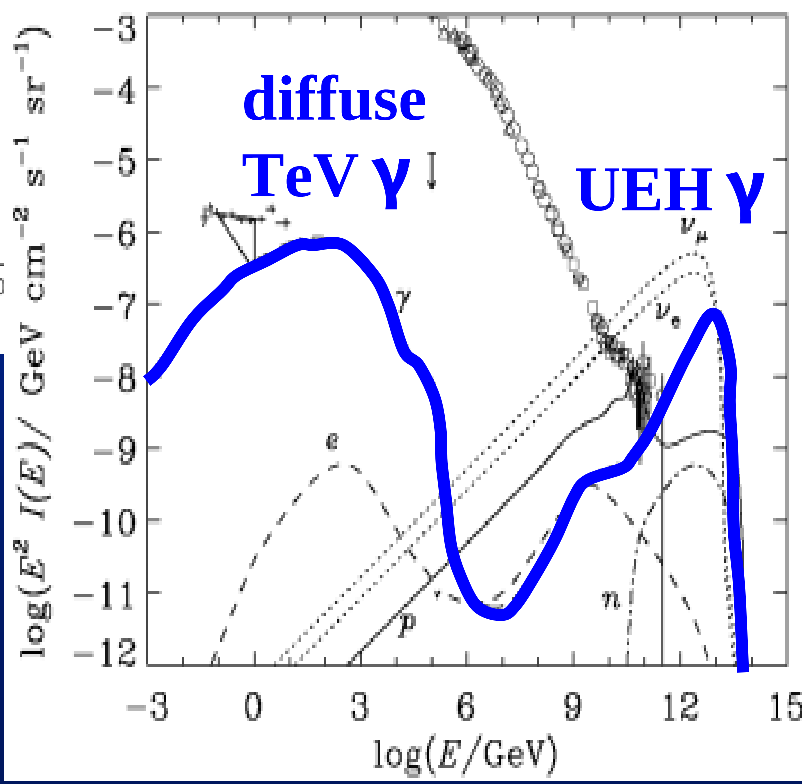
Contents

- Introduction
- Status of EHECR astronomy
- Current detectors
- ASHRA
- Summary

New Windows of Particle Astronomy



Protheroe, et al., astro-ph/9605036

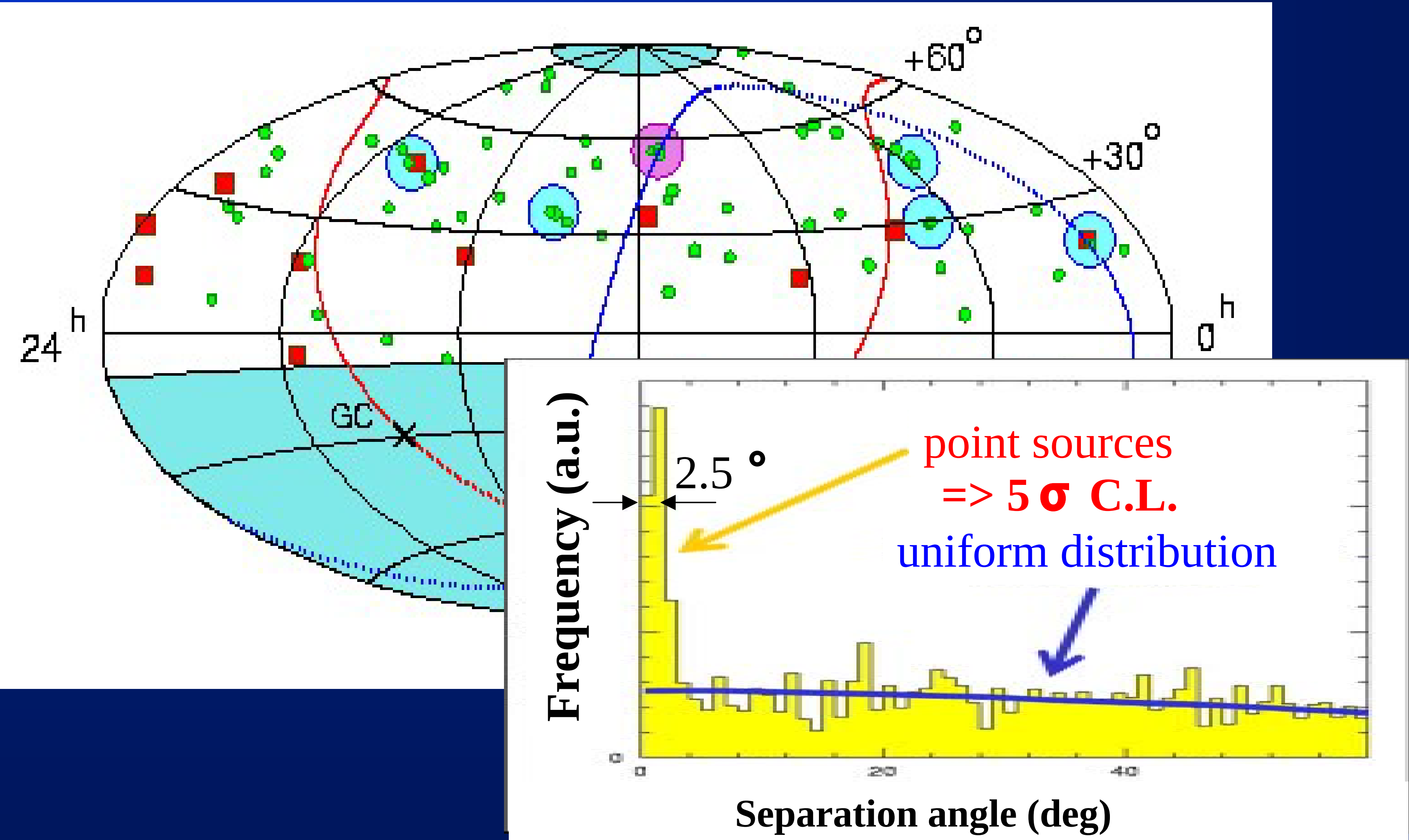


- Probes for VHE objects
  - EHE p, VHE ν , TeV γ
- Probes for GUT-TD
  - UHE γ , UHE ν , diffuse TeV γ

•Combined analysis for physics at origin

AGASA clusters

Clusters from 57 events > $10^{19.6}$eV
5 doublets
1 triplet (astro-ph/9902239)

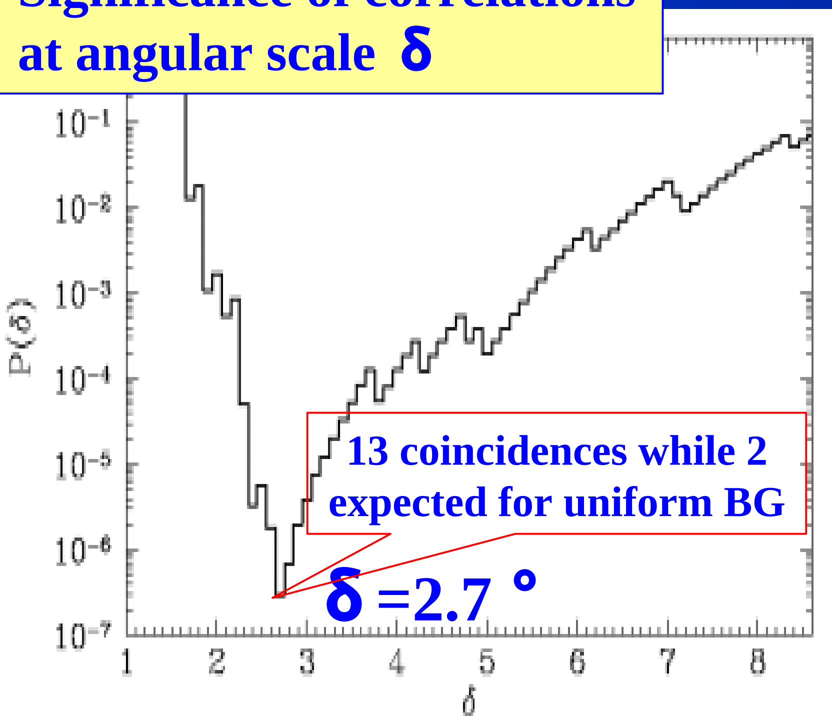


γ -ray-loud BL Lac & EHECR

Gorbunov, Tinyakov, et al. astro-ph/0204360

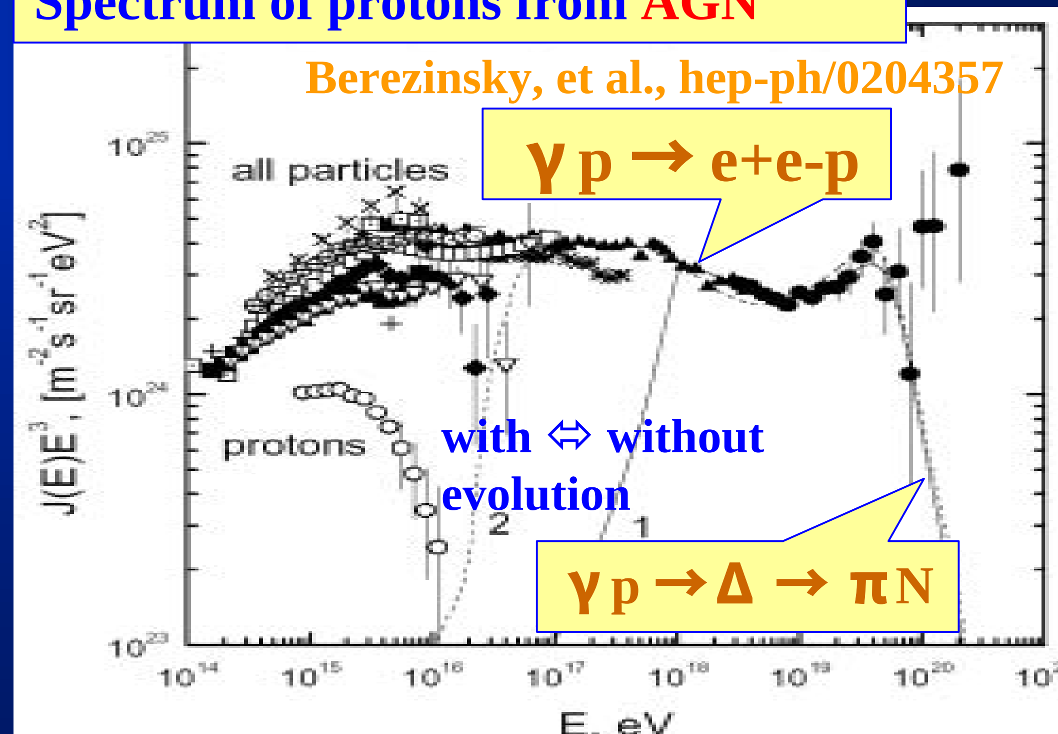
- EGRET & BL Lac (Veron2001) catalog => Selected 14 objects.
- AGASA 39 events (>4×10^{19}eV) + Yakutsk 26 events (>2.4×10^{19}eV)

Significance of correlations at angular scale δ



Prob. from BG fluctuation up to galactic mag. field model & charge assignment => Prob = 10^{-4}~10^{-7}

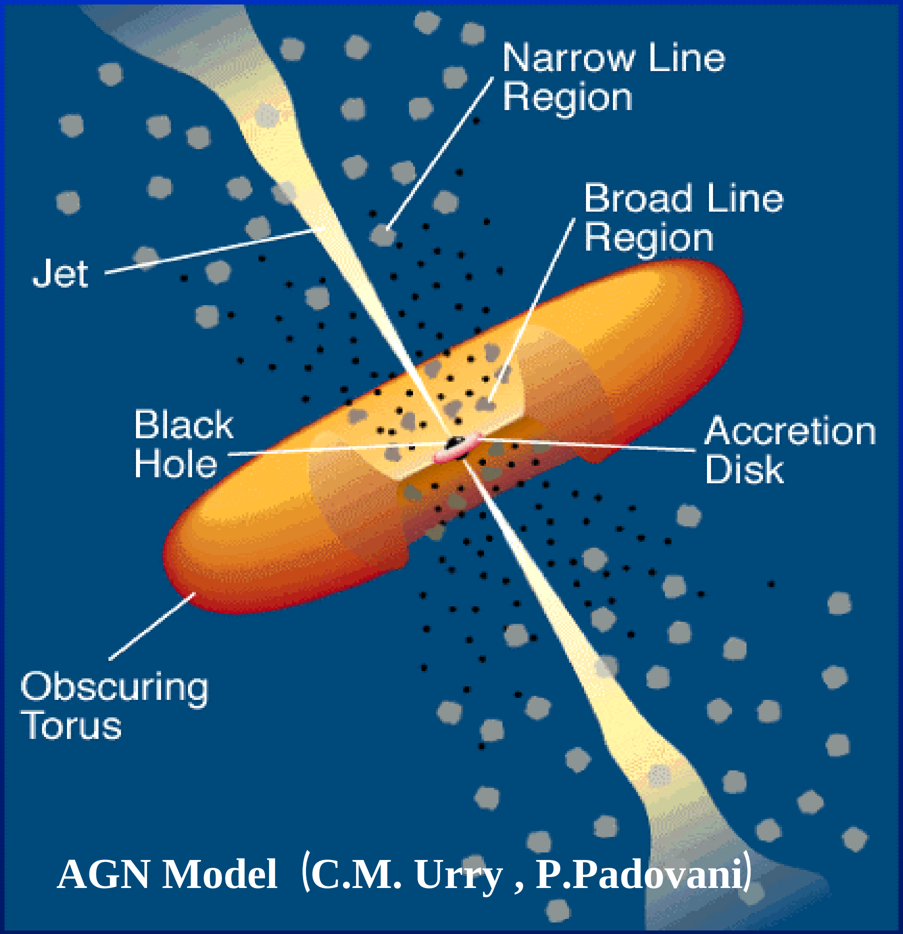
Spectrum of protons from AGN



Emissivity & Spectrum can be reproduced.

Clusters => EG Mag. field L_{coh}~1kpc

γ & ν from AGN



AGN Model（C.M. Urry , P.Padovani）

After p acceleration in AGN-jet,

photo-pion processes:

$$p\gamma \to p\pi^0 \to p\gamma\gamma$$

$$p\gamma \to n\pi^+ \to n\nu_\mu\mu^+ \to n\nu_\mu e^+\nu_e\overline{\nu}_\mu$$

$$\frac{dN_\nu}{dE_\nu} \sim Nrm \cdot \left(\frac{E_\nu}{E_\nu^{Max}}\right)^{-1}$$

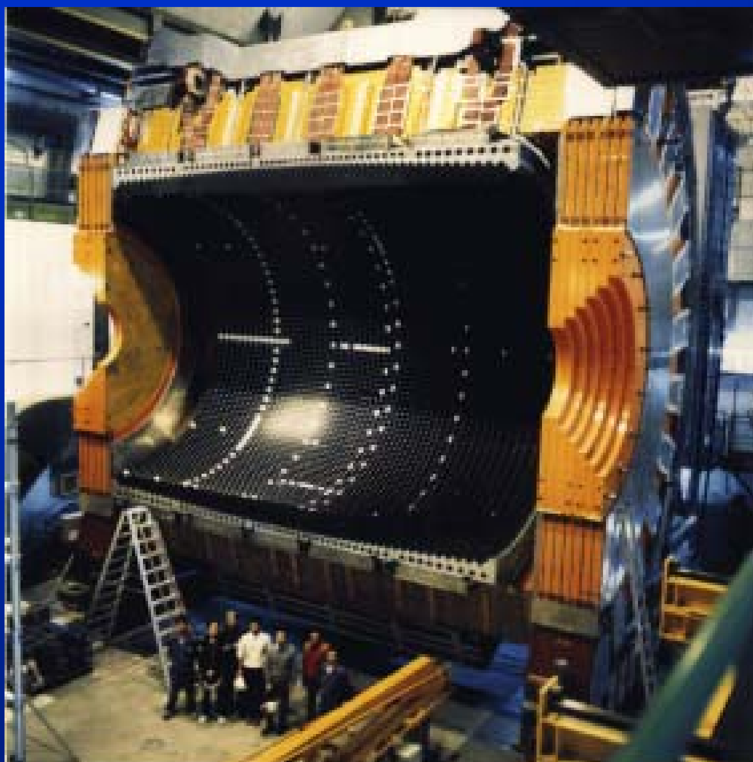
$$L_\nu \sim \frac{L_\gamma}{3} \sim \int^{E_\nu^{Max}} dE_\nu E_\nu \frac{dN_\nu}{dE_\nu} \sim Nrm \cdot \left(E_\nu^{Max}\right)^2$$

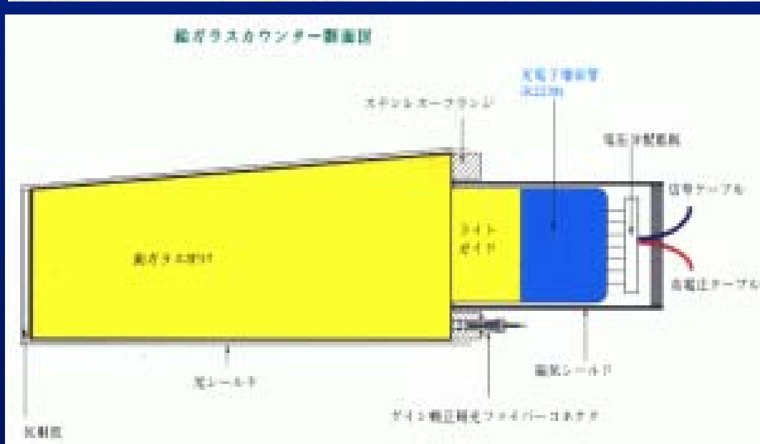
$$E_\nu \frac{dN_\nu}{dE_\nu} \sim \frac{L_\gamma}{3}\left(E_\nu^{Max}\right)^{-1}.$$

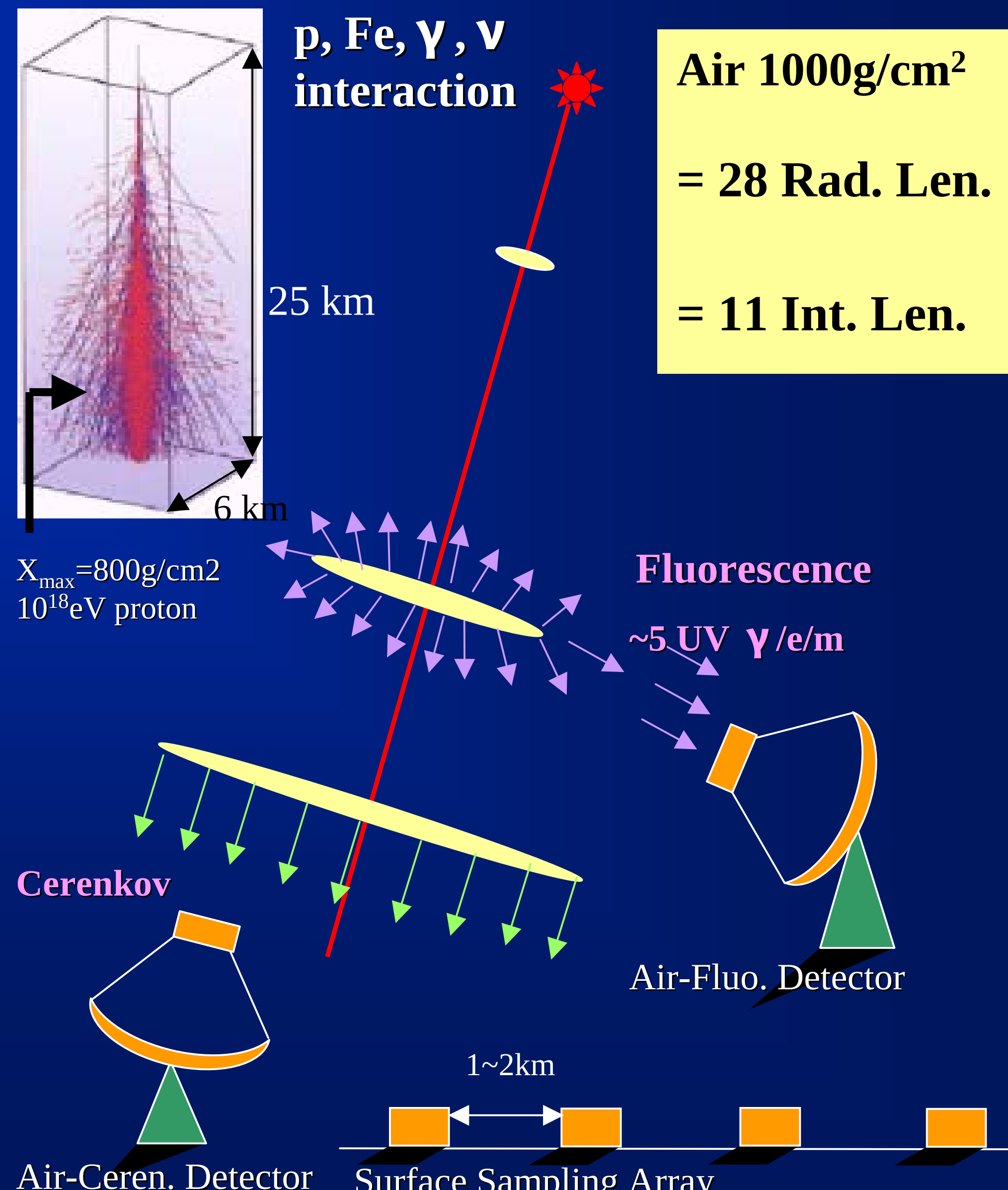
1. EHE- γ & VHE- γ (diffused)
2. EHE- ν

incontrovertible evidence for EHE proton acceleration in AGN

VHE particle detection

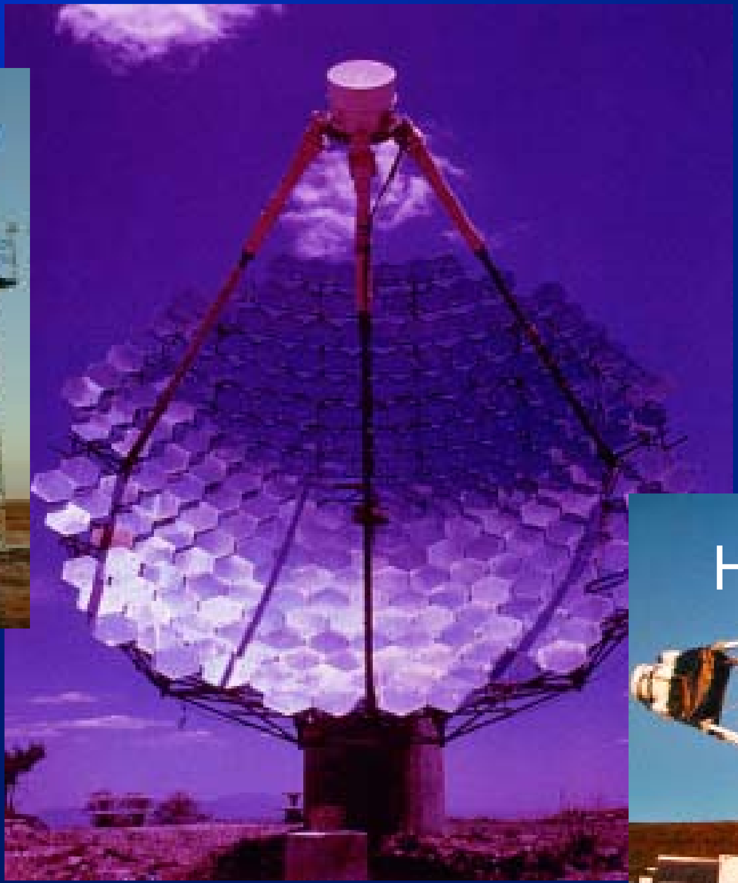




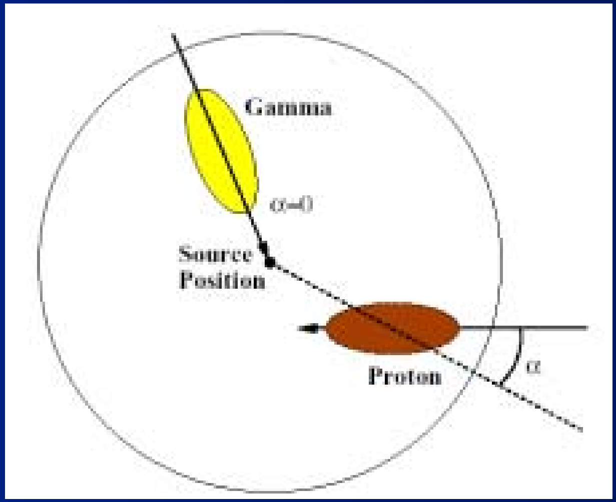


Air Cerenkov Detector

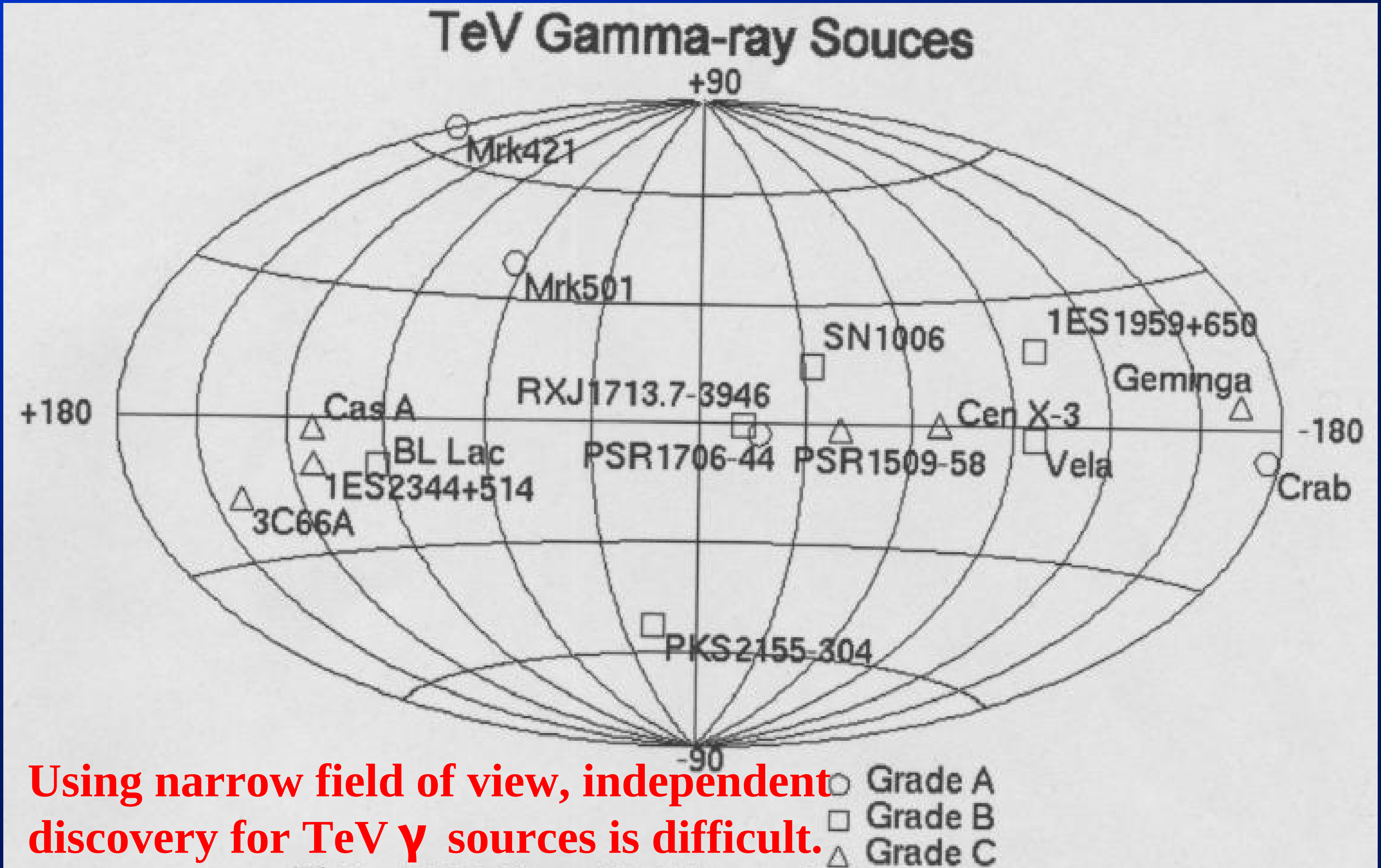

CANGAROO


Whipple

FOV〜0.001sr

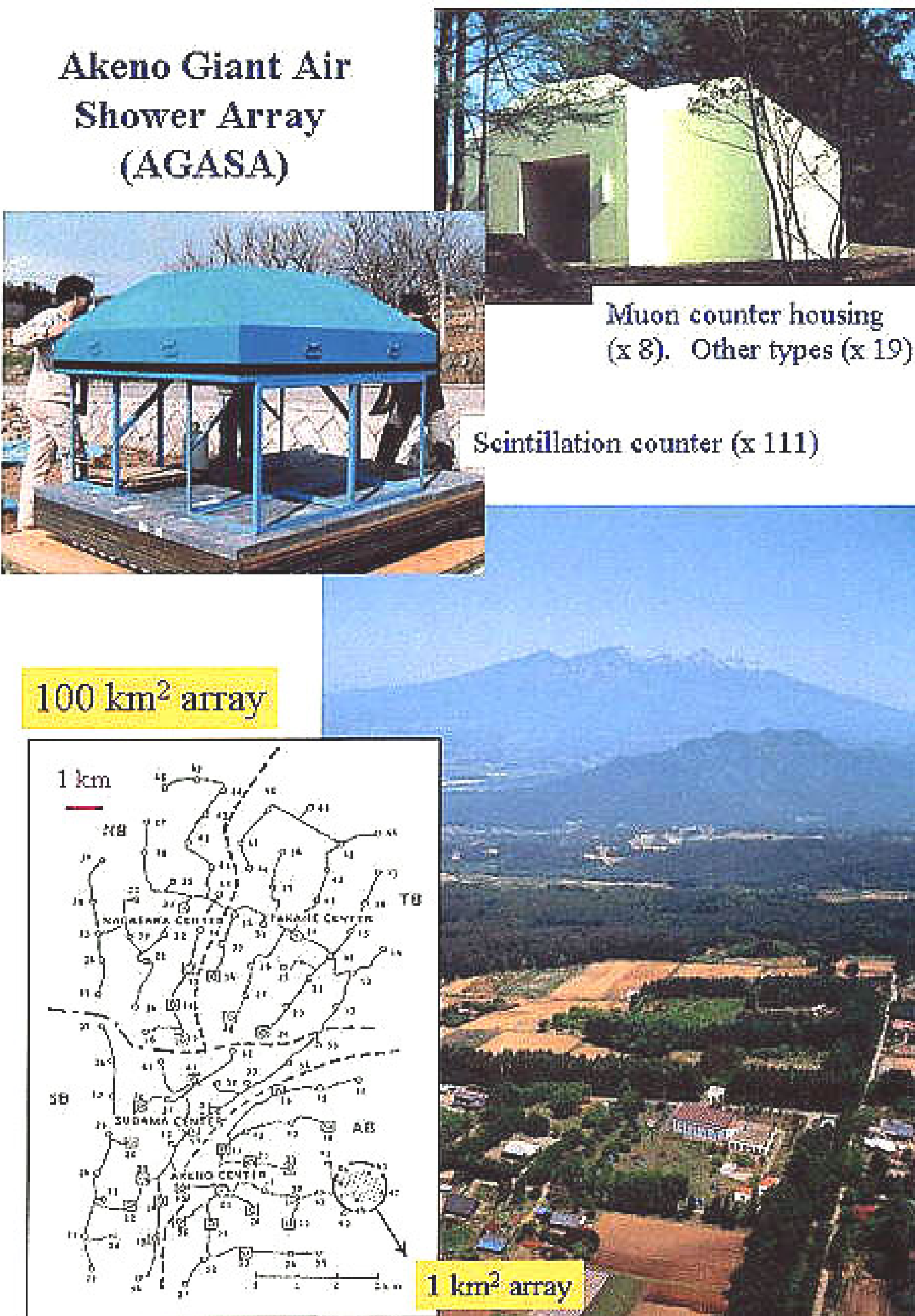


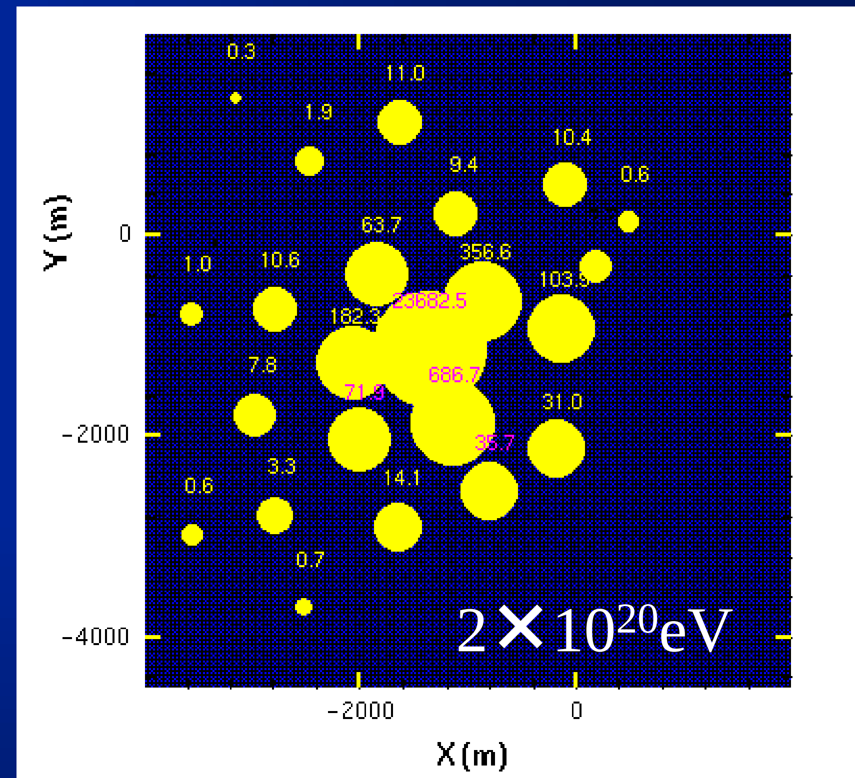
TeV γ Map



Using narrow field of view, independent discovery for TeV γ sources is difficult.

Surface sampling array

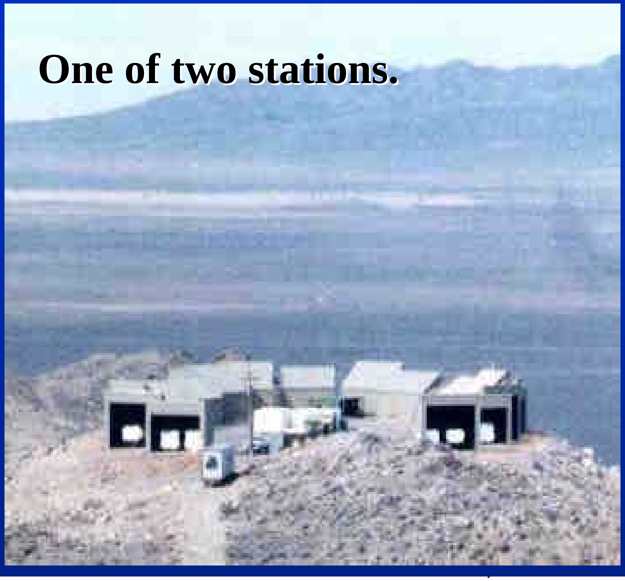


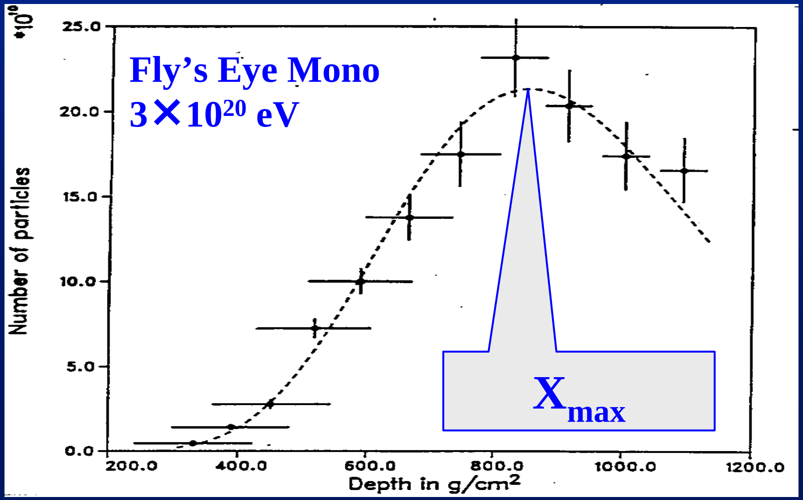


Pointing 2〜3°

Reconstruction is fully MC-dependent.

Air fluo. detector (HiRes)

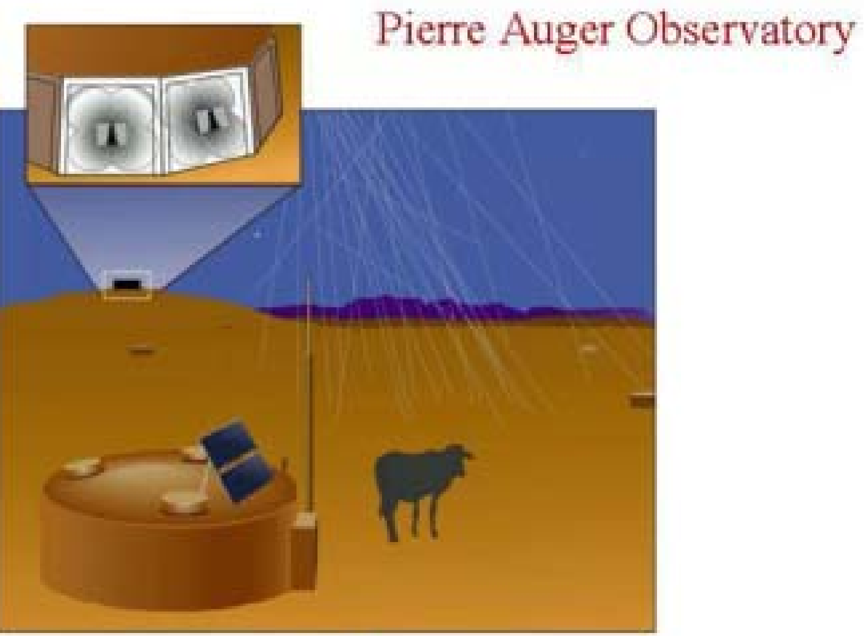


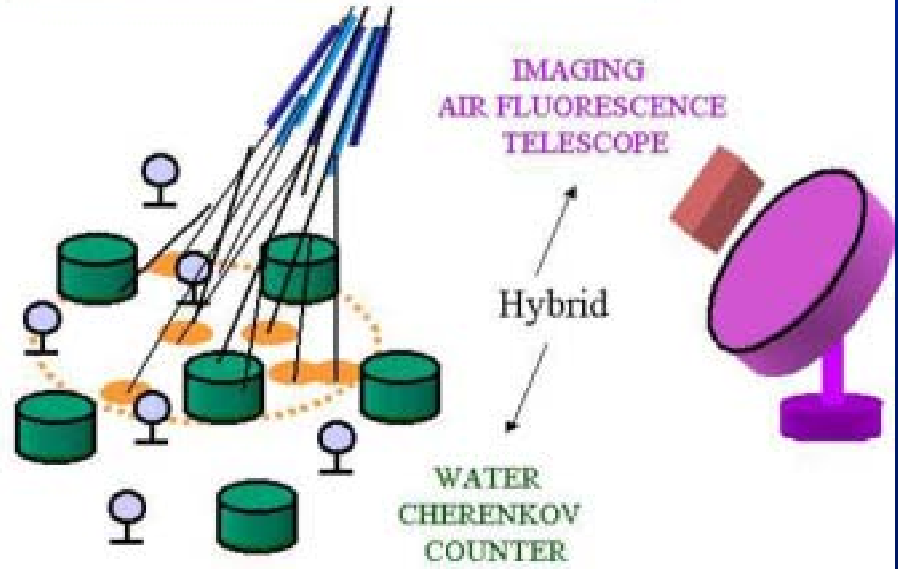


PMT array ＝> Resolution~1°

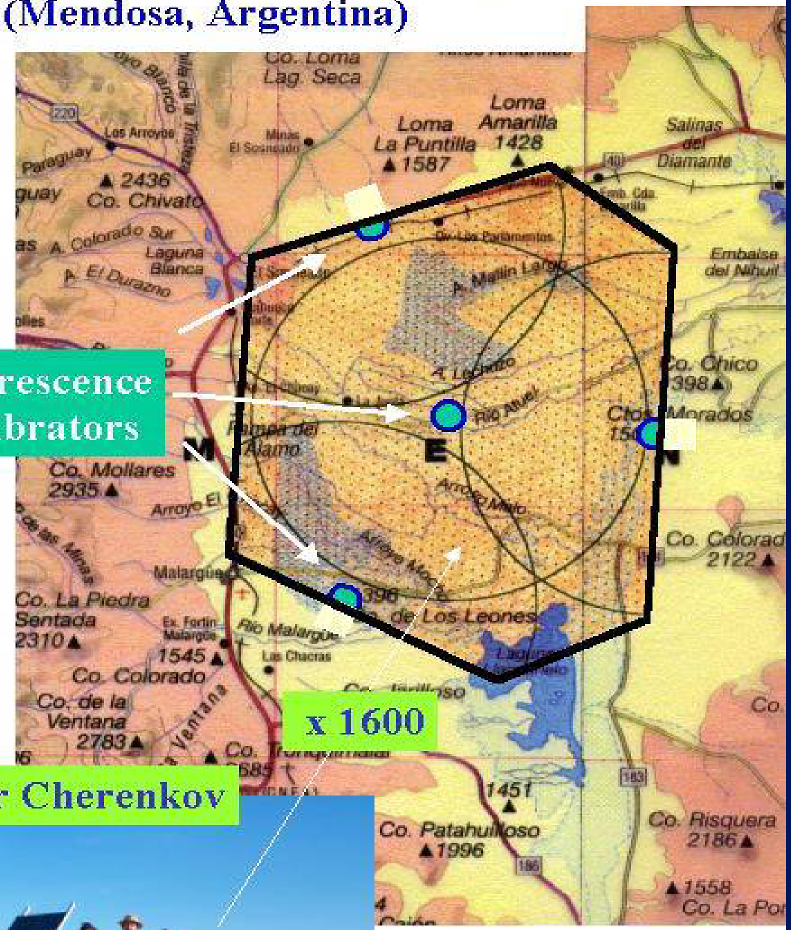
AUGER

~40× AGASA





Southern hemisphere Auger
(Mendosa, Argentina)



7000 km² str
by water Ch..
from 2005?

ASHRA

- **Target objects**
  - Precise ID of EHECR sources
  - Discovery of VHE phenomena
    - VHE ν sources
    - Transient sources
    - New particle interaction
- **Imaging air Cerenkov & fluorescence with CCD**
  - All-sky Survey => 2π sr
  - Higher resolution => 1 arcmin
  - Simultaneous observation
    - TeV γ,
    - EHE p/γ,
    - VHE ν

- **ASHRA station**
  - 3 stations in a desert (phase2)
  - 12 telescopes / station
  - All-sky (2π sr) / 80M pixels

Plan & Targets of ASHRA

2002	2003	2004	2005	2006	2007

R&D

Phase 0

1st TeV γ obs. with II+CCD

Crab peak

Production & test of prototype sub-telescope

Phase 1

1+1/3 station ($5M)

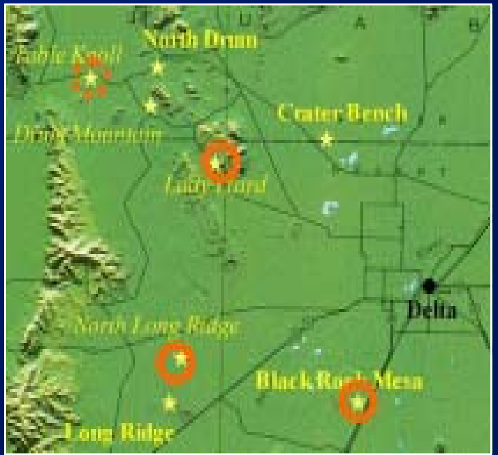
All-sky survey

TeV γ , EHE ν ,EHECR

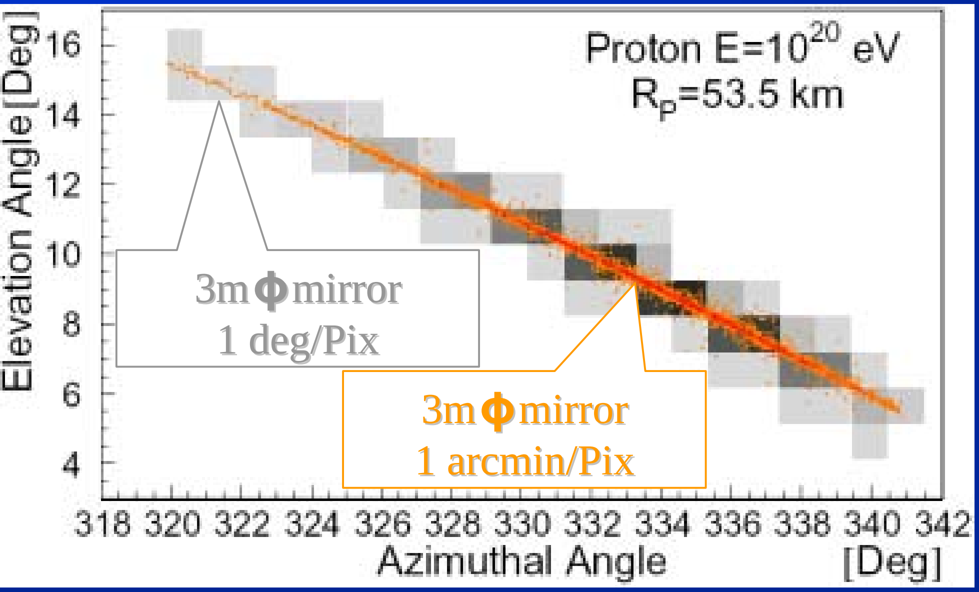
Phase 2

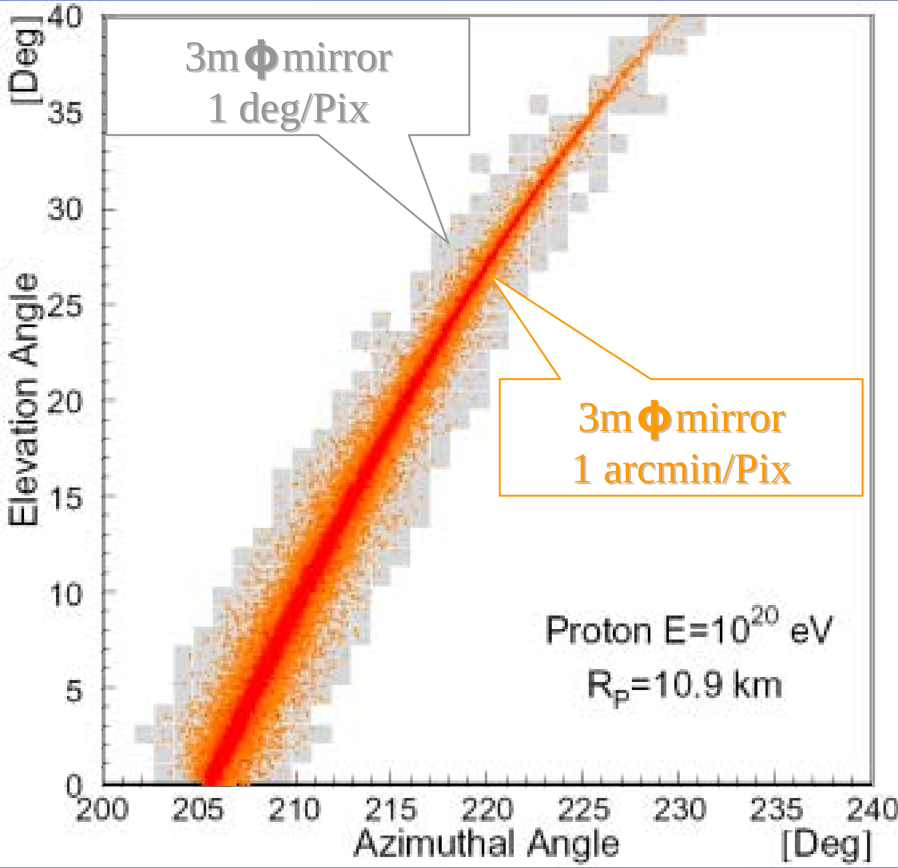
- +2 station (+$10M)
- Full all-sky observation

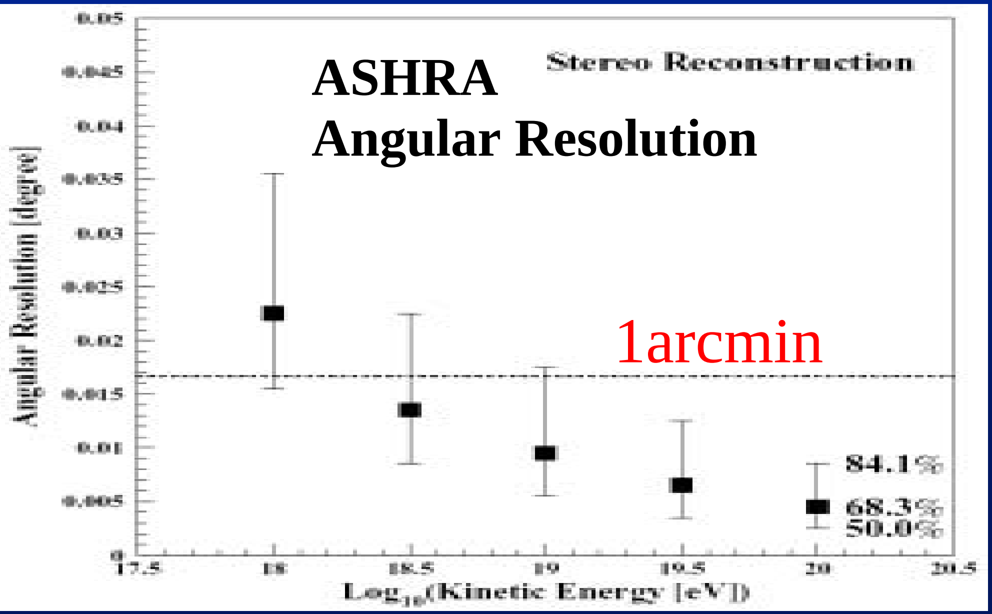
TeV γ、EHE ν、UHECR



Pixel resolution & angular resolution



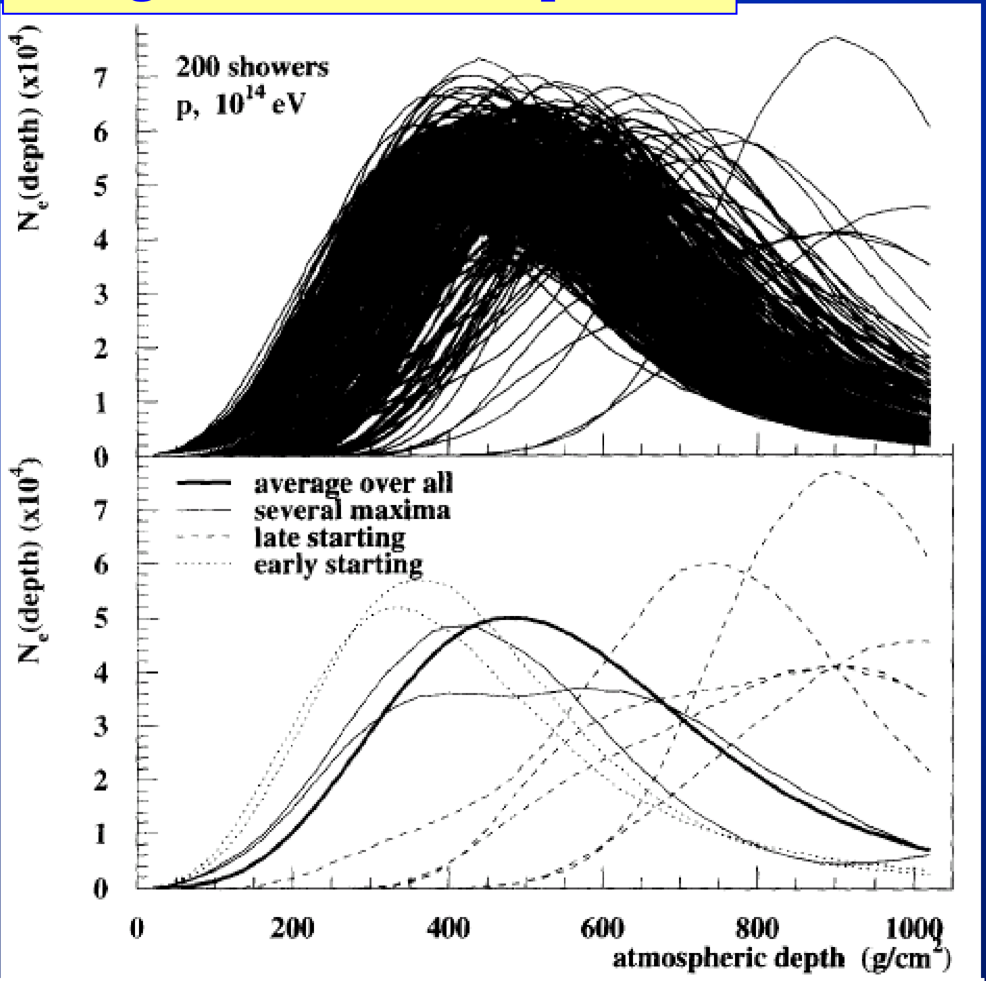




- < 1 arcmin at E > $10^{18.5}$eV
- 0.3 arcmin at E ~ 10^{20}eV

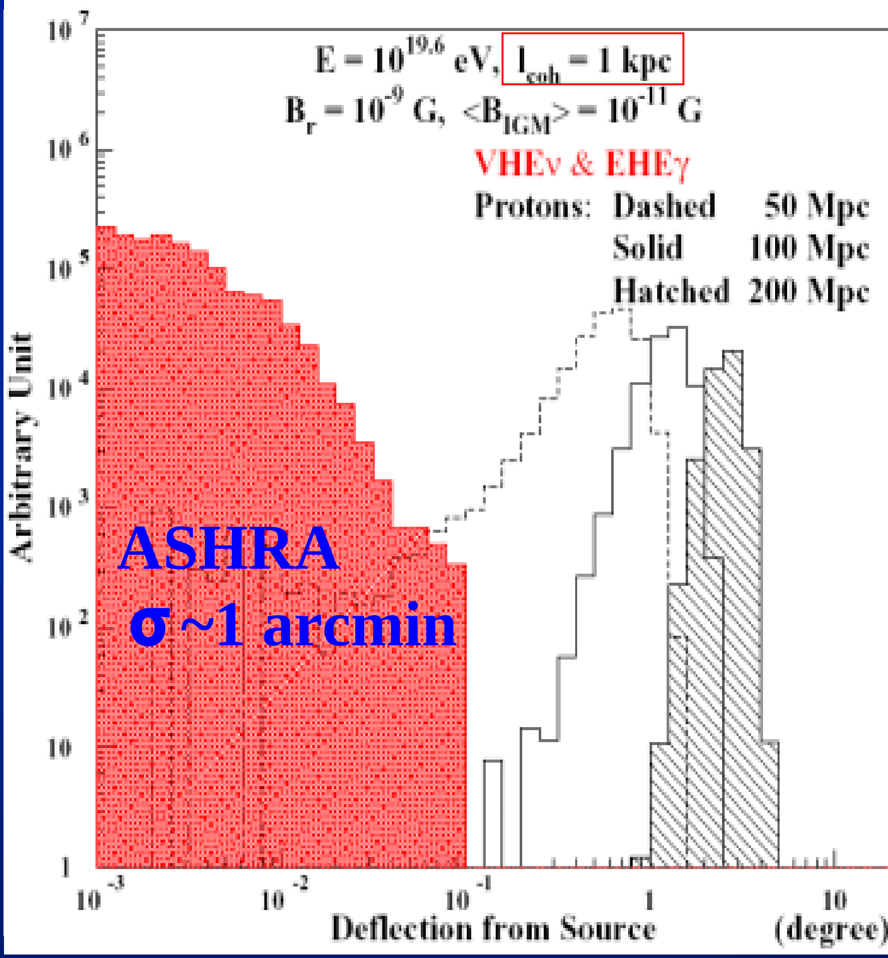
Charge ID for particles from point source

Longitudinal development



Knapp,Nucl.Phys.B (Proc.Suppl.) 75A (1999) 89

Magnetic deflection from source

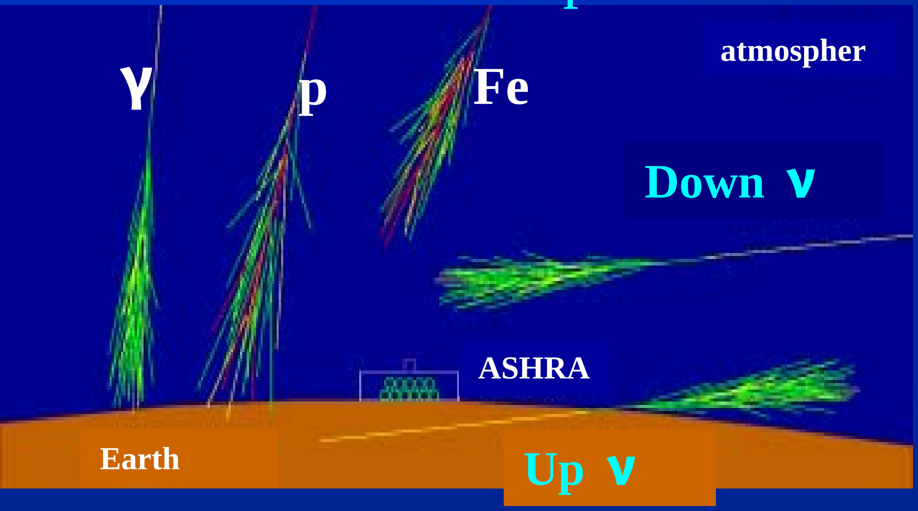


=> Shower fluctuation is too serious to distinguish between p and γ.

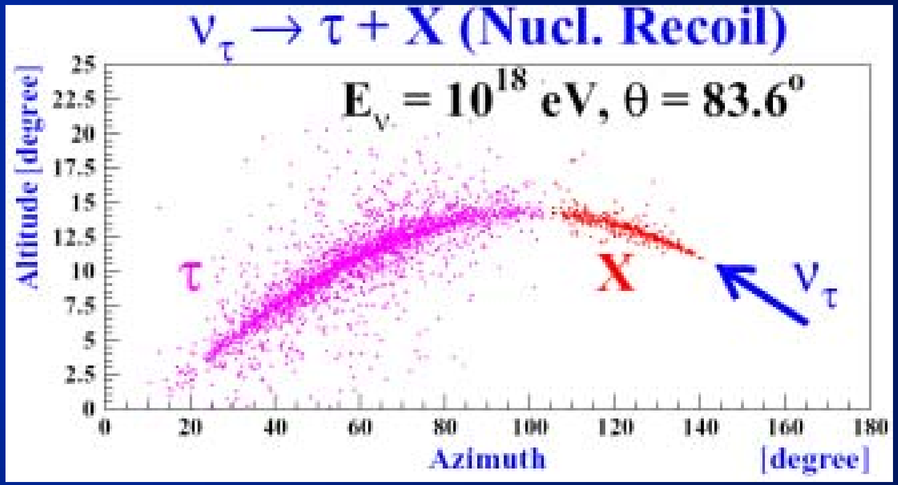
ASHRA precise resolution
=> Substantial charge ID

ν ID & tau- ν ID

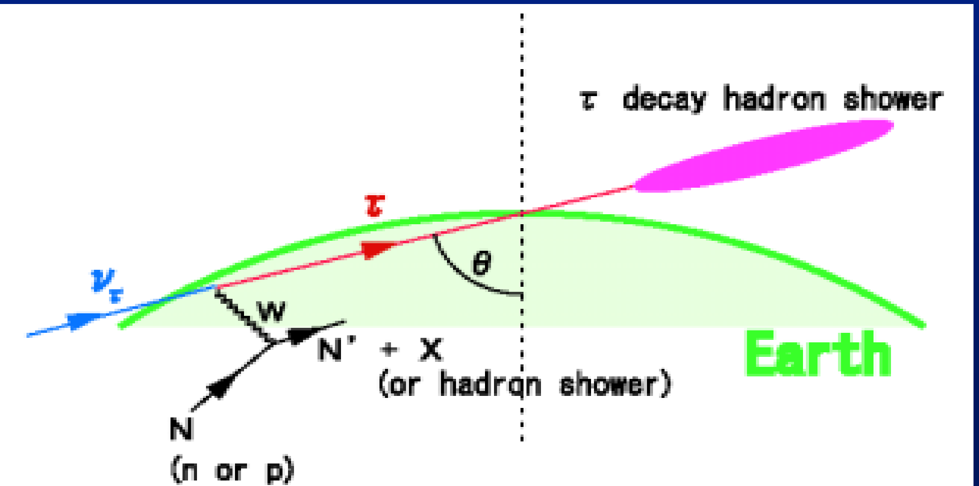
ν ID with AS development



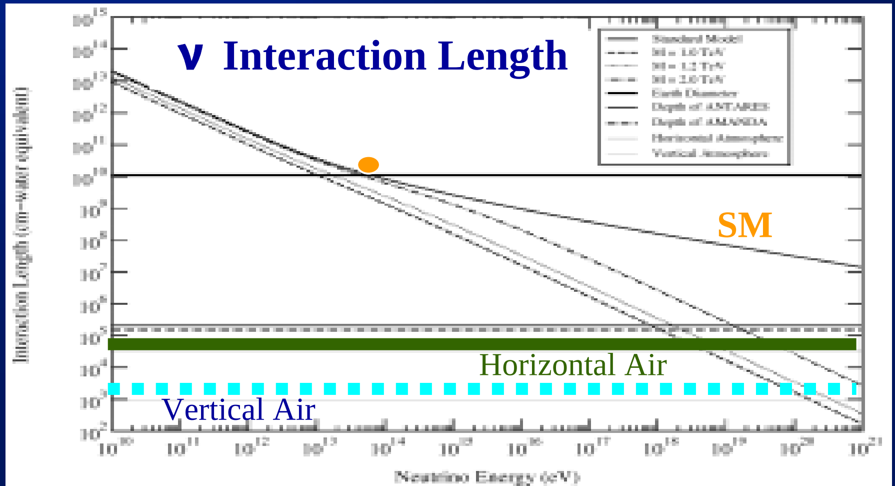
- Double Bang by Tau Neutrino



- Earth-skimming Tau Neutrino

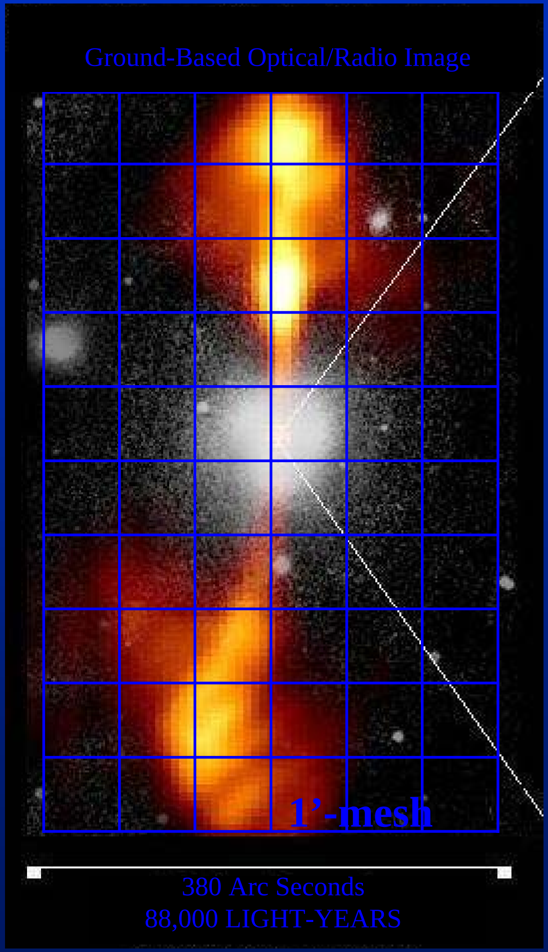


- Extra Dimension



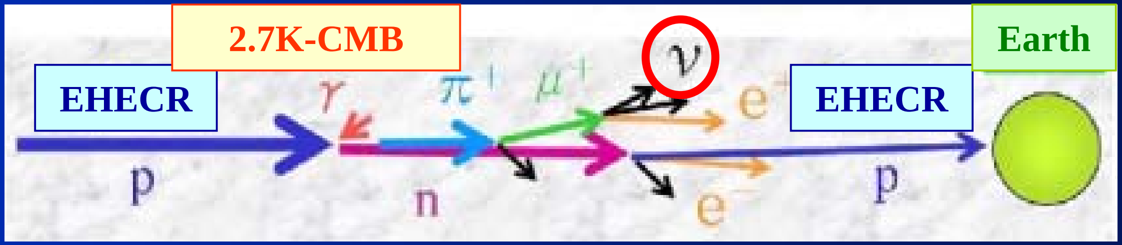
VHE neutrino objects

- p accelerators

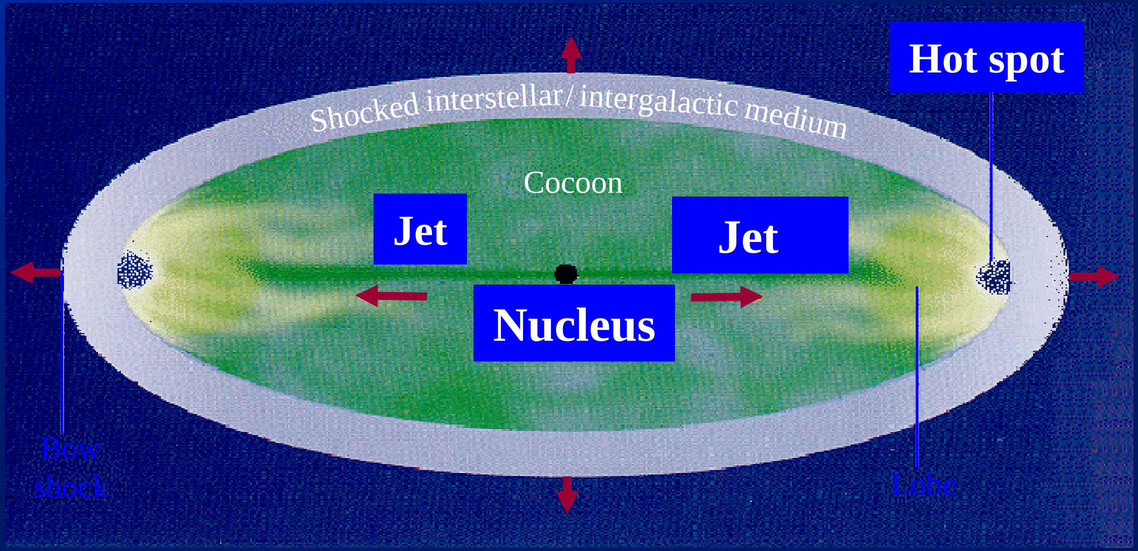


NGC4261

- GZK neutrinos



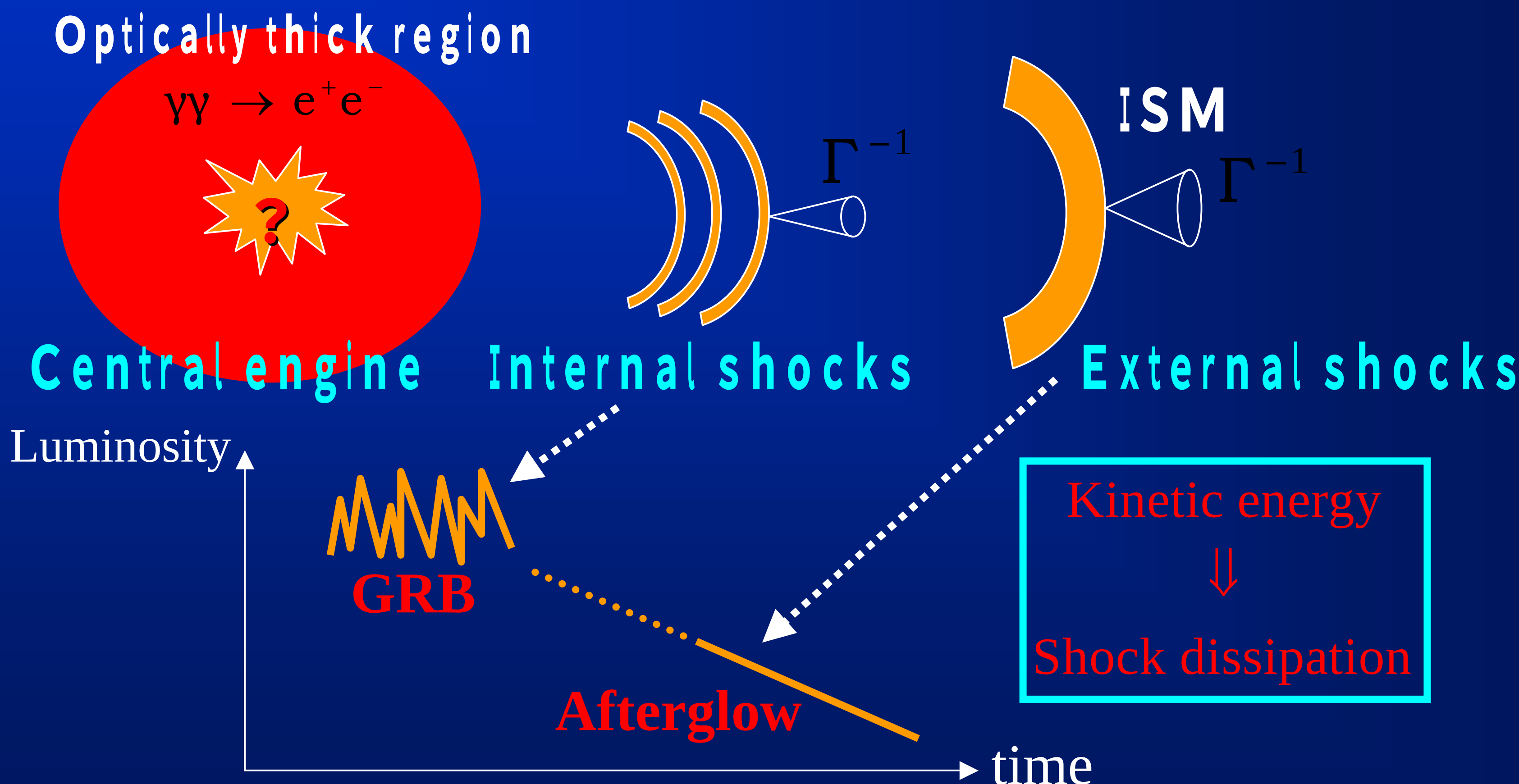
- Optically thick objects



Gamma Ray Burst

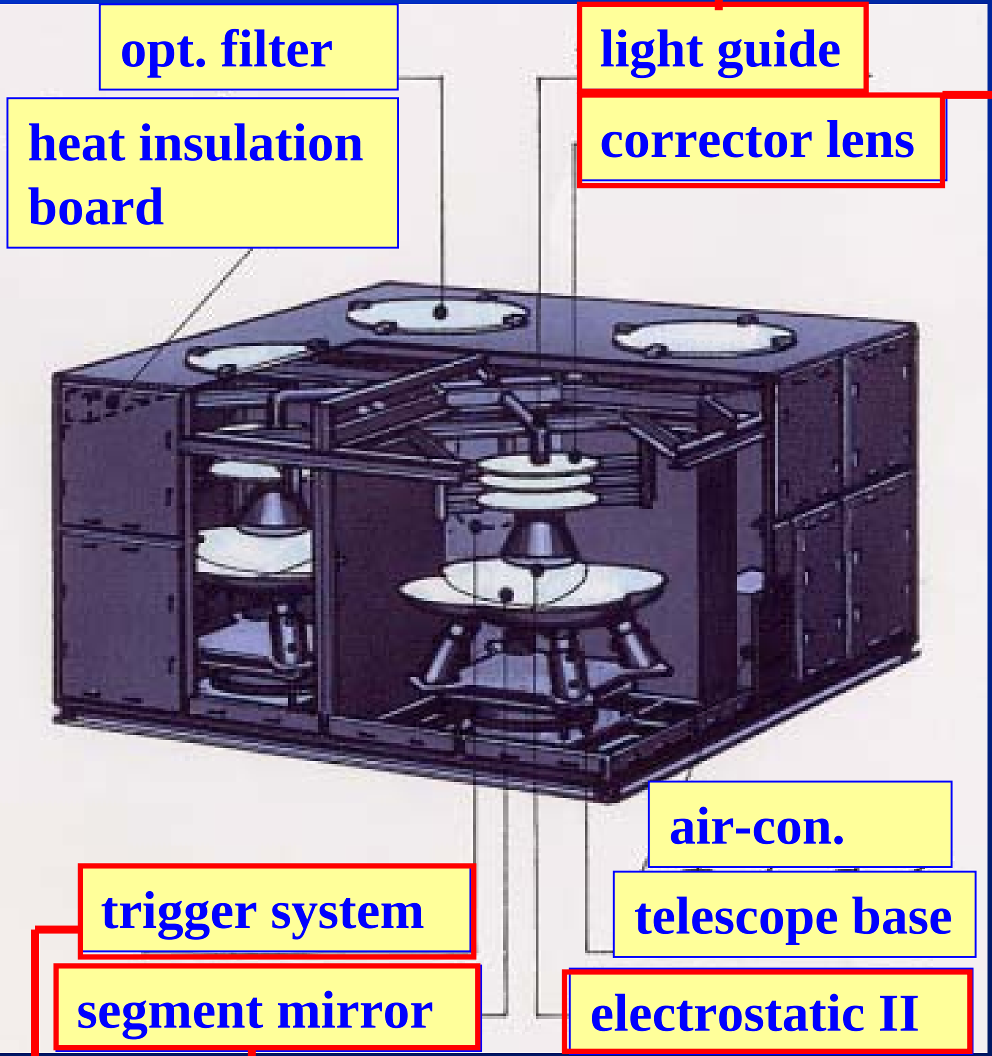
Beppo-SAX identified GRB with ~3 arcmin. resolution.

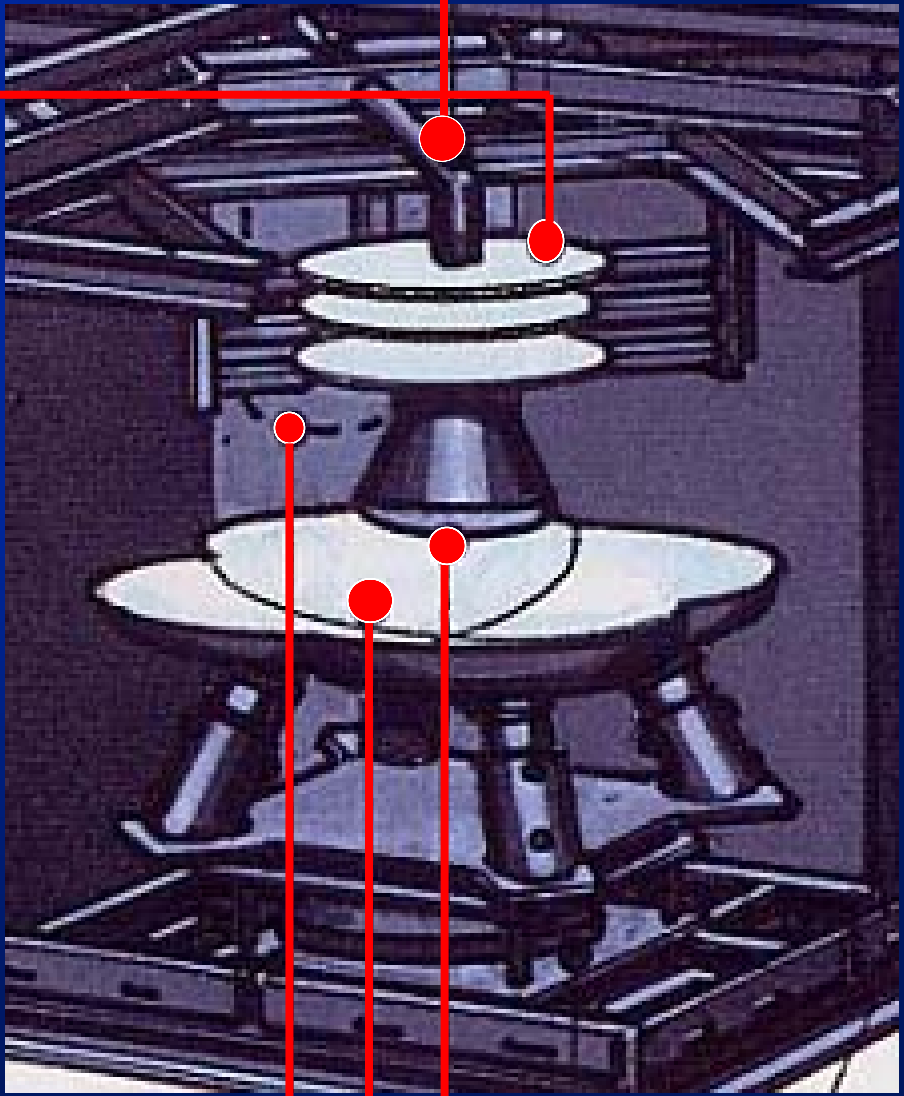
=> Multi-wavelength Analysis (1997~)

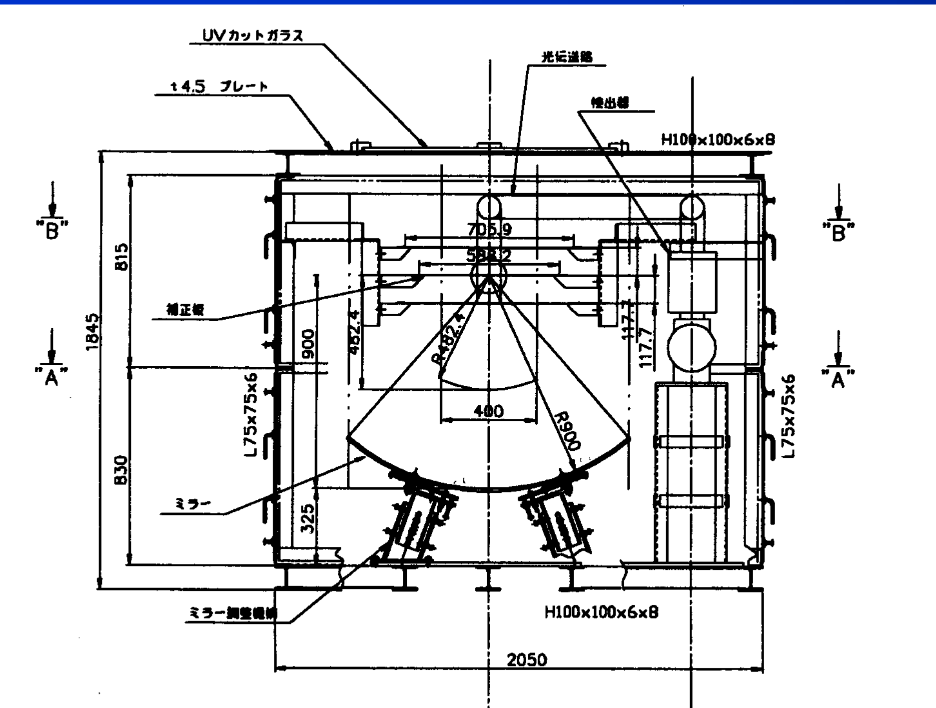


ASHRA all-sky **γ** & **ν** survey with ~1' reso. => New trigger

Optical System of ASHRA Telescope

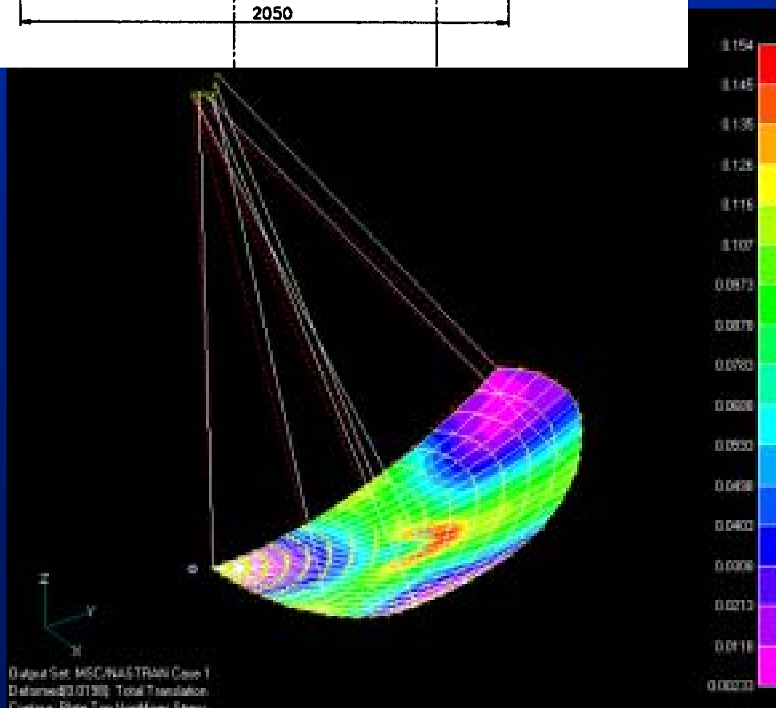


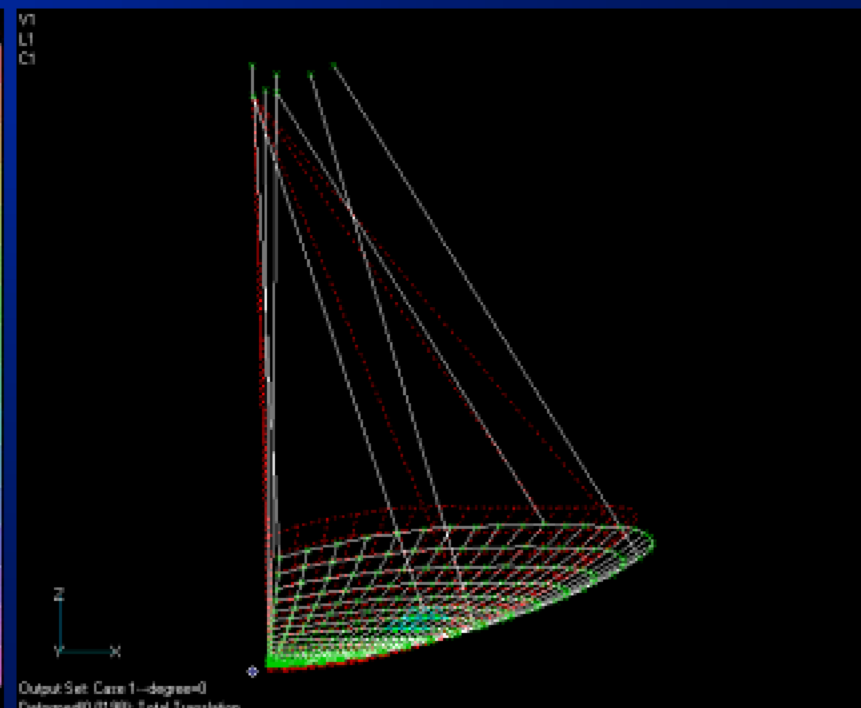




ASHRA proto-1 Structure Analysis

Complete set of sub-telescope will be ready for test at the end of FY2002.



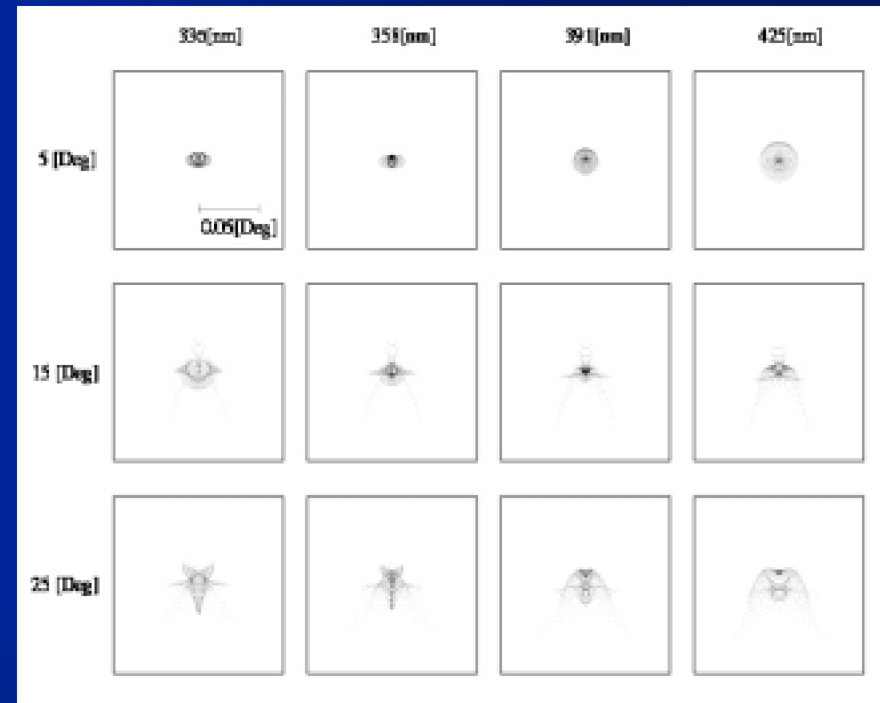


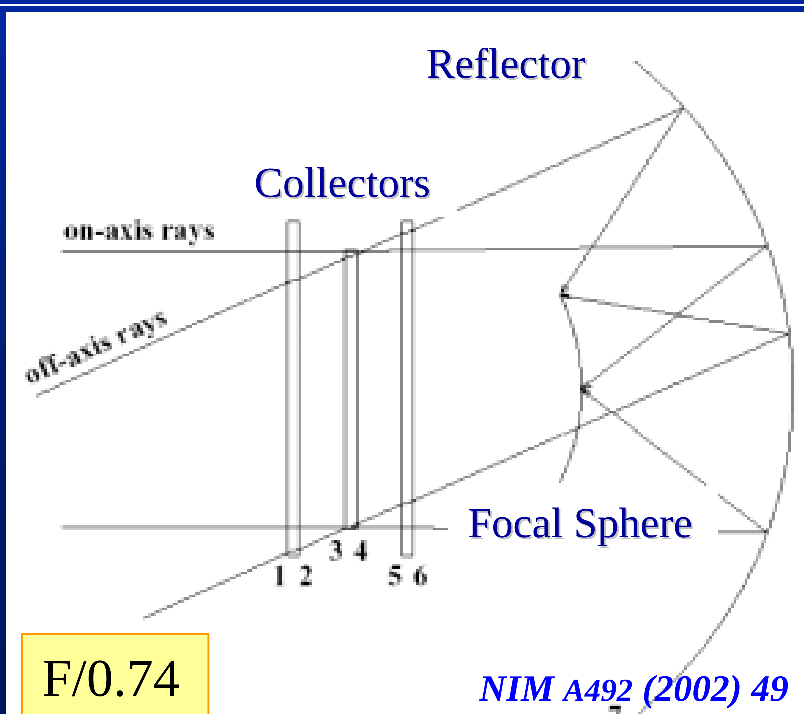
Optics with FOV 50° & Spot size 0.01°

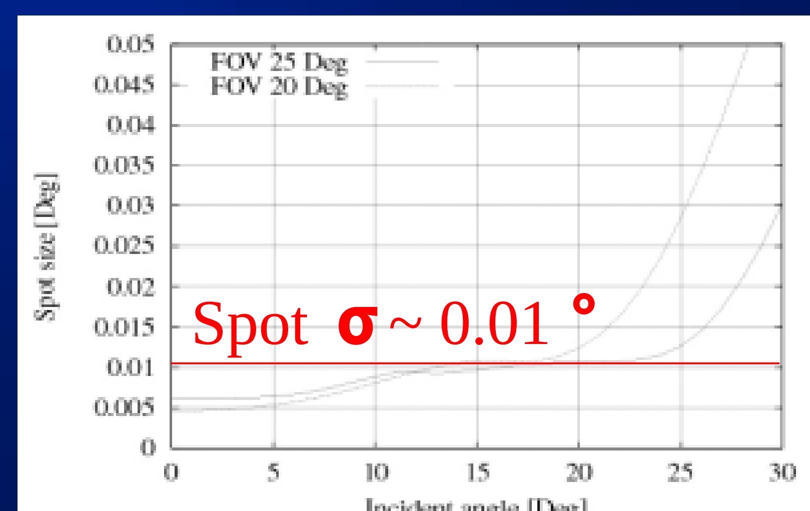
- Modified Baker-Nunn
  - 3 collector lens
  - Spherical reflector
  - Focal sphere

    => Feasible fabrication

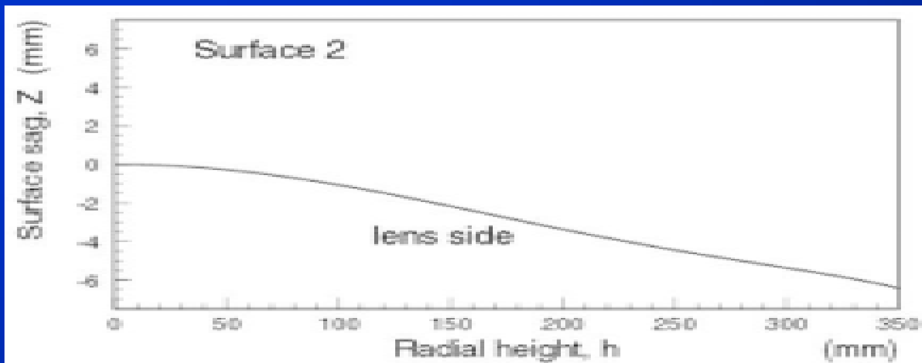
    => Flexible optimization

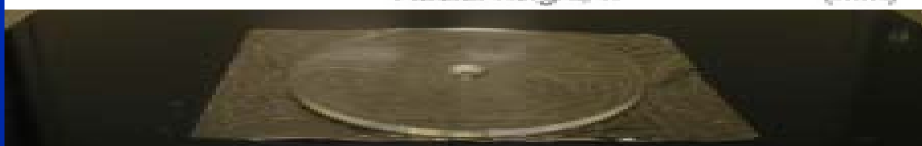


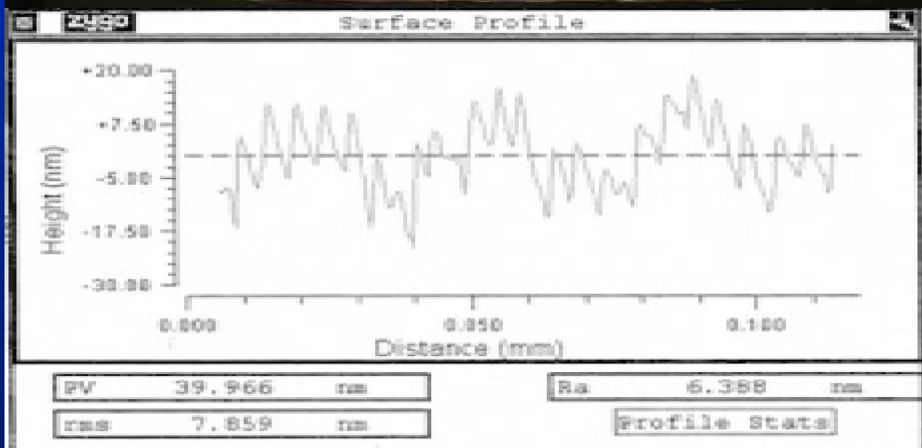


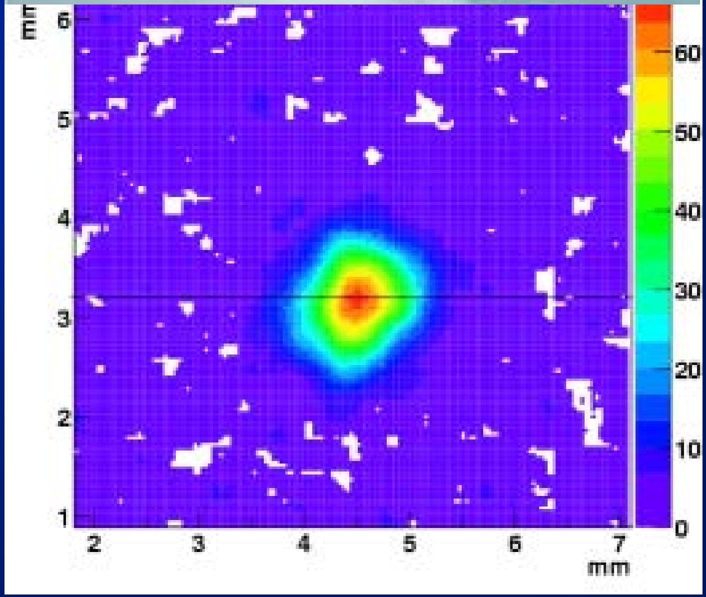


Prototypes of optical elements









- Roughness 6.4nm << $\lambda/8 \sim 40$nm
- Internal loss negligible + 7% reflectivity
- Anti-reflective coat => reflectivity < 0.5%.

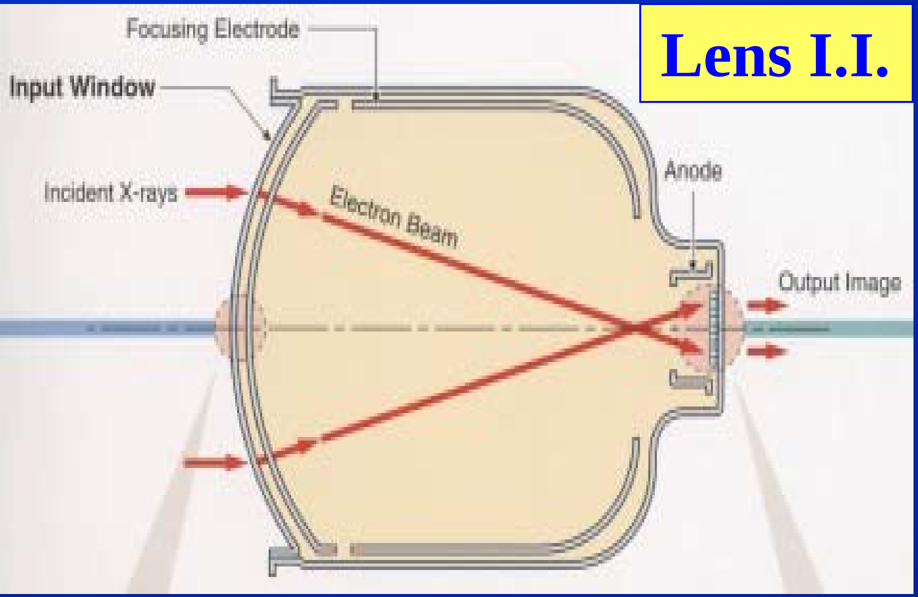
- **Spot $\sigma \sim 0.24$mm < requrement**

Focal sphere =>

Image intensifier

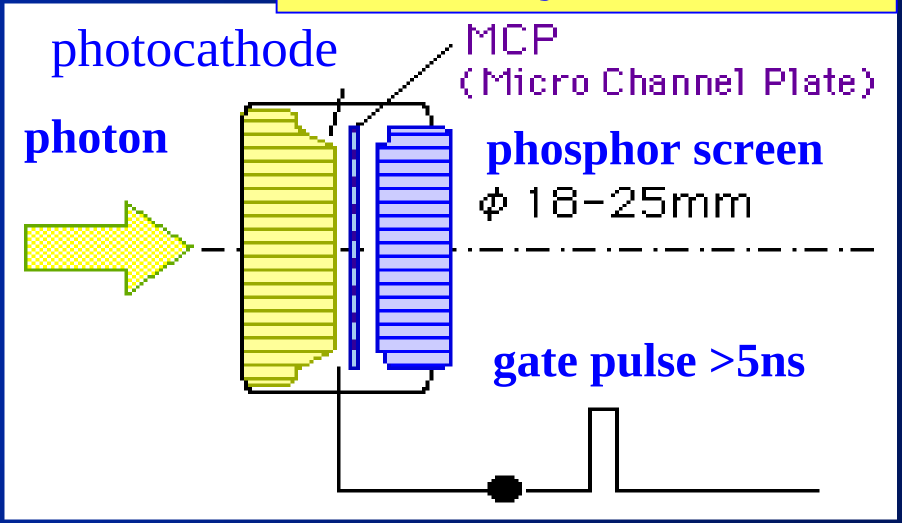
=> CCD

Lens I.I.

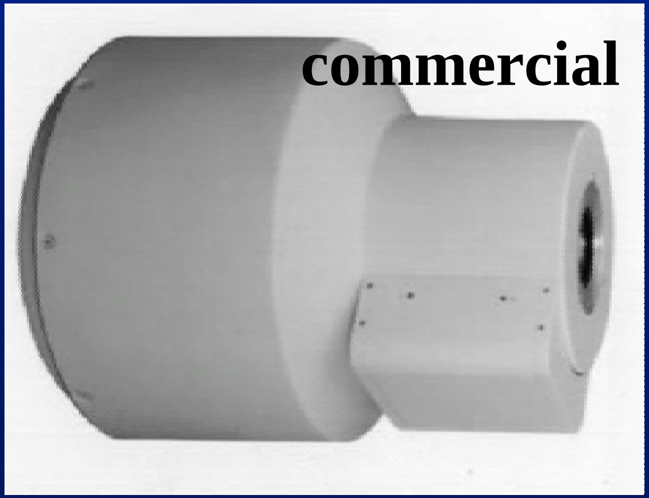


- 4.6 Lp/mm => **σ** ~70 **μ** m @ input surface
- magnification factor ～ 10

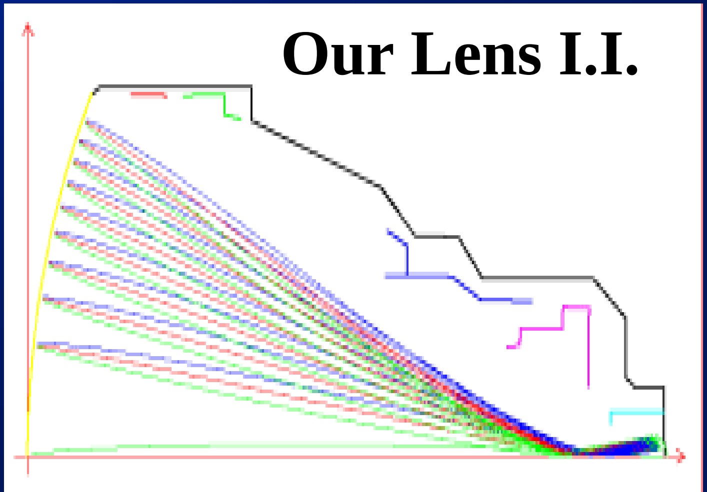
Proximity focused I.I.



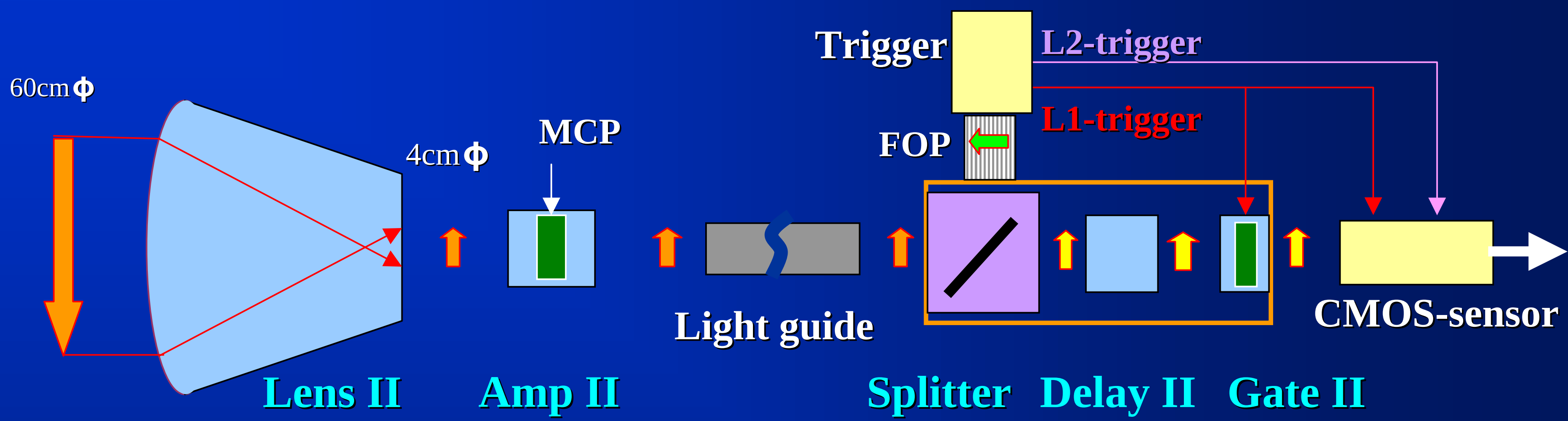
- 46 Lp/mm => **σ** ~7 **μ** m ~ CCD pix. size
- magnification factor = 1



Minimum modification of focal surface



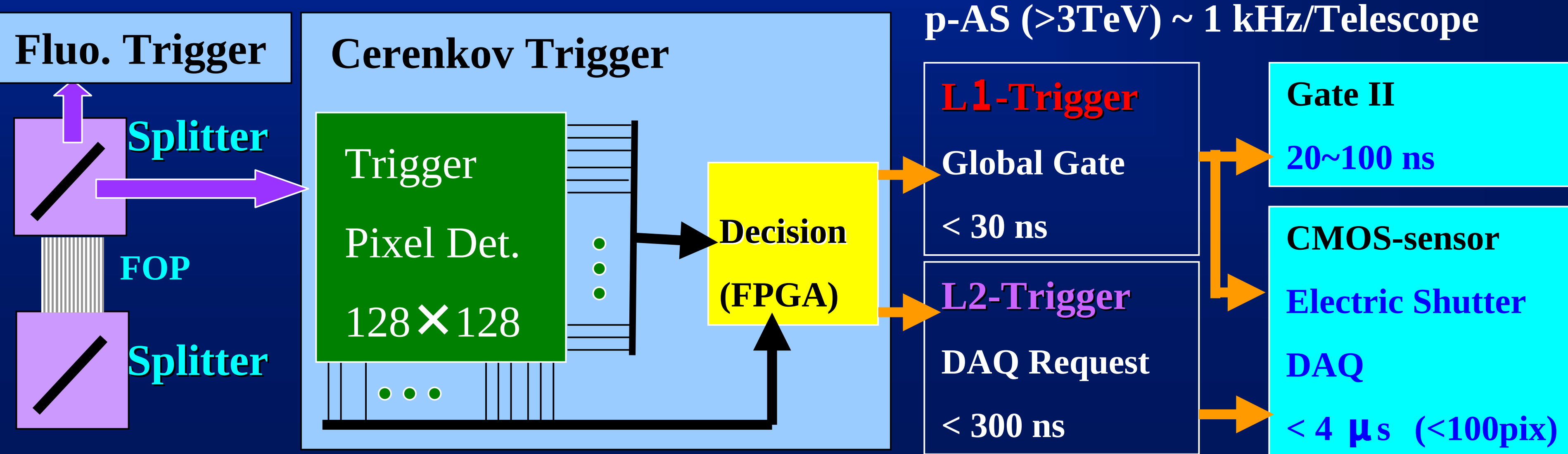
Photoelectric Image Pipeline



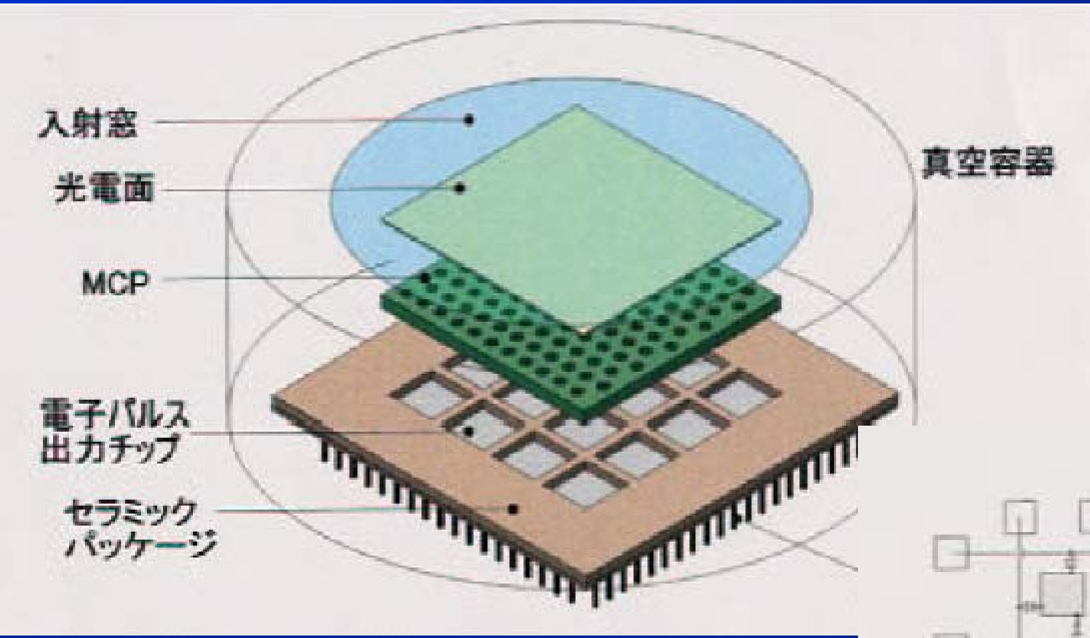
Combined self-trigger

Night Sky BG ~ 0.02pe/10ns/TrgPix

p-AS (>3TeV) ~ 1 kHz/Telescope



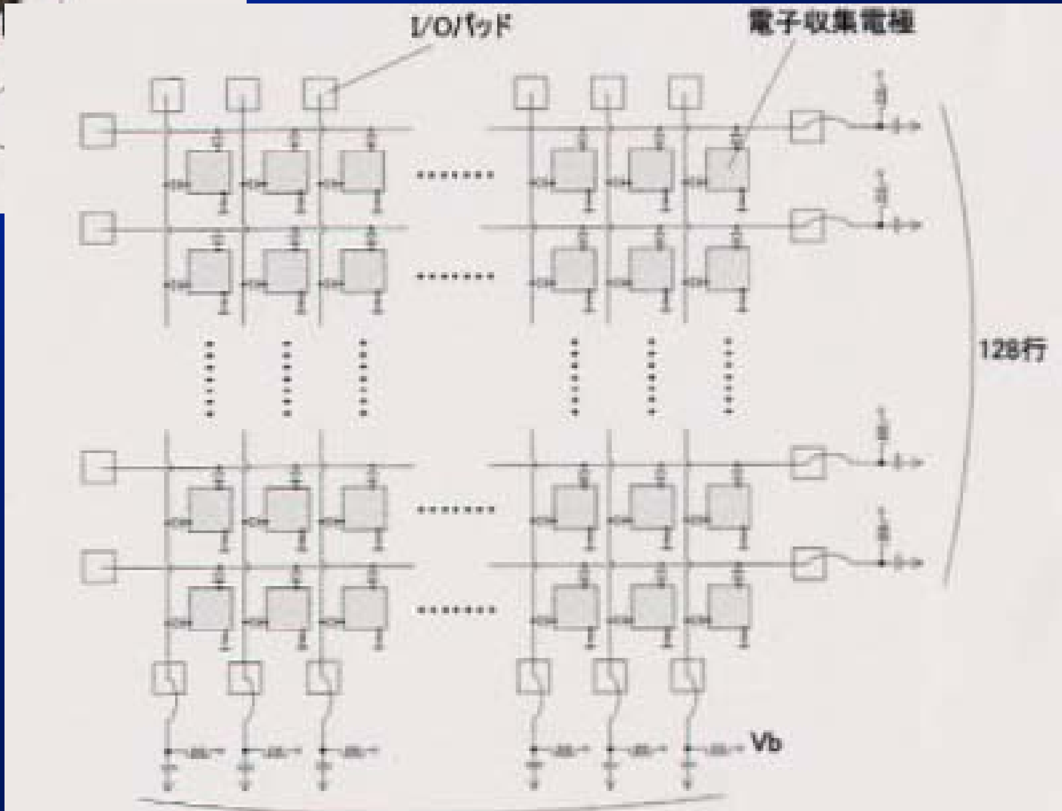
Trigger imager



128✕128 pixels

Pad readout

Projection onto X & Y



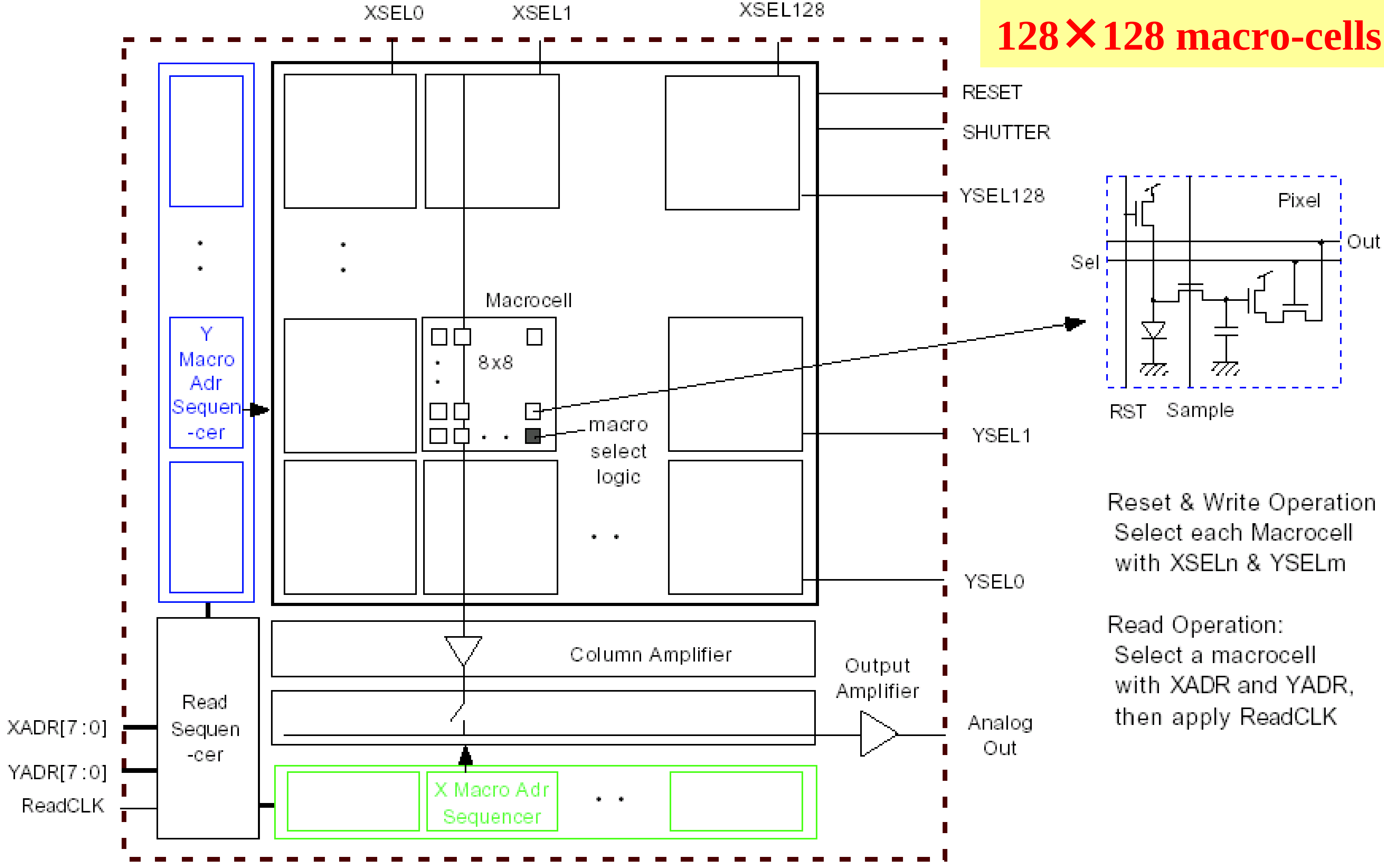
CMOS Image Sensor with 2D e-shutter

XY address

2D e-shutter

Macro-cell readout

128×128 macro-cells

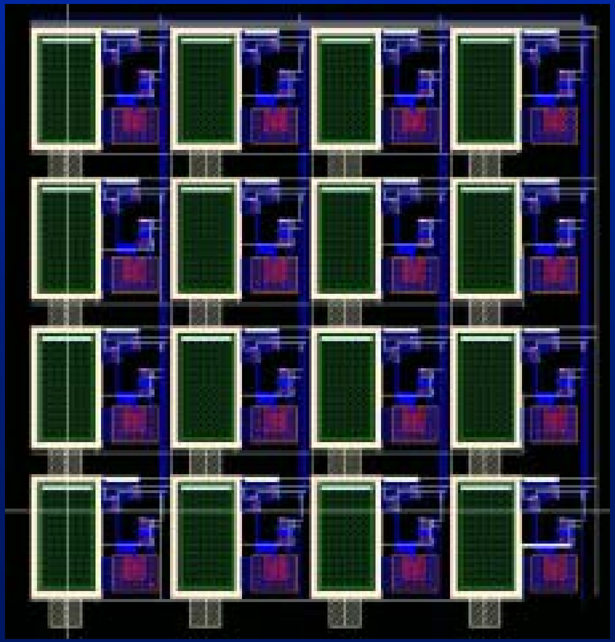


Reset & Write Operation :
Select each Macrocell with XSELn & YSELm

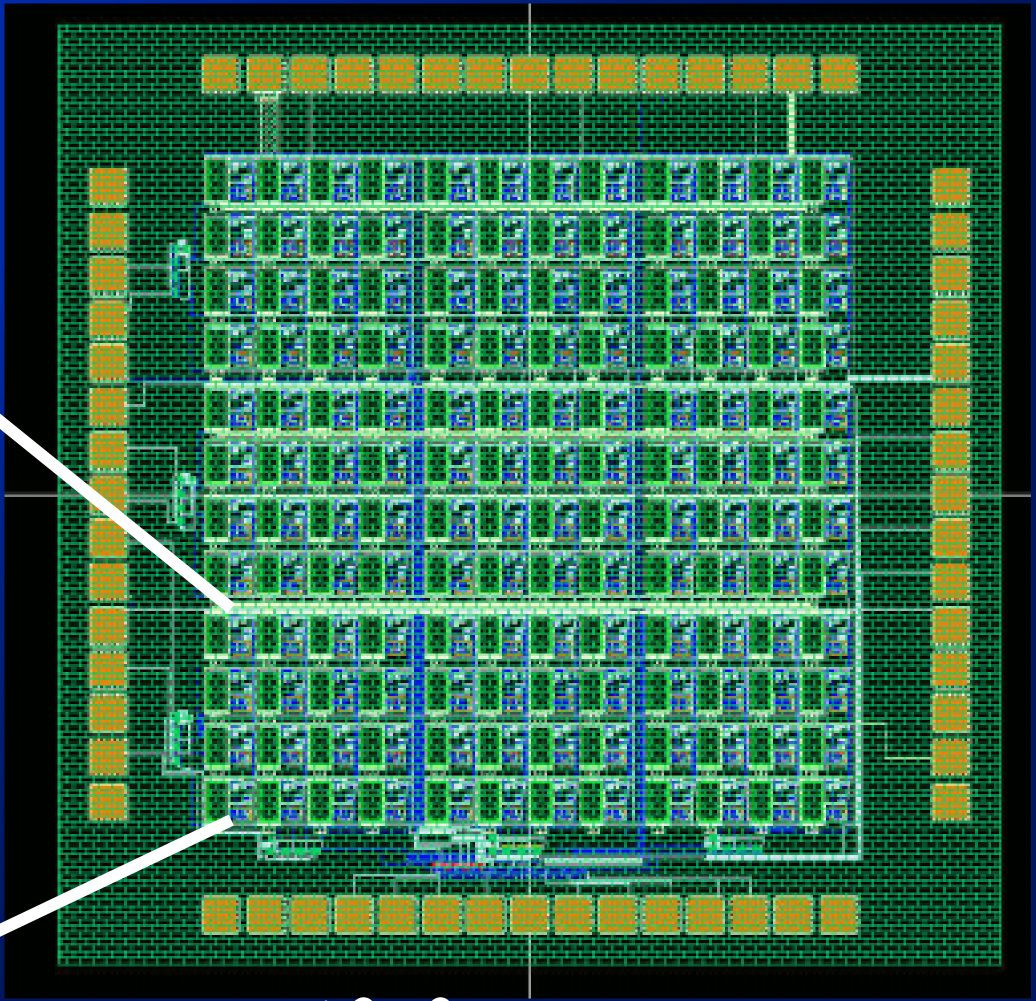
Read Operation:
Select a macrocell with XADR and YADR, then apply ReadCLK

Prototype of CMOS Image Sensor

- Submitted to VDEC
  - 3 x 3 macro-cells
    - Unit of (Reset, Shutter) & Readout
  - 4 x 4 pixels/macro-cell



1 macro-cell



Total : 3 x 3 macro-cells

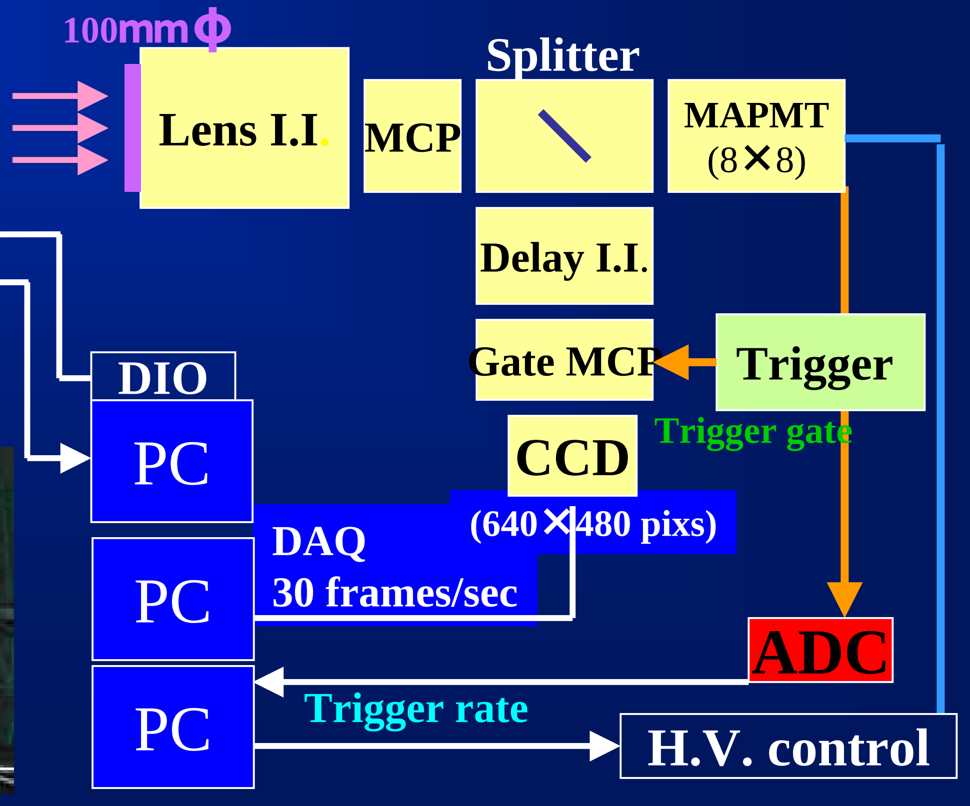
TeV γ Observation with proto-II

3mΦ-altazimuth telescope

Elec. crate Encoder, Servo-amp.

Feed-back control with RT-Linux

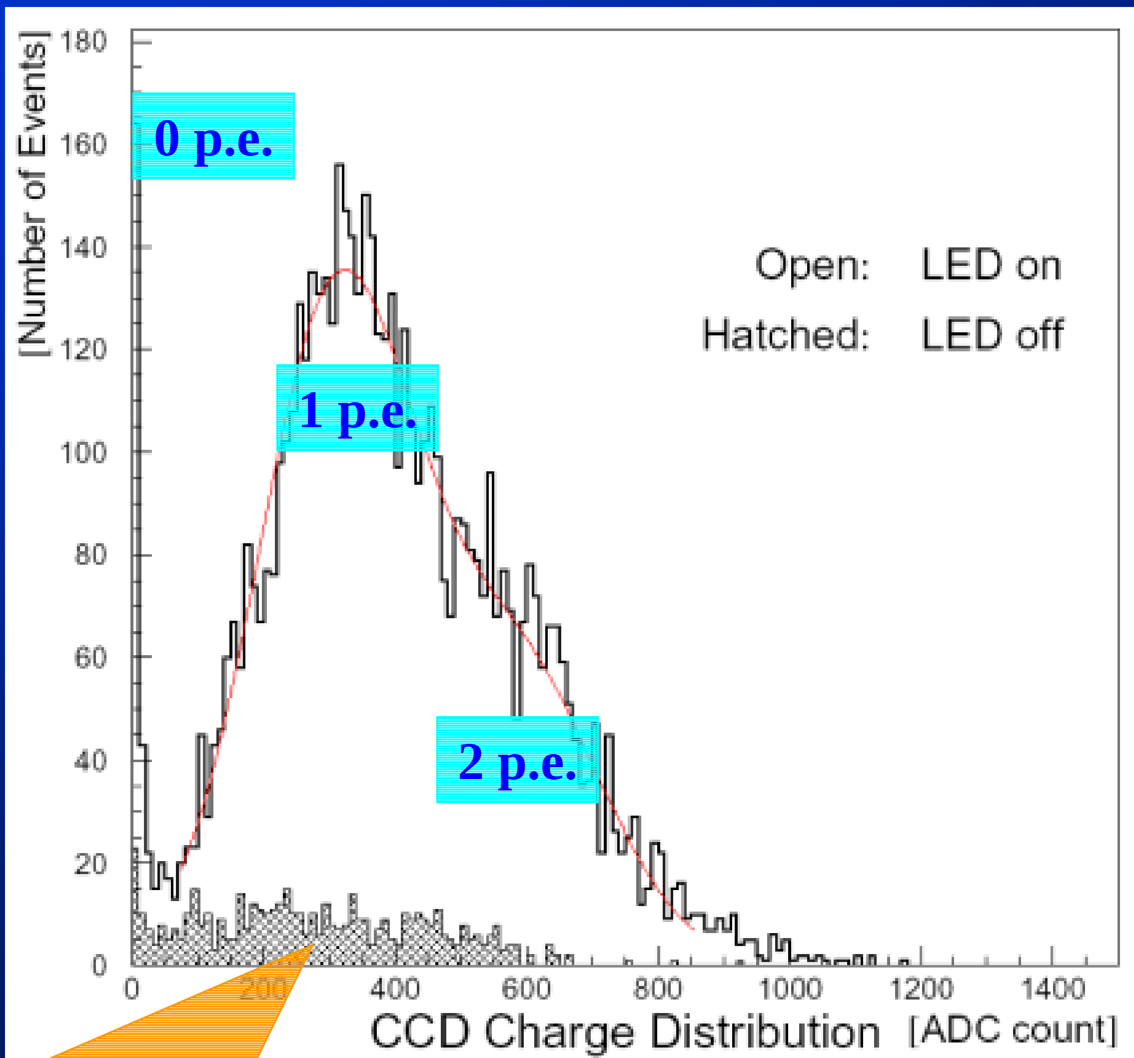
Proto-II



Electronics

near camera

Single p.e. distribution with prototype II

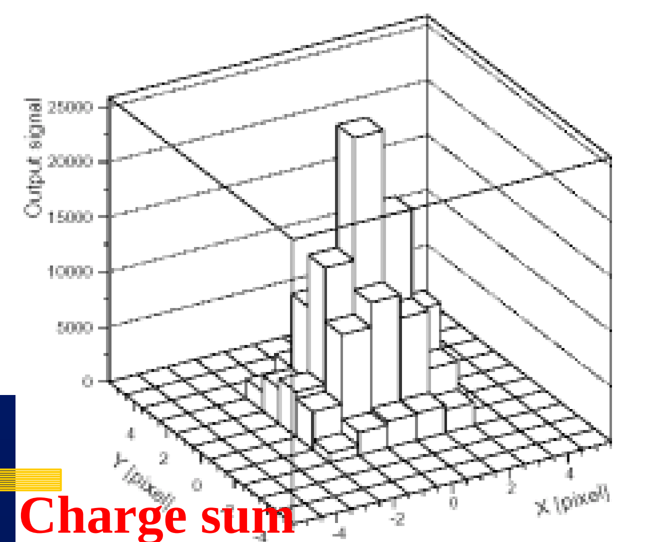


Dark current fluctuation obtained by artificial random trigger

Self-triggering ⇒

- high S/N ratio of ~30
- very good separation of single photoelectron

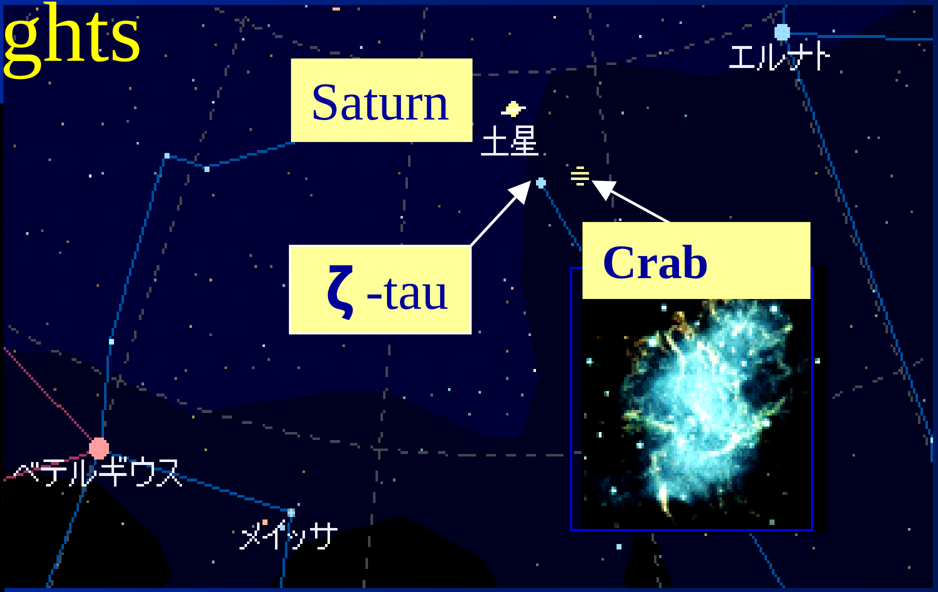
CCD image of single photoelectron



Charge sum

Tracking precision & star lights

II+CCD Image of Saturn (mag. -0.4)

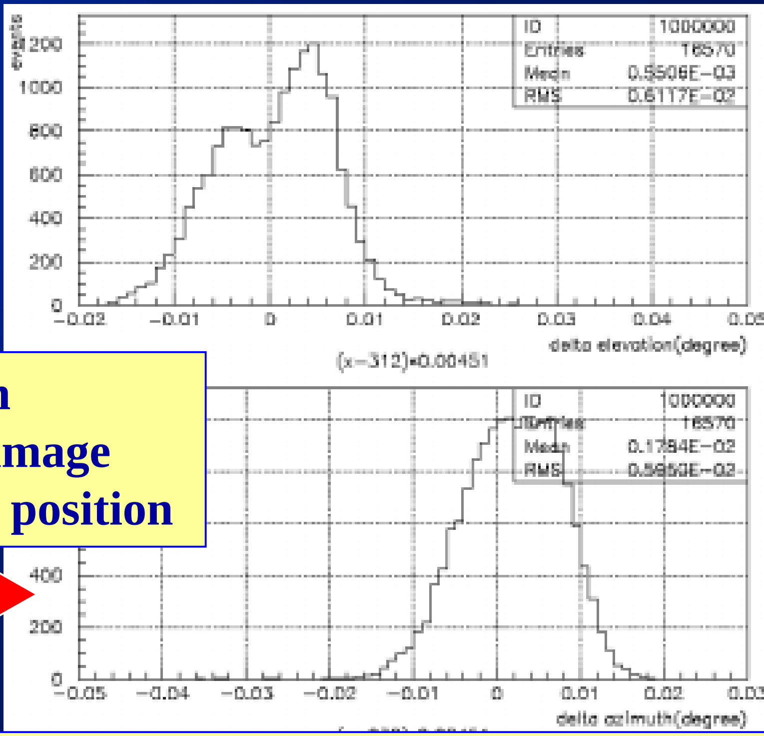


II+CCD Image of ζ -tau (mag. 3)

1.9 °

Lens-II view

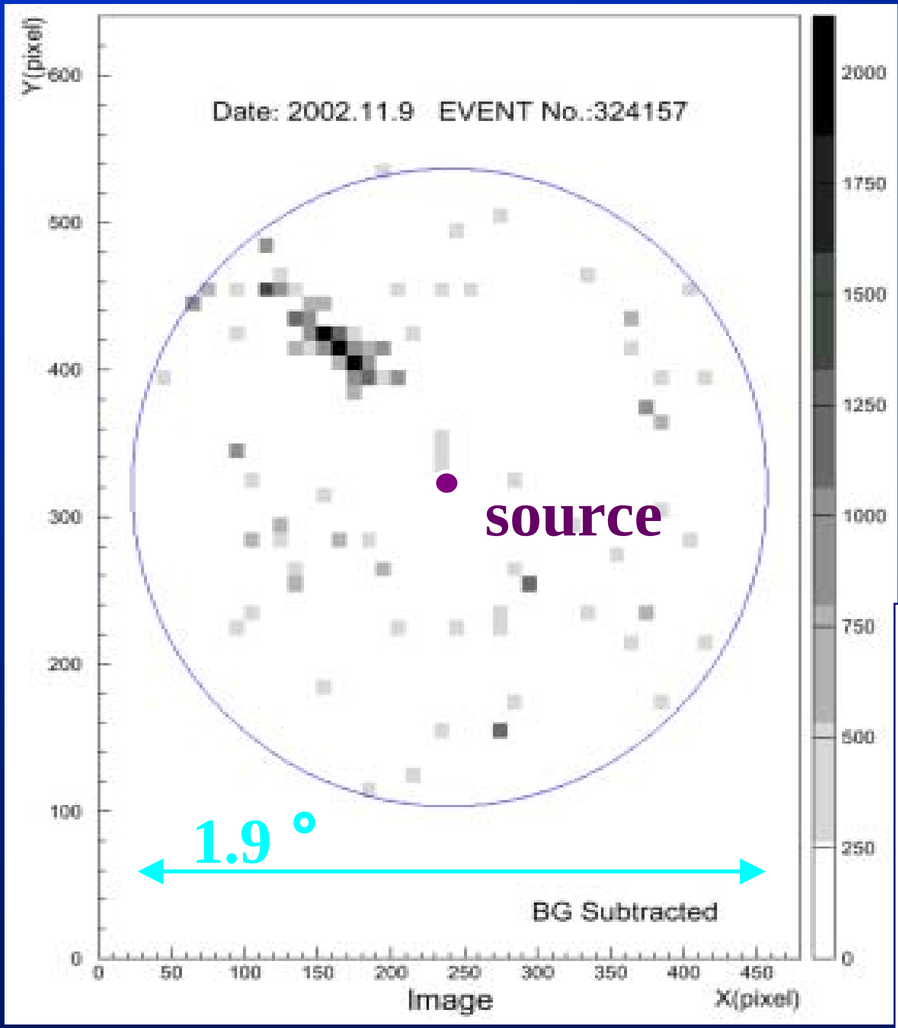
discrepancy between center of gravity of image and expected source position



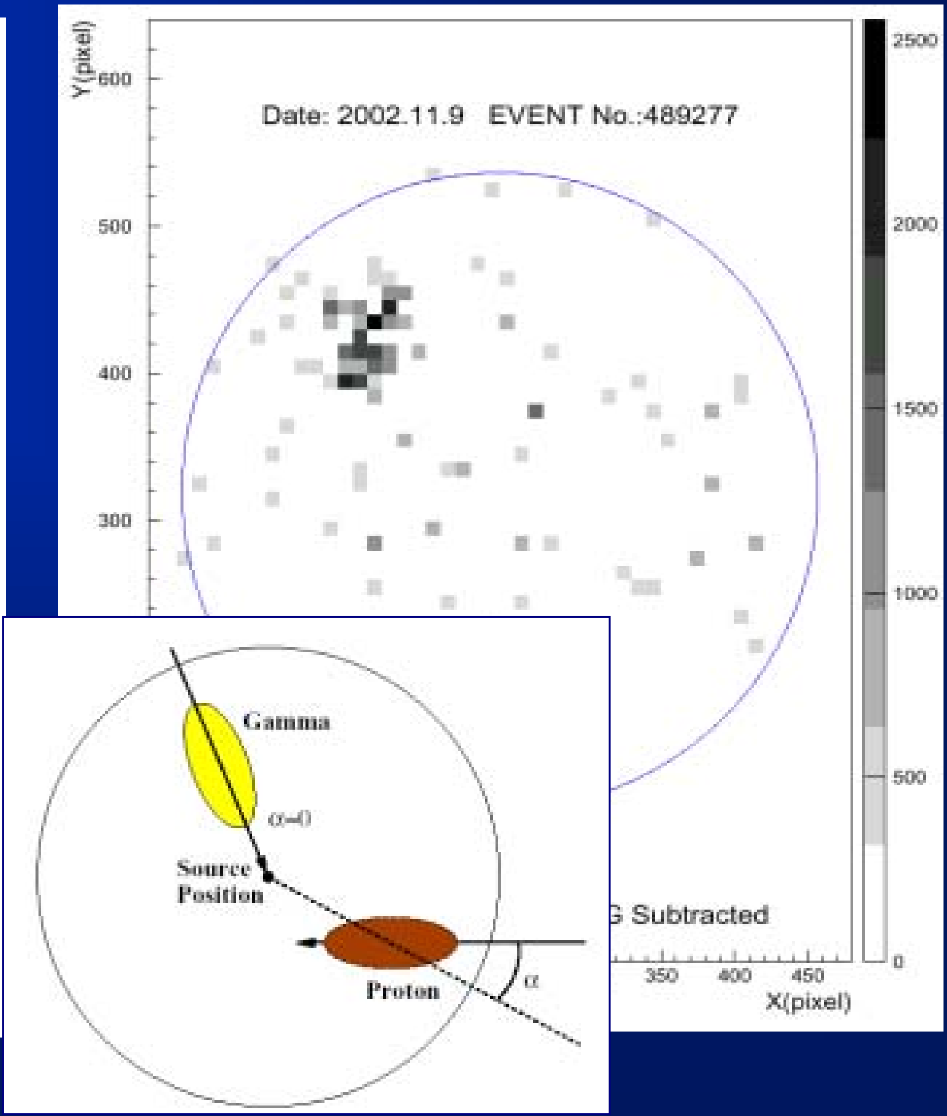
=> Tracking accuracy ~0.006 °

Shower Event Examples

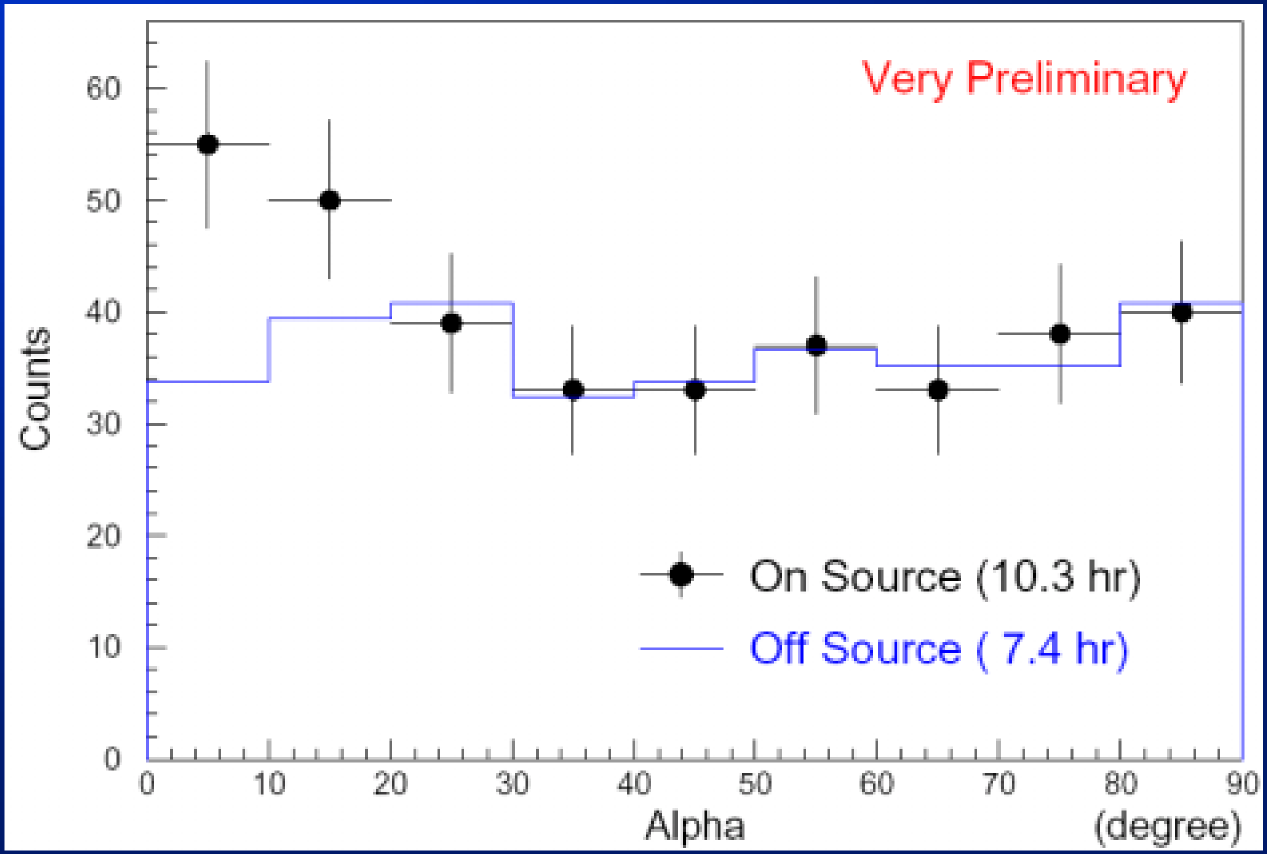
γ - like



p- like

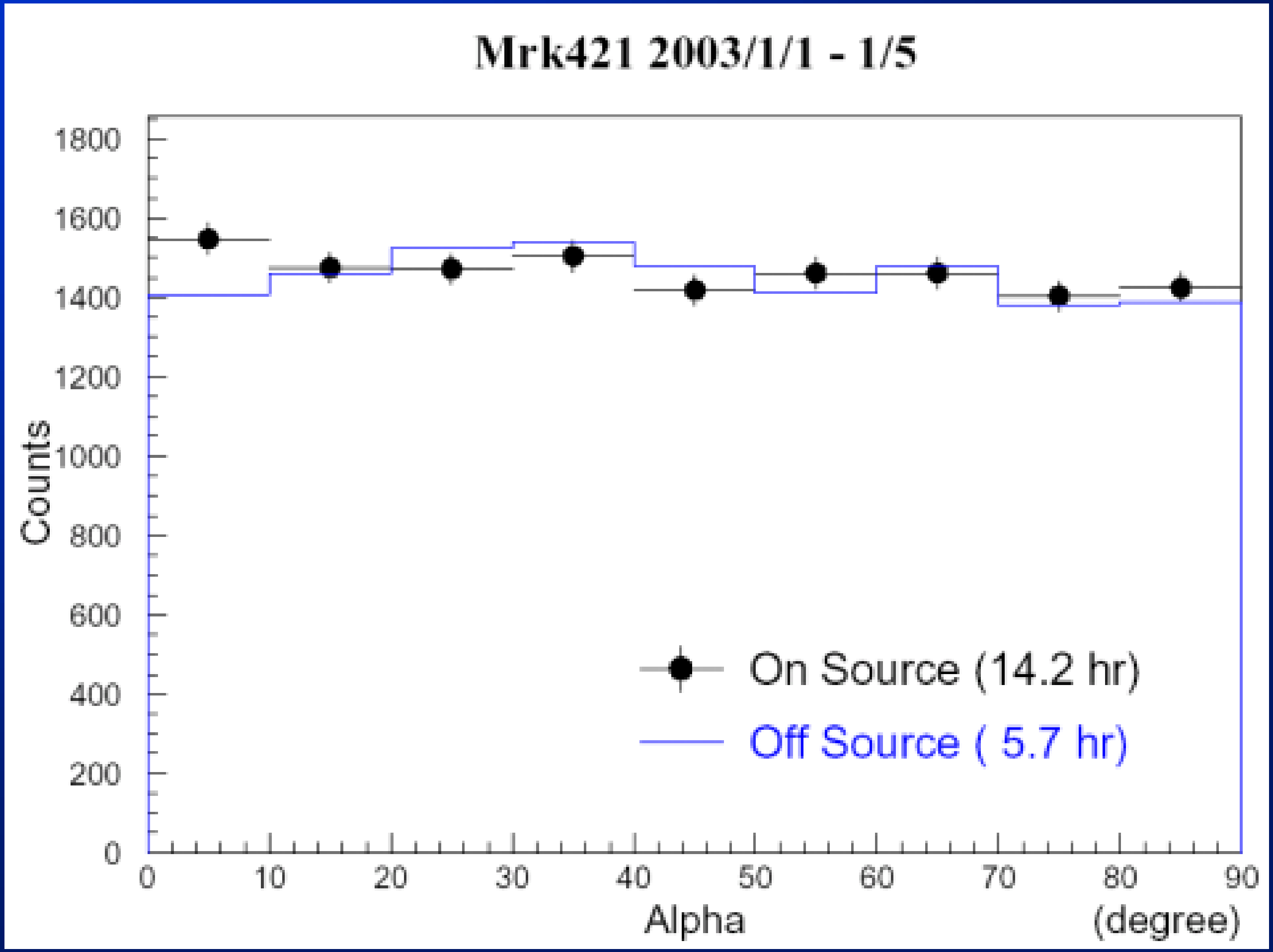


Crab observation @ Akeno with II+CCD



Note: Measured night sky BG at Akeno is 5~6 times larger than Utah.

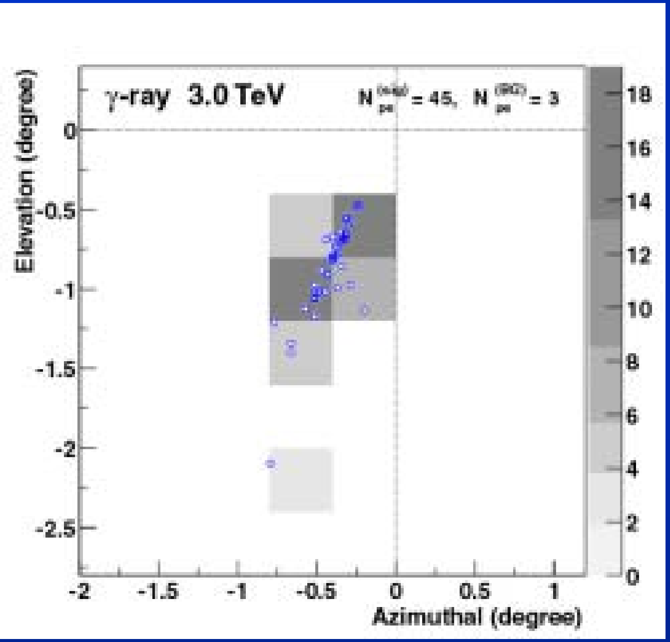
Mrk421 observation @ Akeno with II+CCD

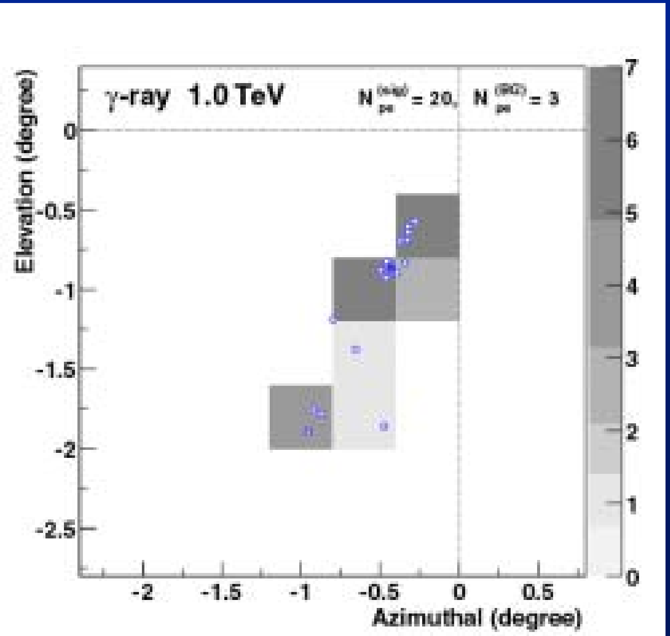


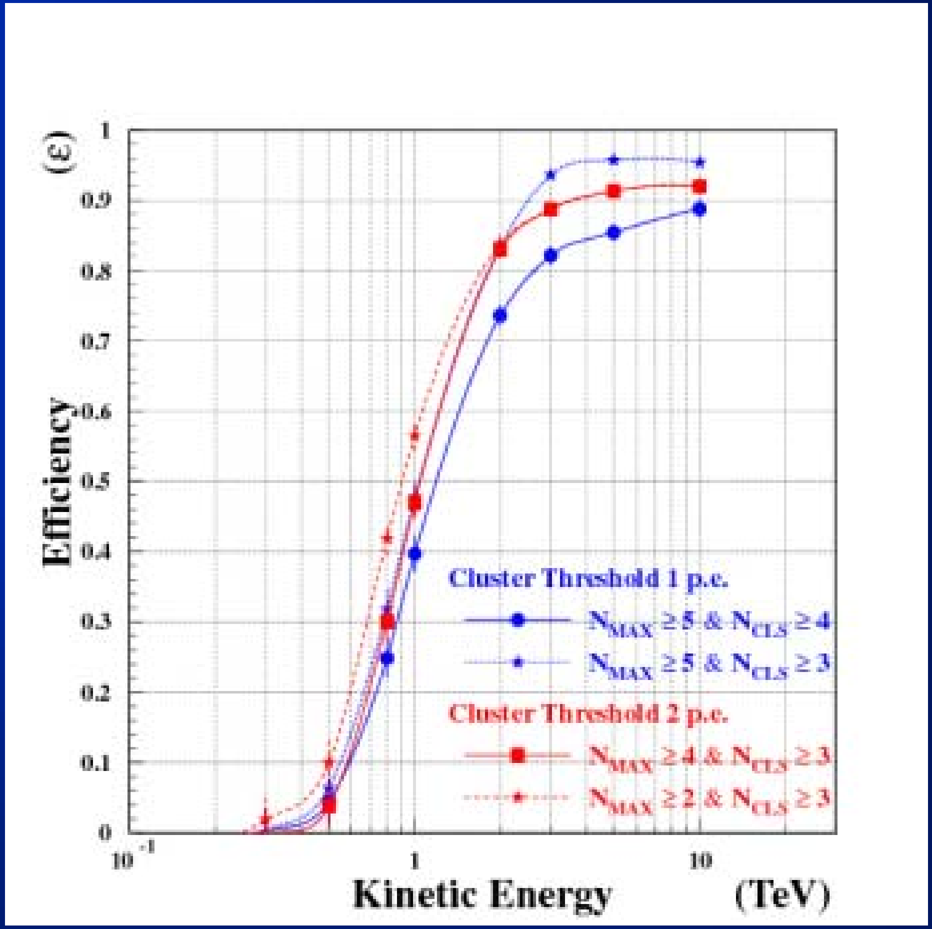
Continue the observation in Jan. – Feb. 2002.

TeV γ observation with ASHRA is really feasible.

MC performance: TeV- γ



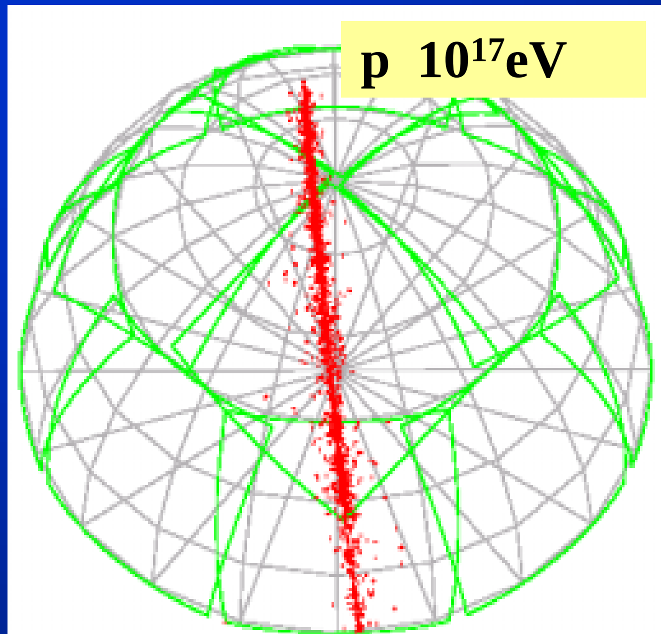


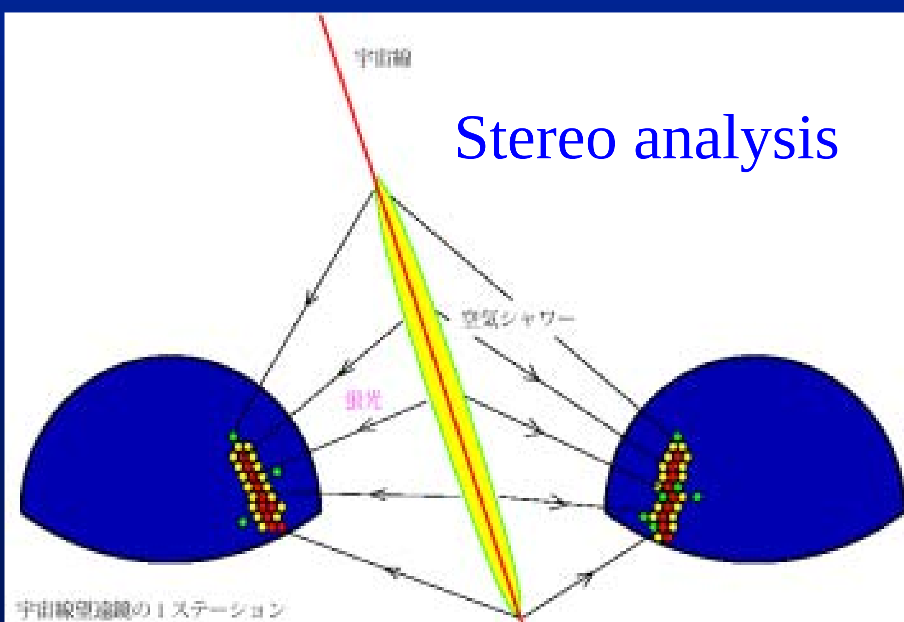


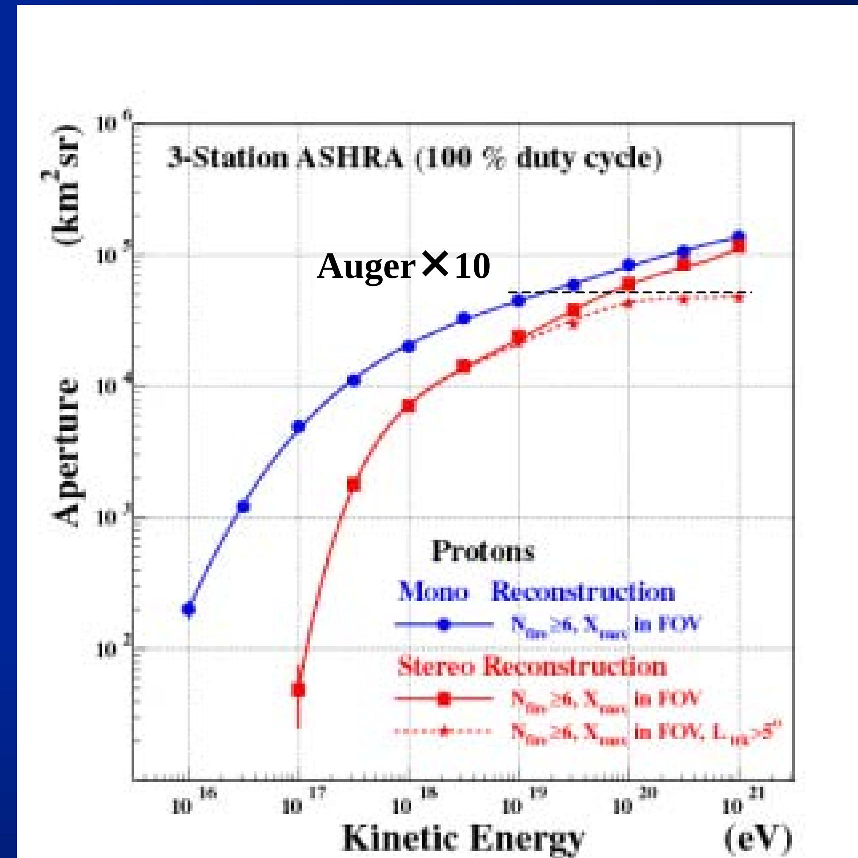
- Energy threshold ~ 1 TeV @ 1600m alt
- No need of time-sharing

=> Better pointing accuracy.

MC performance: EHECR



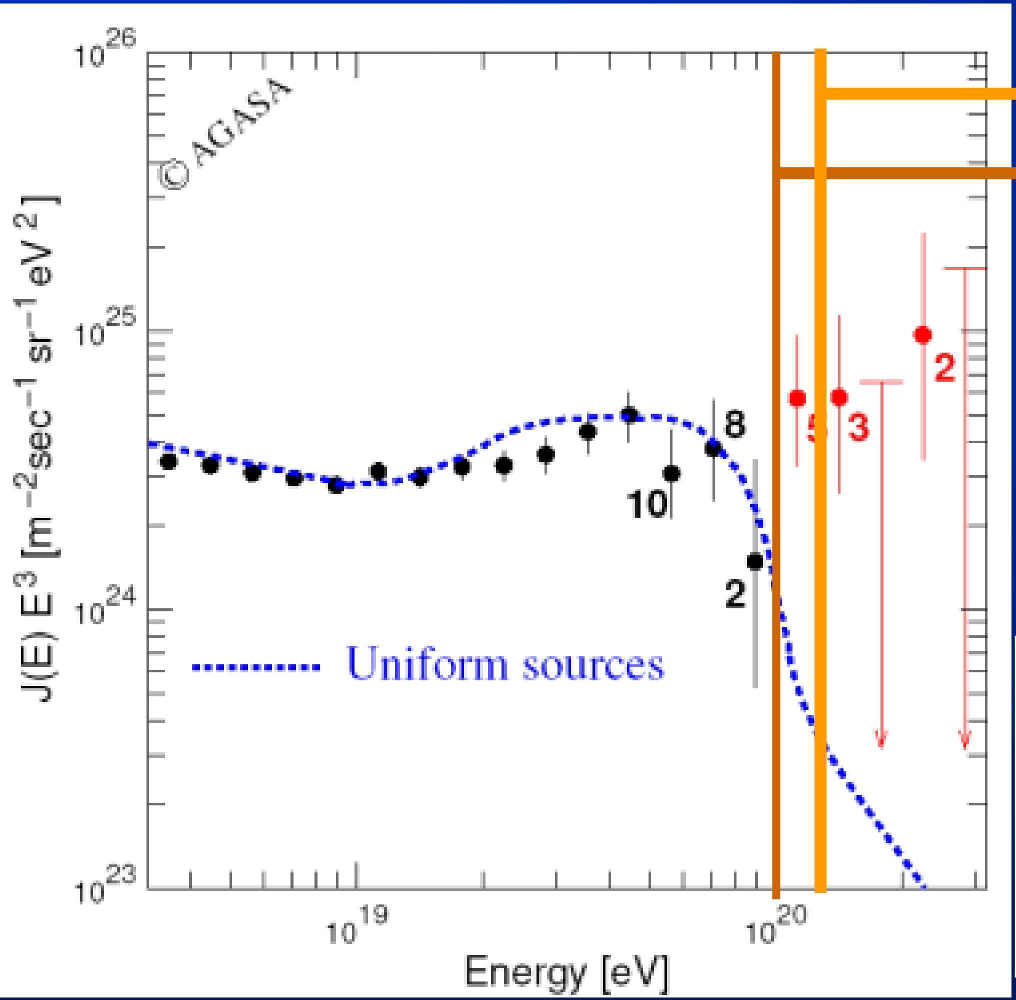




Stereo Event Rate (duty10%)

Threshold	Events/yr
10^{19}eV	1324
$10^{19.5}$eV	259
10^{20}eV	34

AGASA super-GZK spectrum



sys. shift -19%

AGASA

11yr

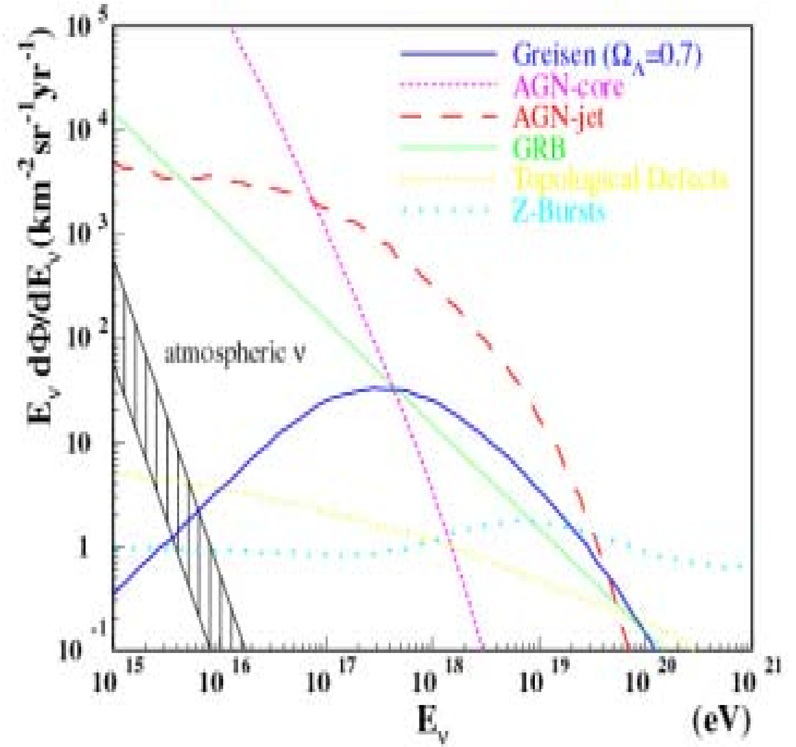
Auger 1yr

ASHRA-I 2.7yr

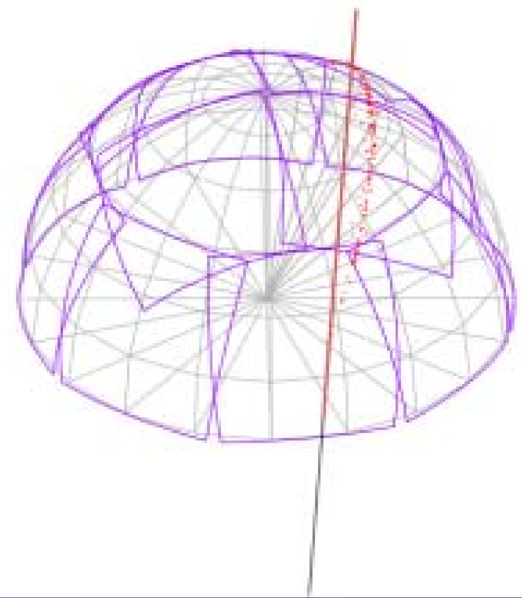
ASHRA-II 1.2yr

obs.	10	5	36
exp.	1.6	1.0	5.8
C.L.	4.0 **σ**	2.6 **σ**	13 **σ**

MC performance for EHE ν

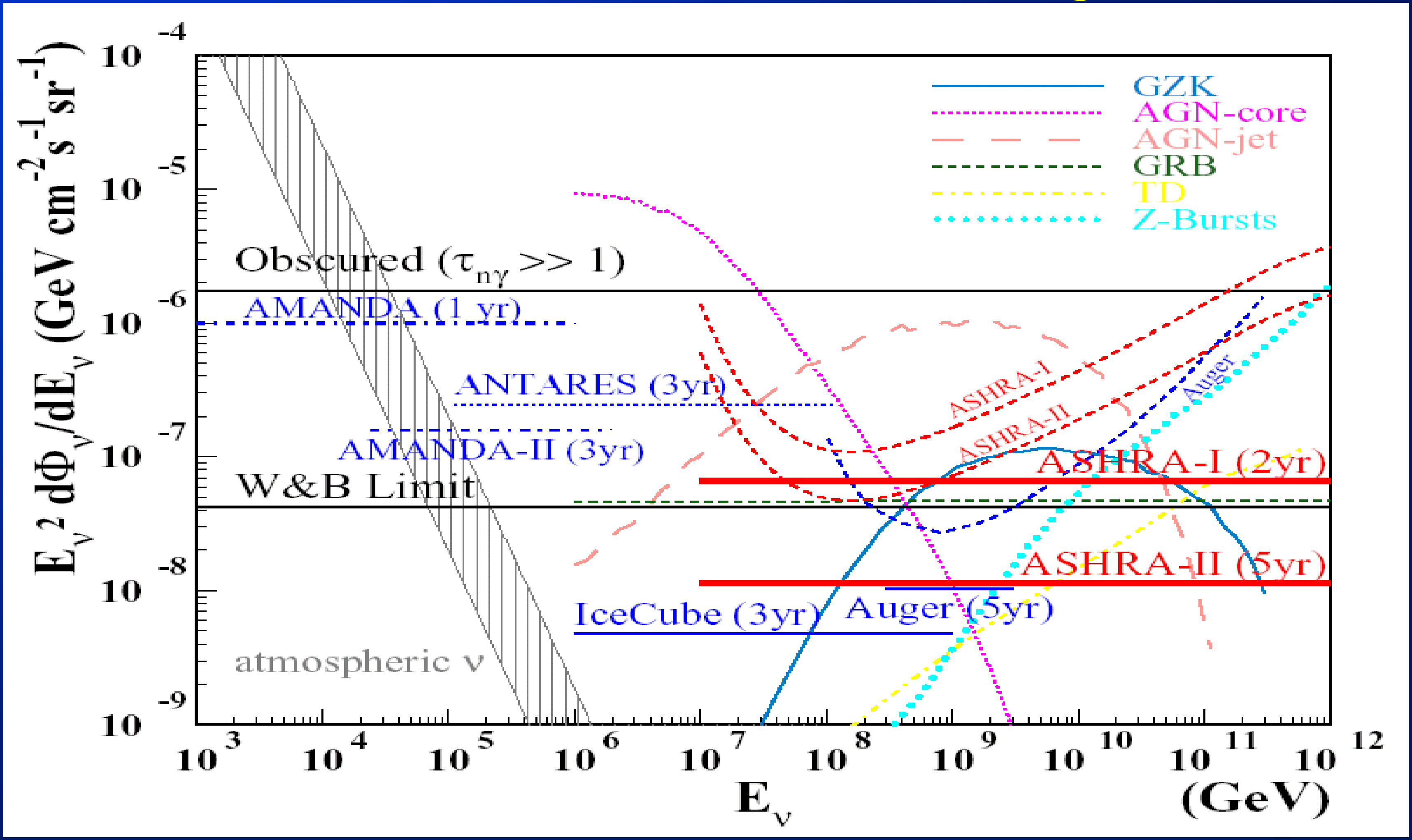


Earth-skimming tau ν



Model	Events/yr
GZK ν	1.9
AGN-jet	25.9
AGN-core	5.4
GRB	1.6
TD	0.3
Z-burst	1.3

Neutrino sensitivity



VHE ν 流量と到達感度。E-²流束に対する90%CL上限値(直線)と1年の観測でエネルギー一桁あたり１事象期待される流束(曲線)。天体の光学的厚さの極限におけるVHE ν 流量上限の2直線(Obscured, W&B Limit)も示す。

Summary

- Highly competitive with excellent cost-performance

For fluorescence observation

	ASHRA-phase2	Auger	IceCube	AGASA	HiRes
Start Year	2007 ?	2005 ?	2010 ?	1990	1998
Det. Method [Readout Device]	Fluo. + Cerenkov [IIT+CMOS]	Gnd + Fluo. [PMT]	Wat Cerenkov [PMT]	Gnd [PMT]	Fluo. [PMT]
Point Accuracy(°)	0.01~0.02	1.0~2.0	0.4	1.0~2.0	0.5~0.8
Protons / yr ($>10^{20}$eV)	34	41	--	1	6
ν s / yr AGN ($>10^{16}$ eV)	26	27	16	--	<1
GZK	2	--	--	--	--
Cost ($)	12M	50M	200M?	2M	6M

The astronomy event of the new epoch could be the simultaneous observation of TeV-γ, neutrinos from cataclysmic events associated with the source of the EHE cosmic rays.

ASHRA is getting ready for starting up this challenge using advanced all-sky survey and 1 arcmin resolution imaging techniques in a cost-effective way.

ASHRA Collaboration

Now 25 collaborators in 15 institutes

T.Aoki, Y.Asaoka, Y.Arai[A], S.Inoue[B], R.Ogawa[C], M.Kawasaki[D], K.Kori[D], M.Sasaki, M.Jobashi, S.Sugiyama[E], Y.Tanaka[F], T.Terasawa[D], T.Torii[G], K.Nakai[H], S.Nagataki[D], S.Nakamura[I], Y.Higashi[A], T.Fukunaga[J], T.Masuda, N.Manago, T.Morinaga, M.Sasaki, M.Yamaguchi[K], Y.Watanabe[L], E.Loh[M], C.Jui[M]

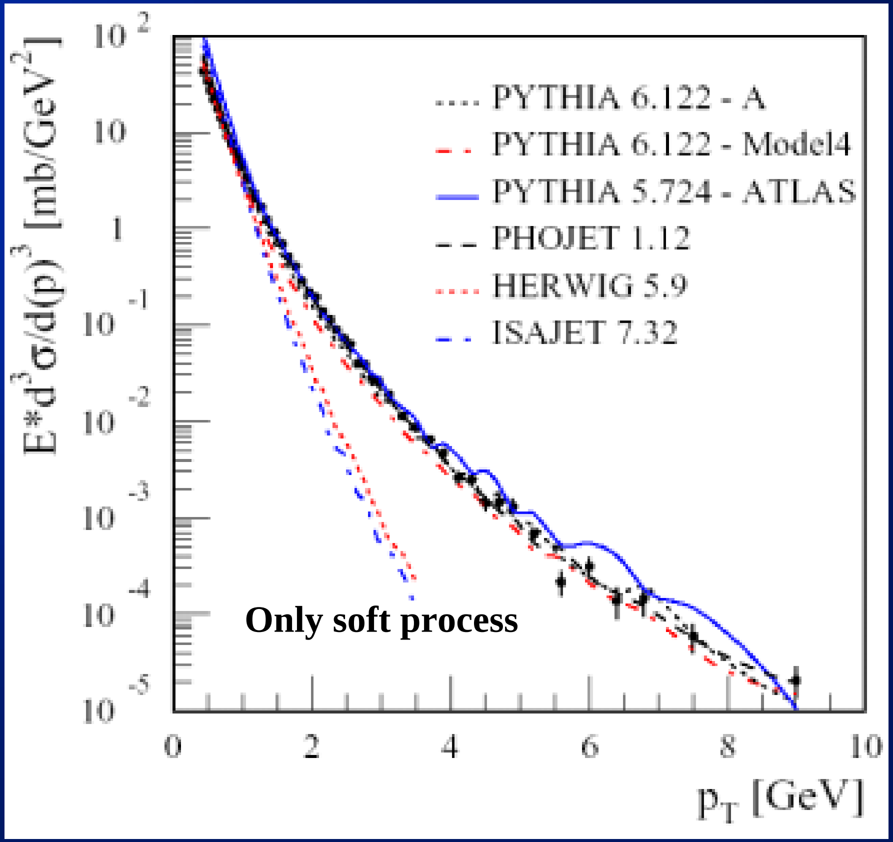
ICRR Univ.Tokyo、KEK[A]、Max Planck Institute for Astrophysics[B]、

Toho Univ.[C]、Univ.Tokyo[D]、National Astronomical Observatory[E]、Nagasaki Institute of Applied Science[F]、Waseda Univ.[G]、Tokyo University of Science[H]、Yokohama National Univ.[I]、Tokyo Metropolitan Univ.[J]、Tohoku Univ.[K]、Tokyo Institute of Technology[L] , Univ.Utah[M]

P_t w.r.t. arrival direction

- 1^{st} interaction：
  - Soft process dominant.
  - $P_t \sim$ 0.3GeV
- PYTHIA simulation
  - Low rate for $P_t > 1$GeV
- Boost to EHECR system
  - 0.7×10^{17}eV (AS) <= 14TeV (LHC)
  - $\gamma \sim 0.7 \times 10^4$

P_t dist. in LHC minimum bias events



ATLAS TDR 15, CERN/LHCC 99-15 (1999)

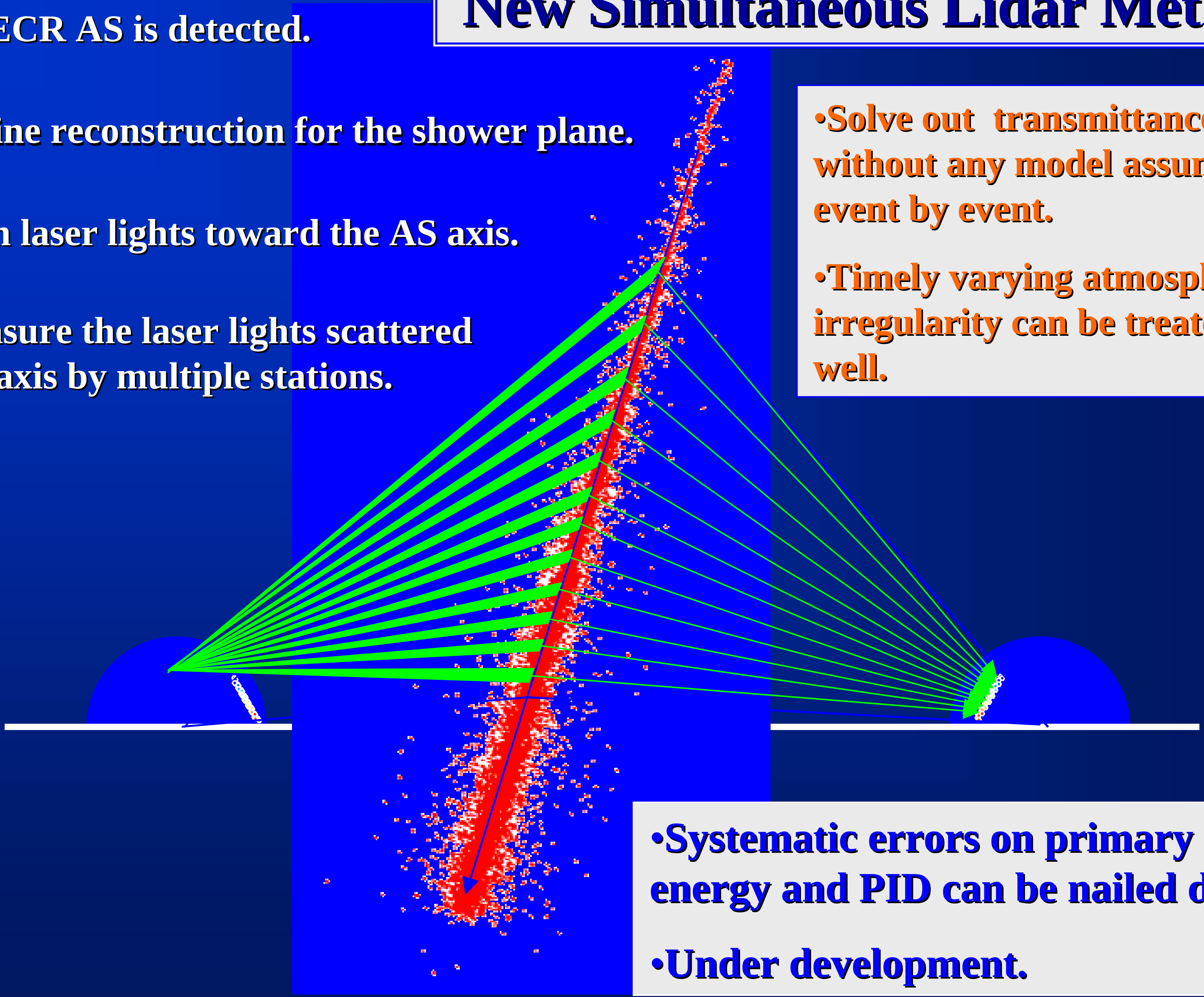
New Simultaneous Lidar Method

1. EHECR AS is detected.

2. Online reconstruction for the shower plane.

3. Scan laser lights toward the AS axis.

4. Measure the laser lights scattered at the axis by multiple stations.

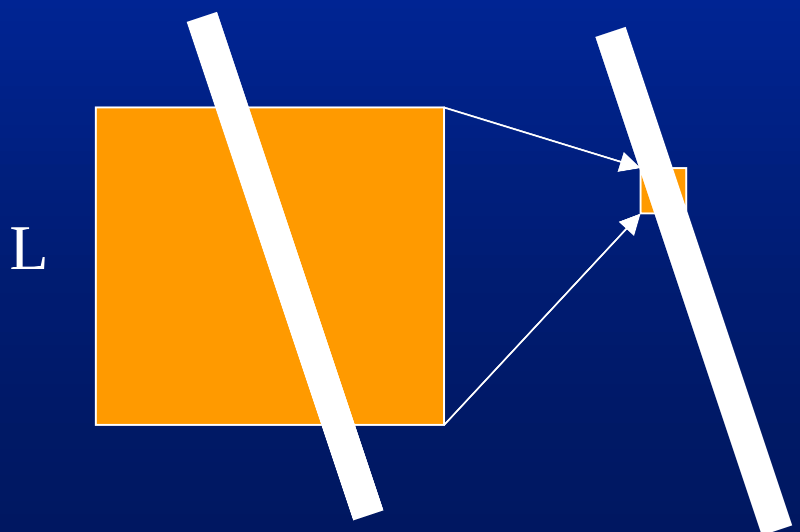


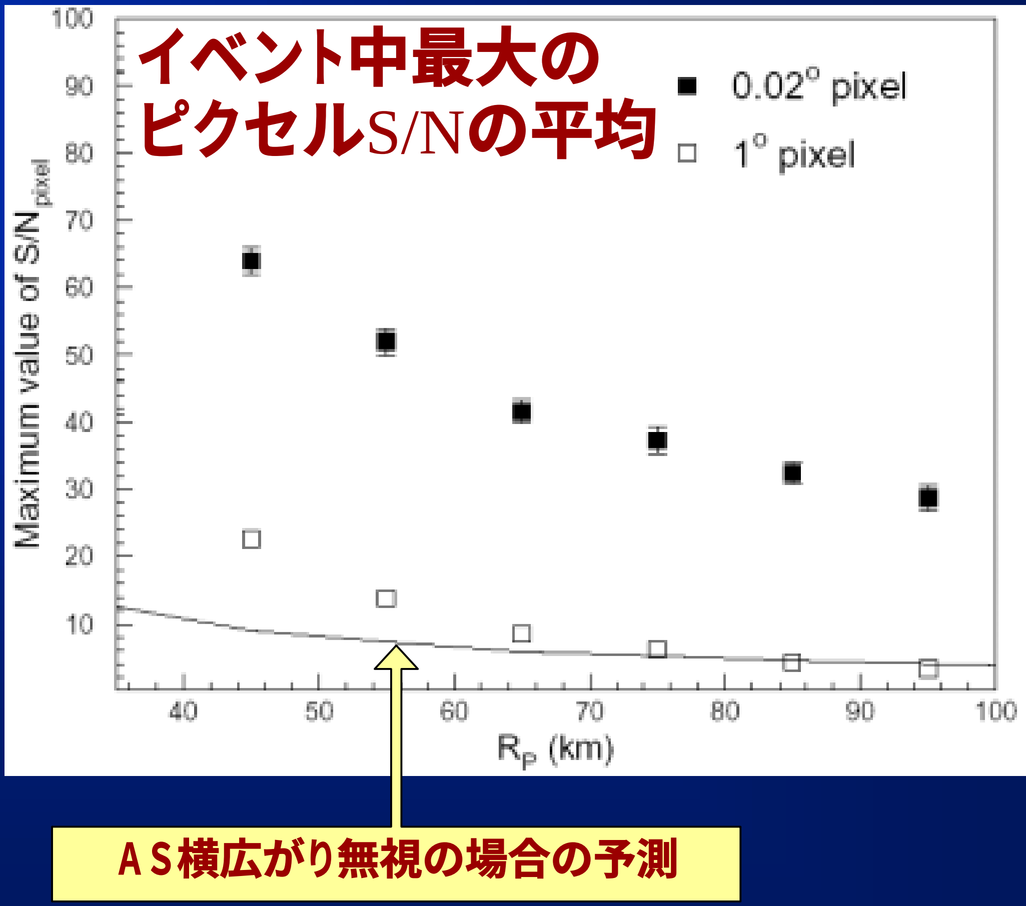
- Solve out transmittance T(X) without any model assumption event by event.
- Timely varying atmospheric irregularity can be treated well.

- Systematic errors on primary energy and PID can be nailed down.
- Under development.

高解像度による感度の向上

- ピクセルS/N：
  $\propto$(集光面積/角解像度)$^{1/2}$
  ＡＳ横広がりが無視できる場合のみ



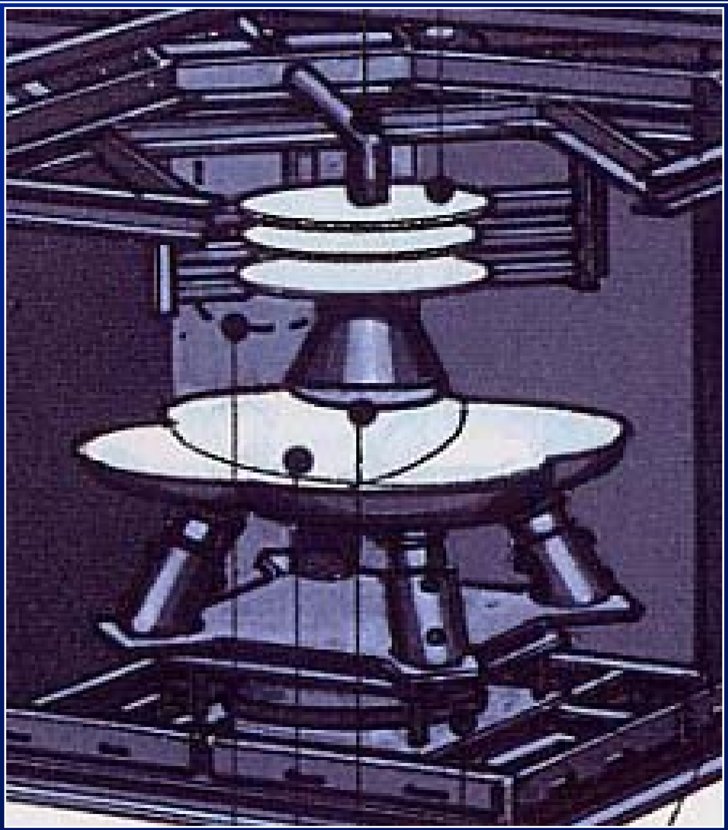


$t \propto L,\ S \propto L,\ B \propto L^3$ $t \propto L,\ S \propto L^2,\ B \propto L^3$

Progress of Optics

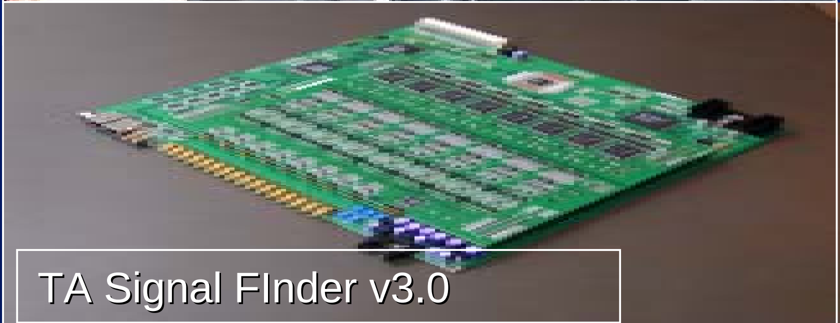
- TA … Davies-Cotton
  - FOV ~ 16° / Telescope
  - Focal spot size ~ 0.3°

- ASHRA … Baker-Nunn
  - FOV ~ 50° / Telescope
  - Focal spot size ~ 0.01°



Progress of Imaging Device

- TA … PMT+ADC
  - 16 × 16 = 256 pixels/tele.
  - Pixel res. ~ 1°
  - 256 outputs / 256 pixels



TA Signal FInder v3.0

- ASHRA … IIT+SS-Imager
  - 3K × 3K~10M pixels/tele.
  - Pixel res. ~ 0.015° (=1’)
  - 4 outputs / 10M pixel