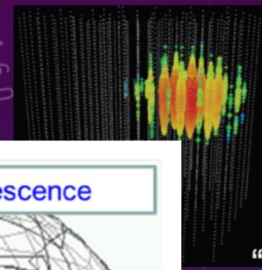
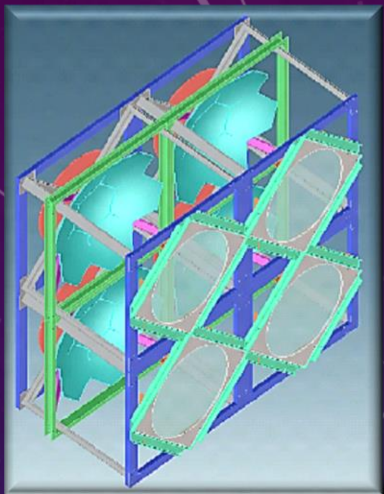
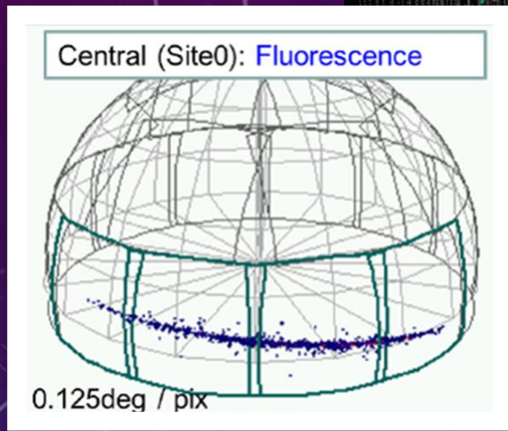
PRL **111**, 021103 (2013)



NTA





Imaging Multi-Astroparticles with NTA

Clear Identification of Astroparticle Emitters & Astro Beam Particle Physics

- Air-shower imaging telescope for SubPeV-EeV ν & γ with summit array
- IACT-lilke resolution (< 0.2°) covering large FOV (> π sr) and watching huge air-mass.
- Simultaneous Obs. SubPeV-EeV ν , γ , and CR hadrons both with air Cheren. and fluores.
- Near future, it will be the most sensitive and precise ν detector. The first subPeV-EeV wide E-range γ -ray imaging telescope.

Multi-messenger Astronomy Workshop
2017.03.02 ICHA Chiba Univ.
Makoto Sasaki
(NTA Int. Promotion WG)

NTA

Short History

Very High Energy Particle Astronomy Workshop
Toward PeV-EeV Neutrinos!

2013: NTA LoI: by Sasaki & Hou

2014: VHEPA2014 @ Kashiwa
IAC：A.Watson,F.Halzen,T.Kifune

2015: VHEPA2015 @ Taipei
IAC：A.Watson,F.Halzen,T.Kifune

2015: NTA Forum @ ICRC2015 Hague

Kampert, Sokolsky, Watson, Kifune
Hou/Sasaki + several young persons

2016: VHEPA2016 @ Honolulu, Jan.7-9

Set up NTA (PWG)

Halzen（UWM）, Browder（UHM）, Hou(NTU)、Mussa(INF)、Ogawa(Toho)、Sasaki(UT-ICRR)...

NTA

Modified from F. Halzen, VHEPA2016

Detect All VHE Particles

Origin of p accelerator:

p acceleration -> observed CR flux

$$p\gamma \to \Delta \to n\pi^+ \qquad \pi^0 : \pi^+ = 2 : 1$$

$$p\gamma \to \Delta \to p\pi^0 \qquad n + \pi^+ \to pe\bar{\nu}_e + e^+\nu_e\nu_\mu\bar{\nu}_\mu$$

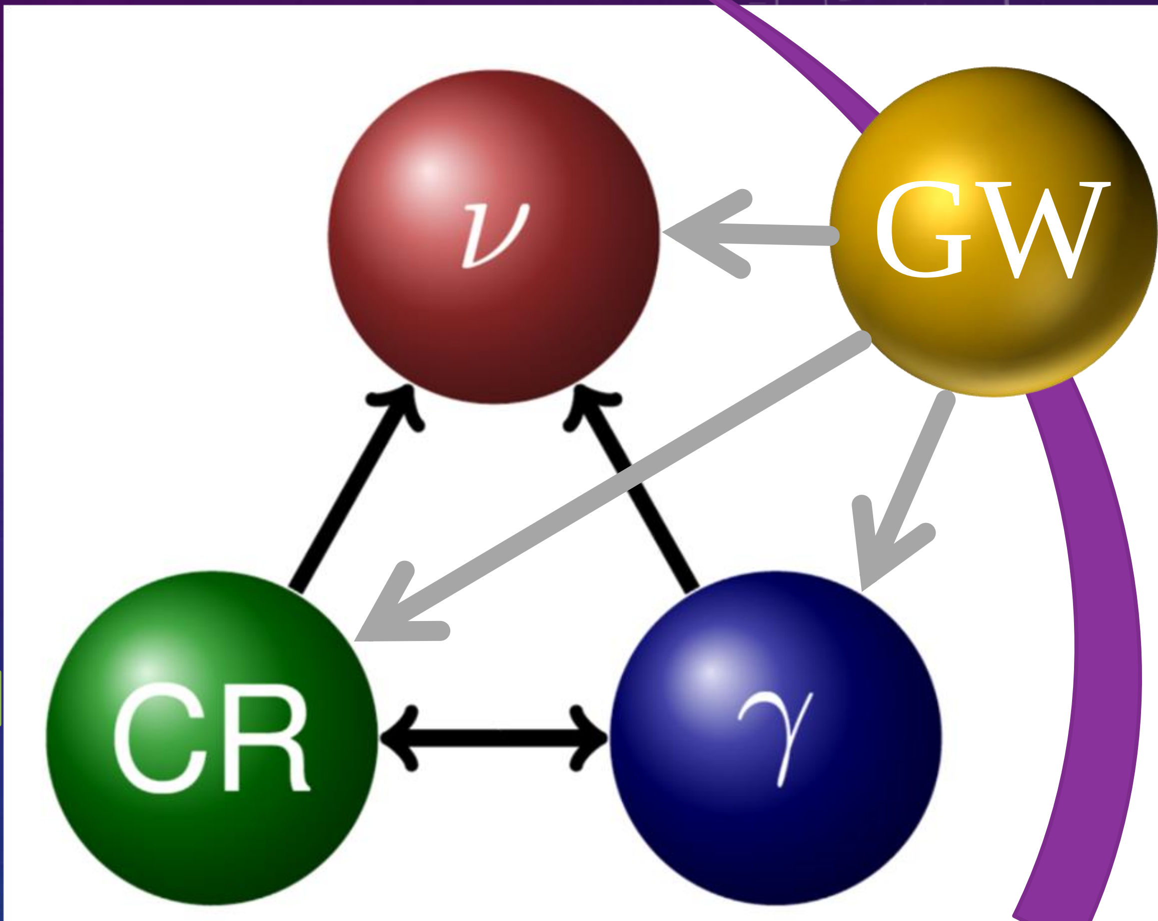
or

$$pp \to \pi X \qquad \pi^- : \pi^0 : \pi^+ = 1 : 1 : 1$$

ν from ***pp*** follows CR−*p* spectrum

$E_\nu \sim$ 1/20 E_p

GeV−PeV γ cascade baund for ν



Detect All of them even if transient (time domain <1s)

⇒ **Imaging AS in wide FOV at same time => NTA**

NTA

Observable
Energy & Distance

NTA ν => source flux

NTA γ => propagated flux (cascaded)

- **Source location & mechanism**
- **Probing media & particle physics**

1) Source physics mechanism: *pγ* or *pp* ?

2) CR high-end cut-off: GZK or composition?

3) "Highest Energy γ-ray physics":

Search for highest E γ-ray in the Universe

interaction with BG photons

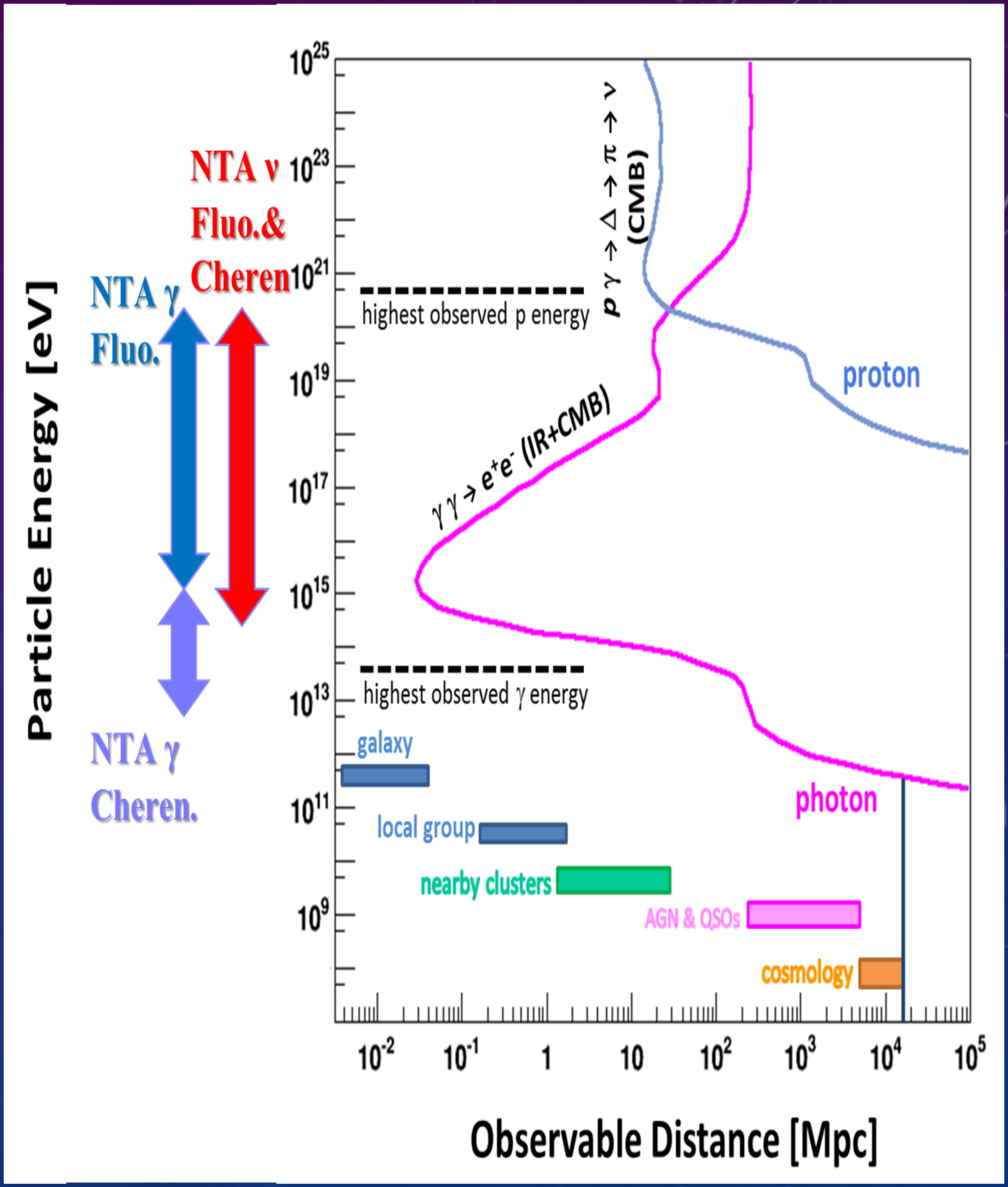
4) Dark matter:

5) Search for non-standard physics:

Lorentz invariance violation

Extra Dimension

6) Transient objects:



NTA

Image ν & γ Air-showers

Earth-skimming tau neutrino (ES-ν_τ)

$E_\nu > 10$ PeV

10-100 times higher sensitivity

than IceCube

but L_{decay} = 49m (E_τ/PeV)

Deep penetrating e & tau neutrino (DP-$\nu_{e,\tau}$)

0.3 PeV< E_ν <10 PeV

Compensate **ES-ν_τ**

Realize cross obs. with IceCube

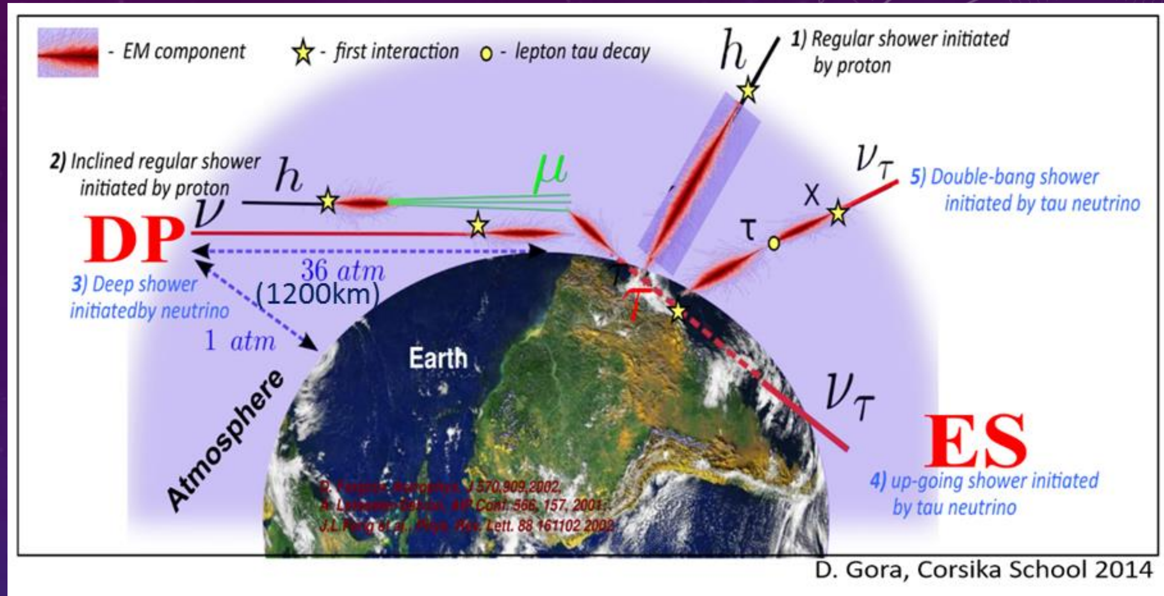
-> Complementary mutual confirm.

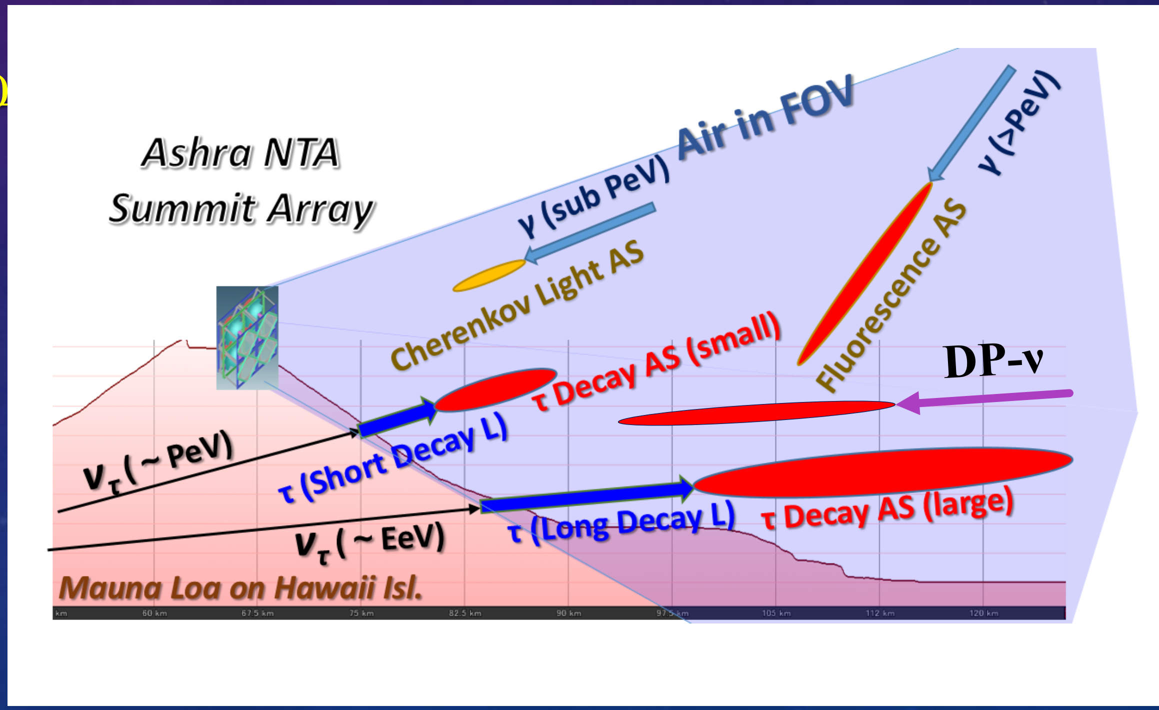
Interestign (anti-) electron neutrinos

AS from γ's and CR-hadrons

Counter part obj. & AS develop.

-> p / γ separation

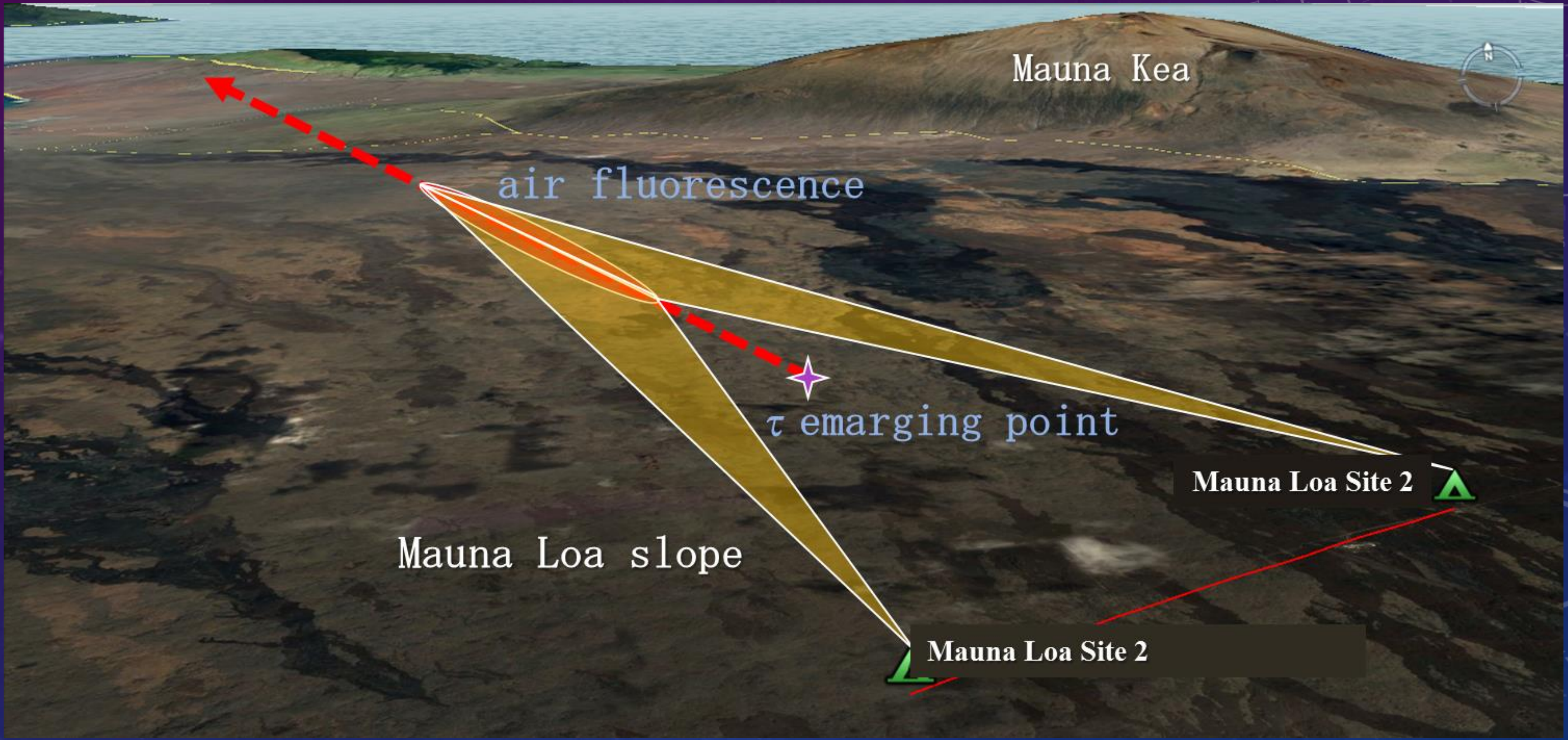




Mauna Loa
one of the best sites for imaging astroparticles

The largest subaerial volcano in both mass and volume, Mauna Loa has historically been considered **the largest volcano on Earth**. It is an active shield volcano with relatively gentle slopes, with a volume estimated at approximately 18,000 cubic miles (**75,000 km^3**). [en.wikipedia.org/wiki/Mauna_Loai]

NTA Stereo Obs. ES Tau Showers



NTA

Summit Array Baseline Design

4 Stations（■）at 3000-3500m asl. on Mauna Loa

9 detector units / 1 station

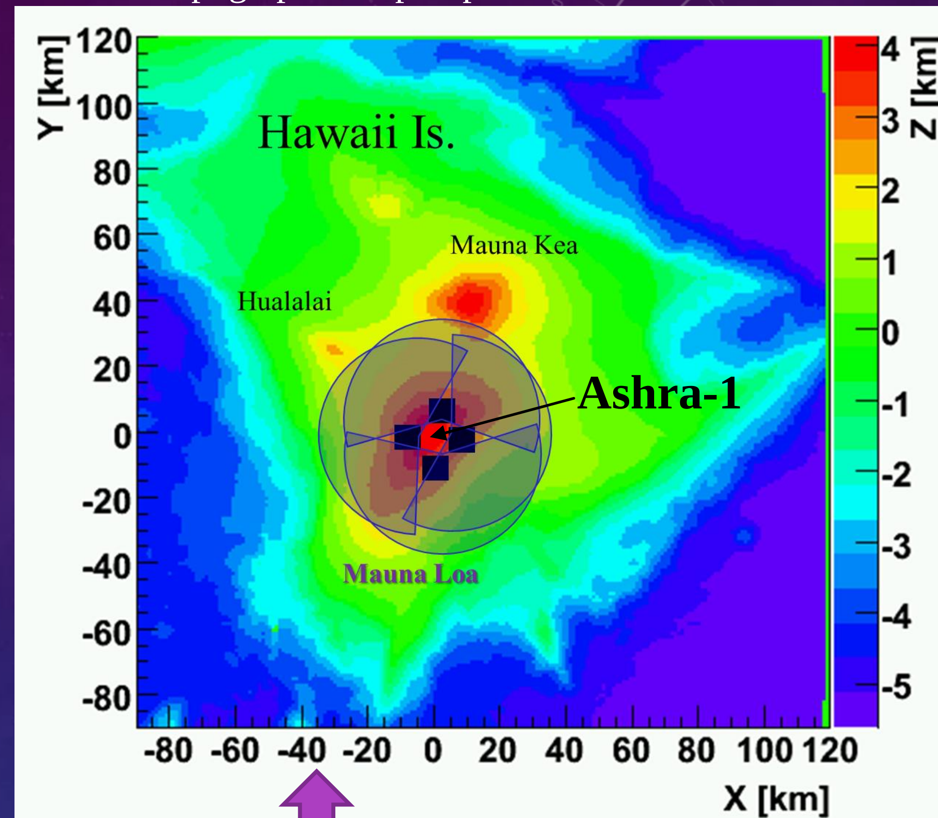
Zenith angle = 30° (65° -95°),

Azimuth angle = 240° with 9 detector units

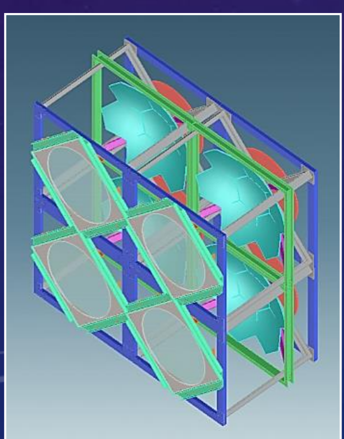
→ Stereo obs. at almost all azimuth angles

Nothernmost station = Ashra-1 Mauna Loa Site

Topographic map implemented in NTA simulation



NTA DU



NTA Detector Unit = Multi-Tel. with 4 LCs

Ashra-1 x 1.5 scaled-up

+ same trigger & readout

Light Collector (LC)

Optics with **ϕ1.5m** pupil

FOV 30° = focal sphere ϕ50cm

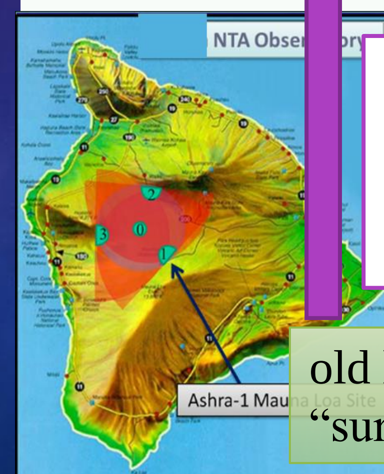
Detector Unit (DU)

4 LCs watch same FOV

Coadded 4 images

⇒ **Effective pupil = ϕ3m**

⇒ **Easy to reject CR-μ**



Enhance sensitivity ~PeV

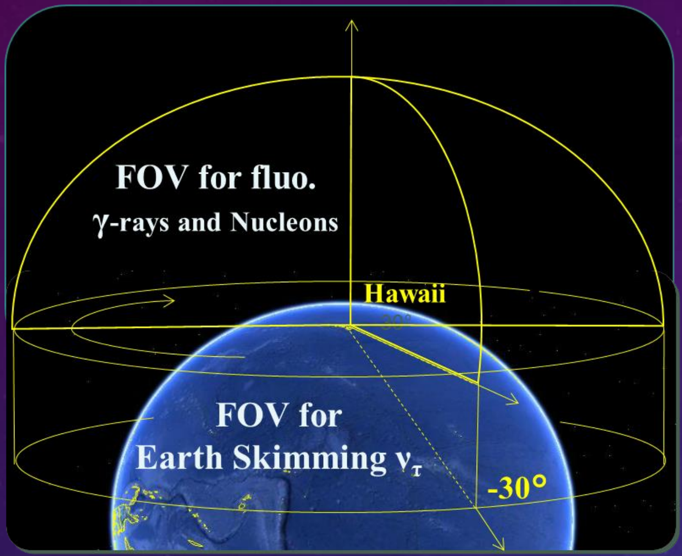
More air-mass can be used

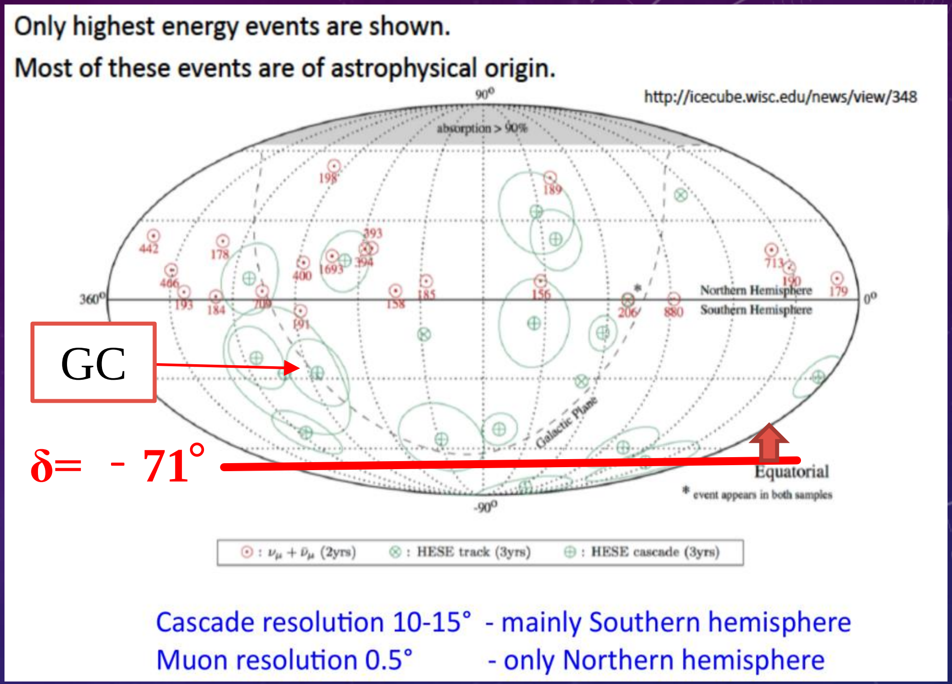
Better multi-static ratio

Better environ. Condition

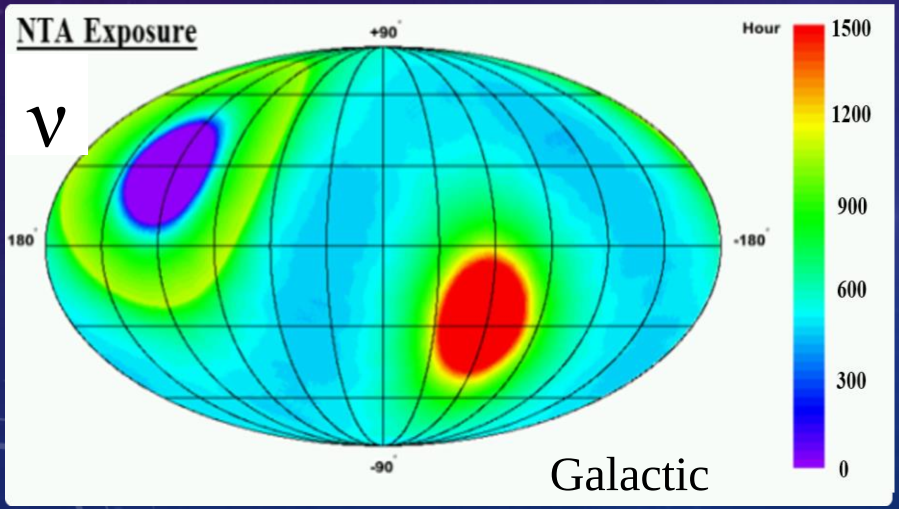
old layout design
“surrounded-by-mtn’s”

NTA FOV and Exposure





https://icecube.wisc.edu/science/highlights



Detector	Latitude	Zenith	Dec. min, max
KASCADE	49.0° N	< 35°	14°, 84°
EAS-TOP	42.5° N	< 35°	7°, 78°
GAMMA	40.5° N	< 30°	10°, 71°
UMC	40.2° N	< 40°	0°, 80°
CASA-MIA	40.2° N	< 60°	-20°, 90°
Tibet	30.1° N	< 50°	-20°, 80°
NTAγ	19.5° N	< 95°	-71°, 90°
HAWC	19.0° N	< 45°	-26°, 64°
GRAPES-3	11.4° N	< 25°	-14°, 36°
IceTop	90.0° S	< 30°	-90°, -60°

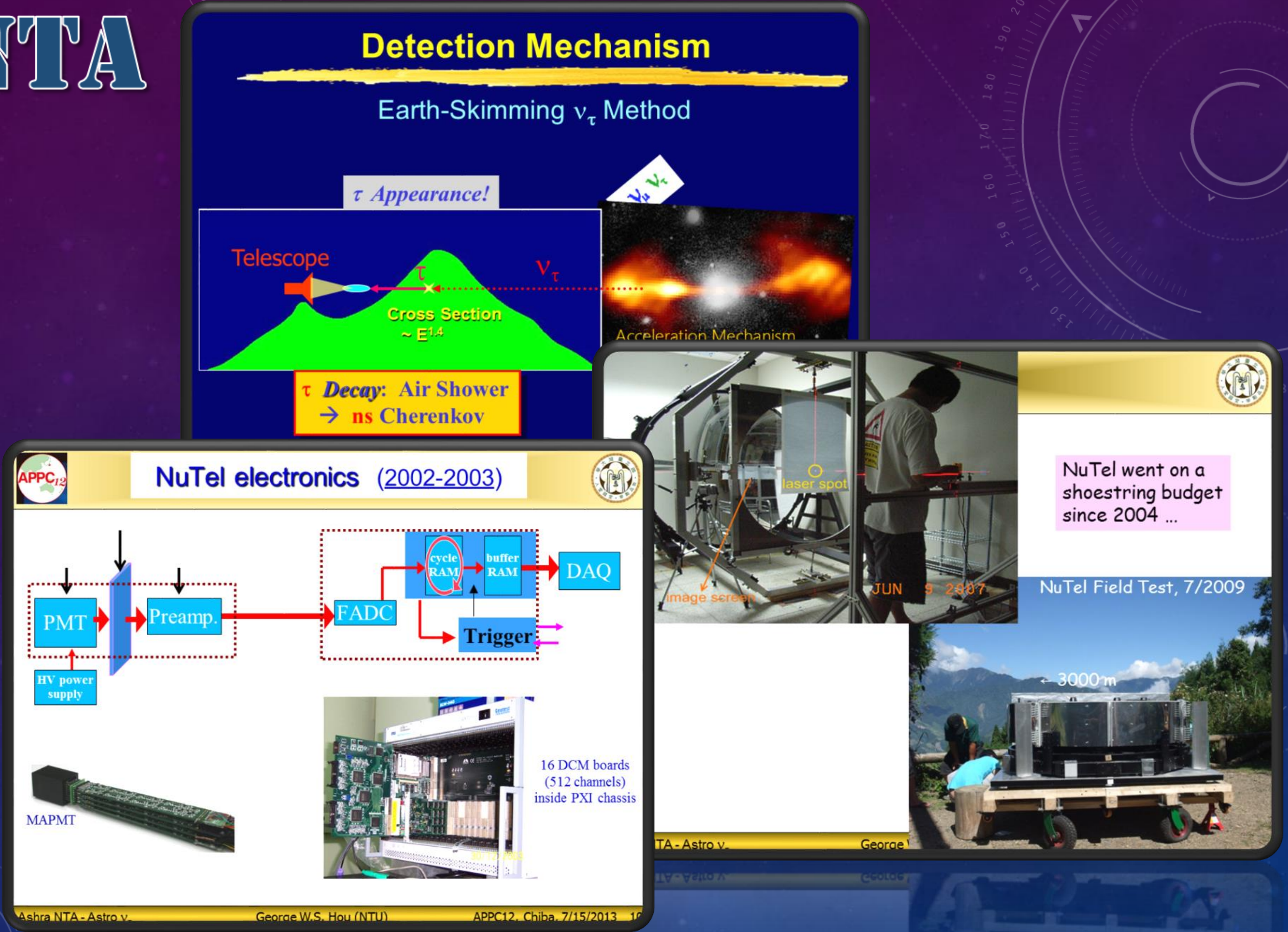
2005年　建設開始

2007年夏　建設完了

Ashraマウナロア観測ステーション

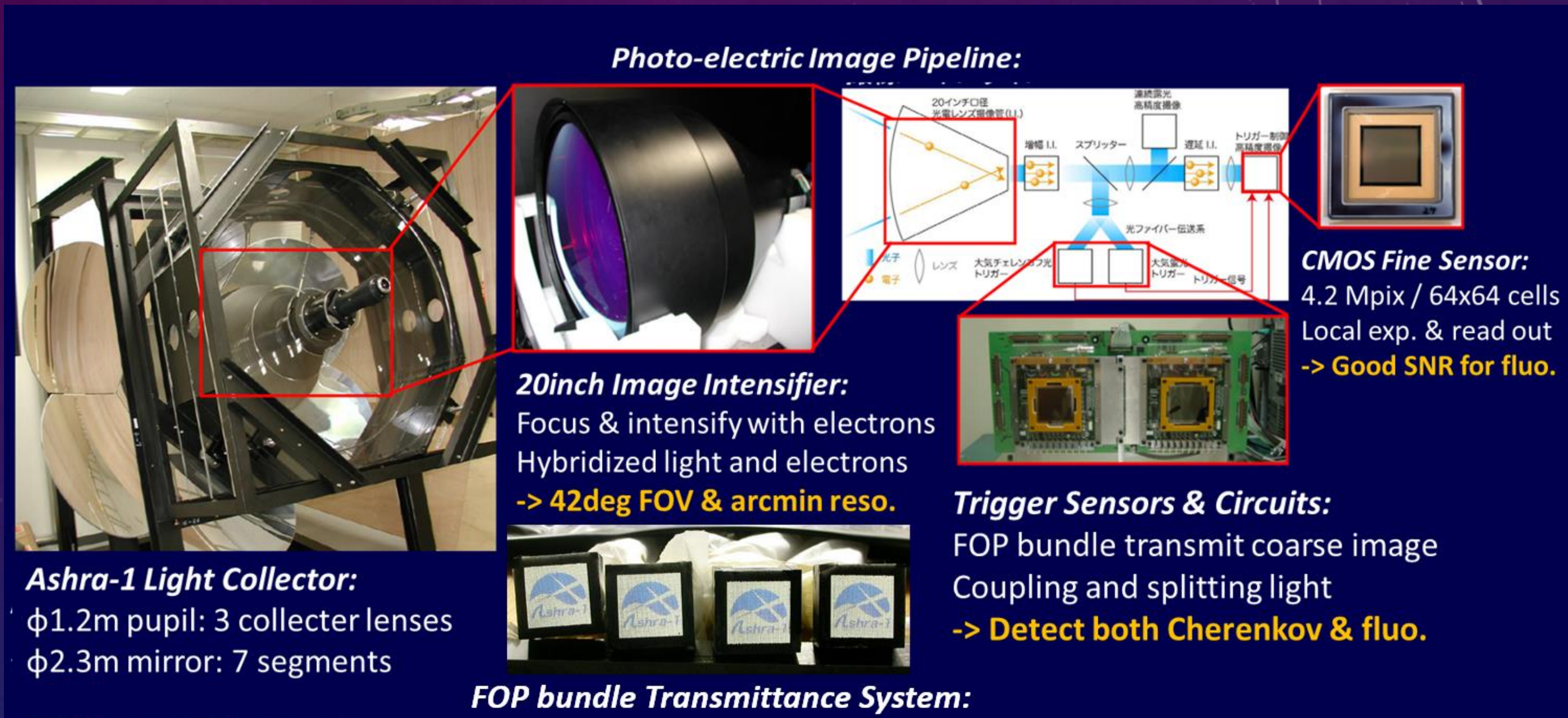
Observation – 1：2008年6月28日 – 2009年6月5日
Observation – 2：2009年10月7日 – 2011年1月4日
Observation – 3：2012年1月11日 – 2013年3月25

NTA



Detection Mechanism
Earth-Skimming ν_τ Method
τ Appearance!
Telescope
τ
ν_τ
Cross Section
$\sim E^{1.4}$
Acceleration Mechanism
τ Decay: Air Shower
→ ns Cherenkov
NuTel electronics (2002-2003)
APPC12
PMT
Preamp.
HV power supply
FADC
cycle RAM
buffer RAM
DAQ
Trigger
MAPMT
16 DCM boards
(512 channels)
inside PXI chassis
Ashra NTA - Astro ν
George W.S. Hou (NTU)
APPC12, Chiba, 7/15/2013
laser spot
image screen
JUN 9 2007
NuTel went on a
shoestring budget
since 2004 …
NuTel Field Test, 7/2009
← 3000 m

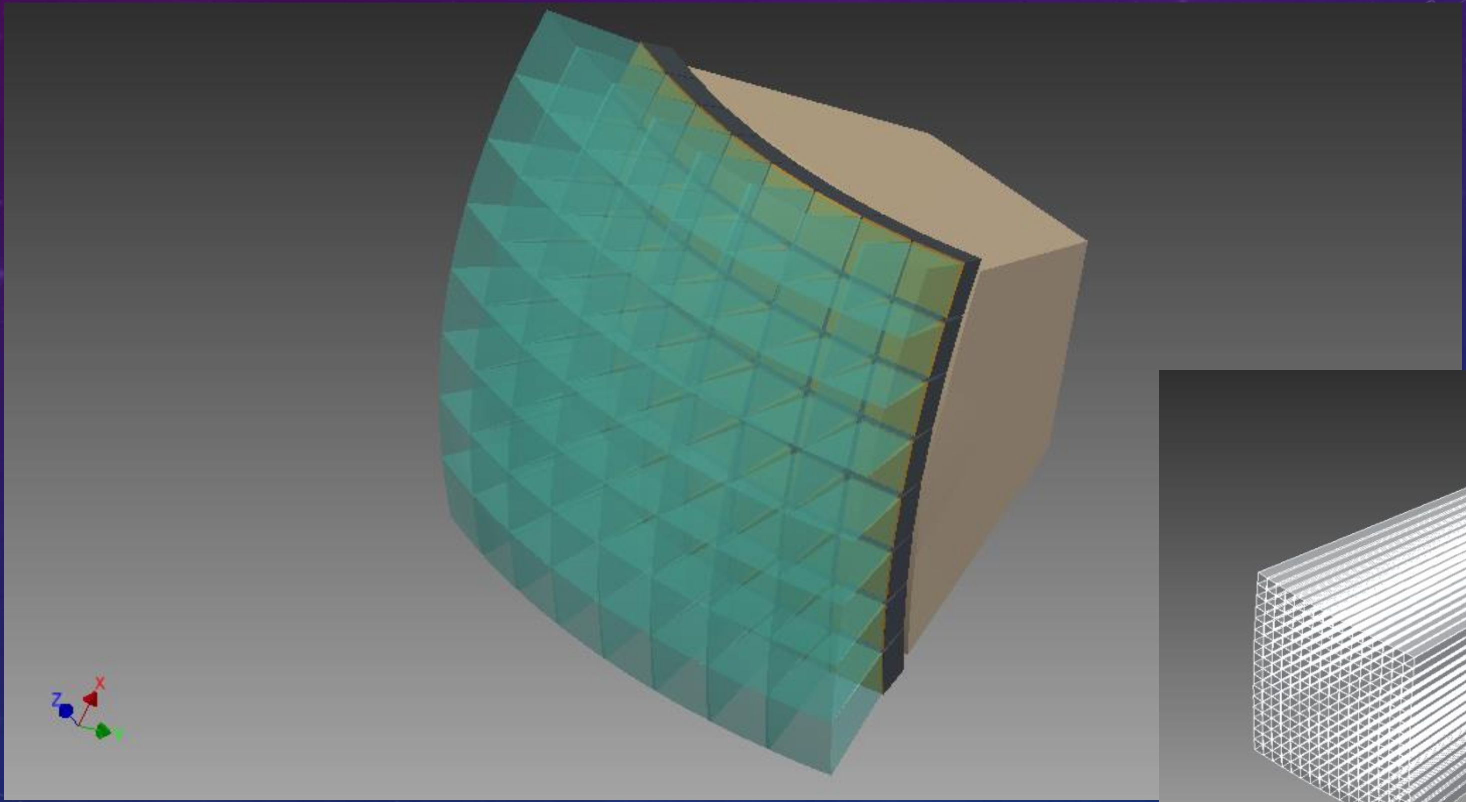
Ashra-1 Detector Unit System as NTA baseline design

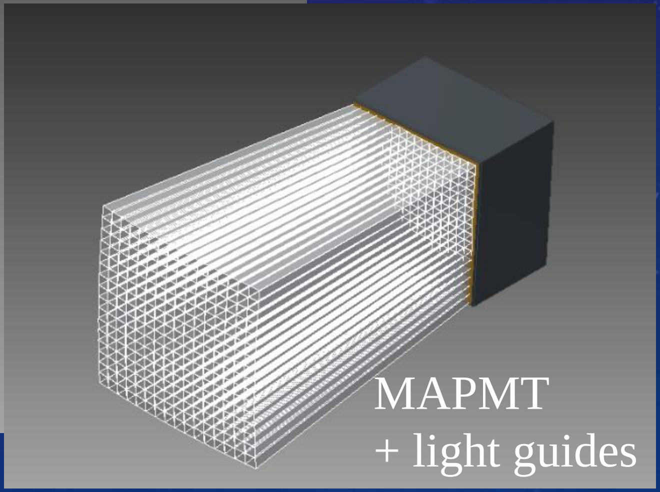


Transfer light images but not electric current.

- simultaneous Cher. & fluo. Trigger
- affordable reduction of pixel cost

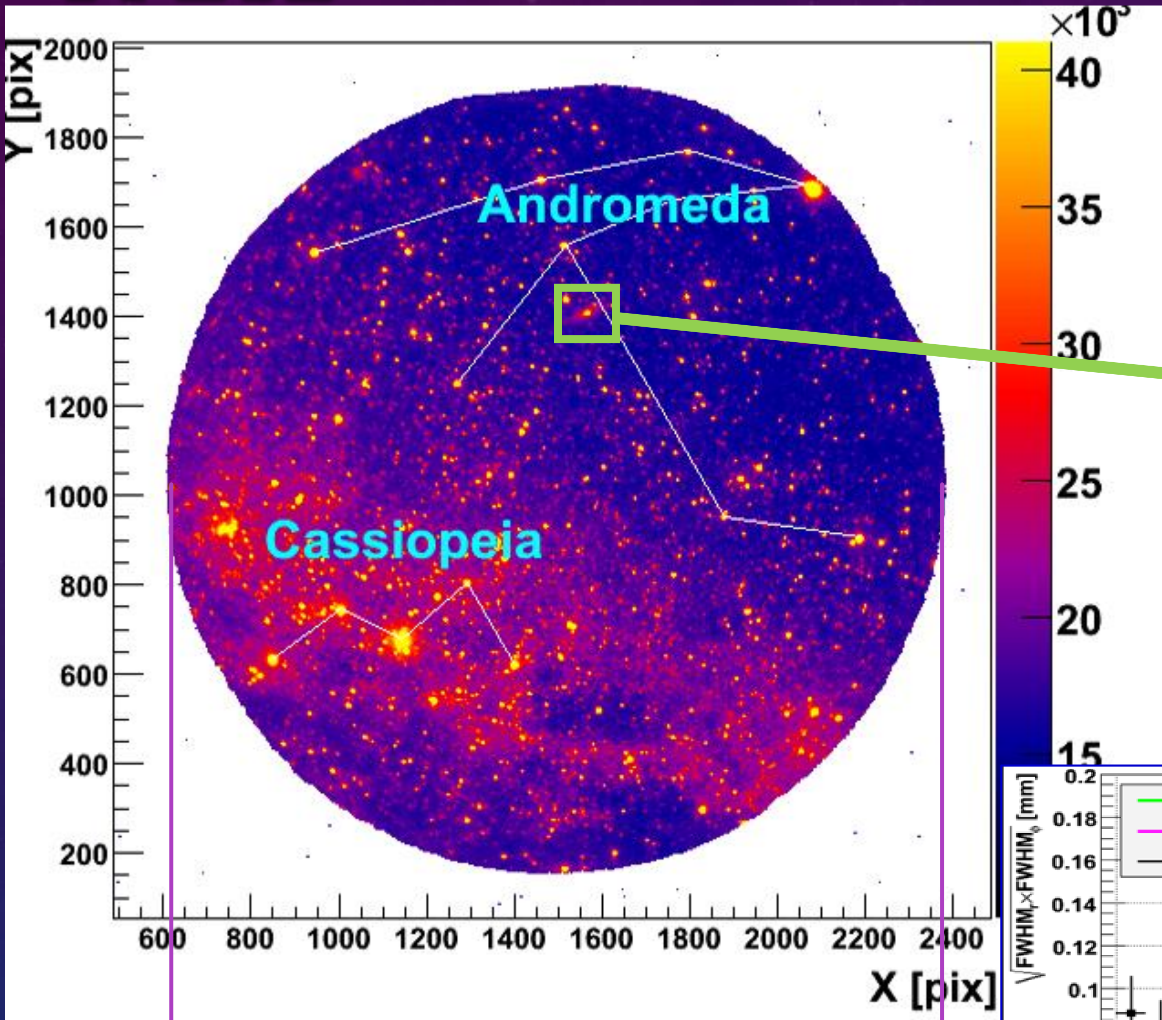
Backup Option of Focal Sphere Camera with 128×128 pix MAPMT Array





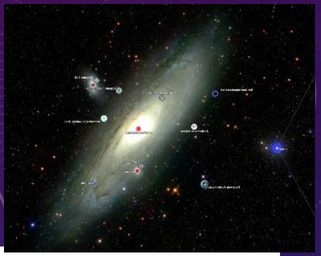
NTA White Paper describes the cost performance evaluations of options. The TDR will fix the unique design of NTA.

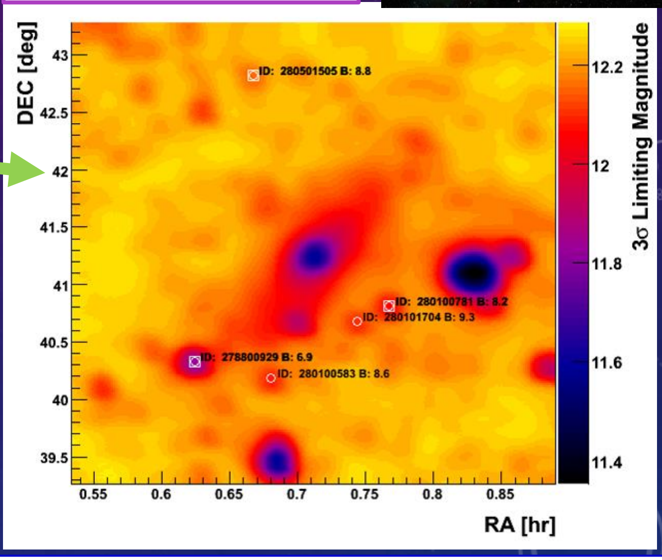
2-3 arcmin. Resol. Over 42deg FOV with Ashra-1 LC

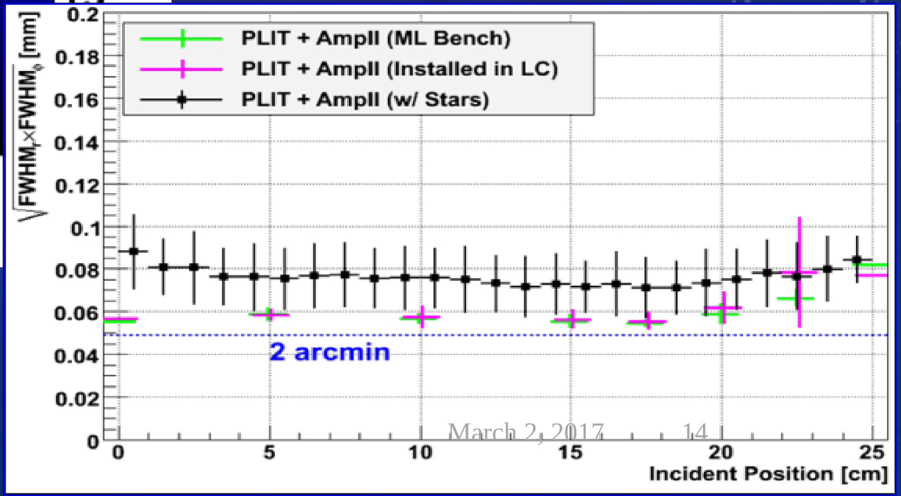


42deg.

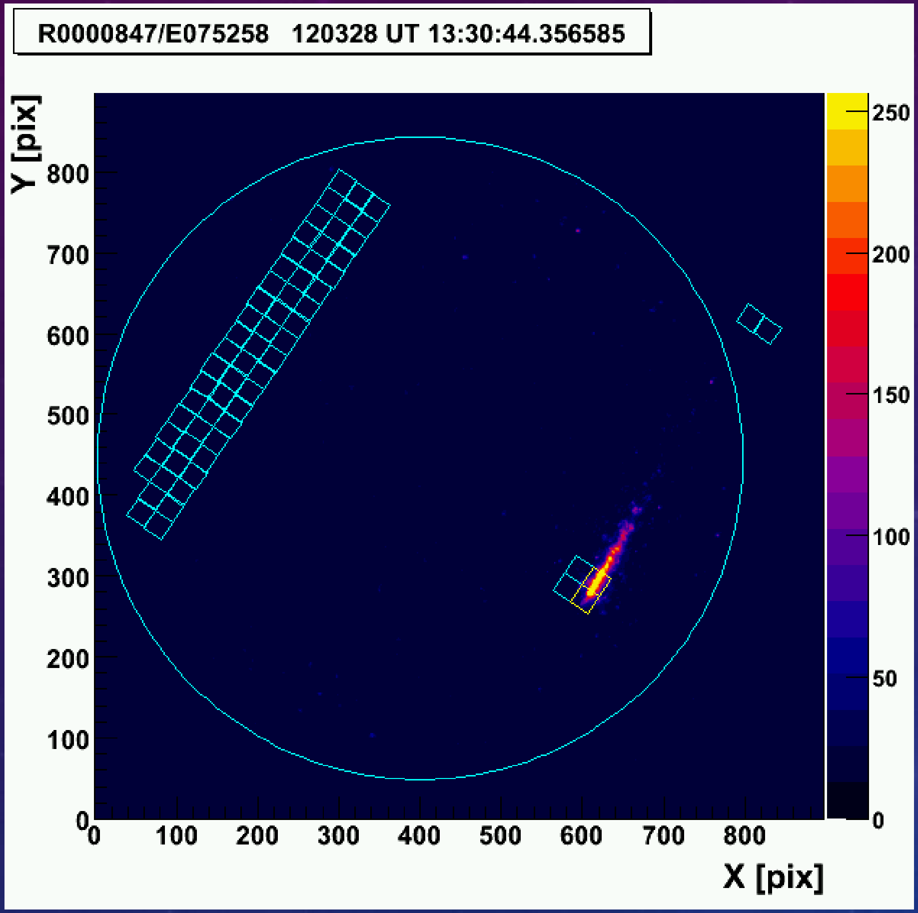
12Mag./1s exposure

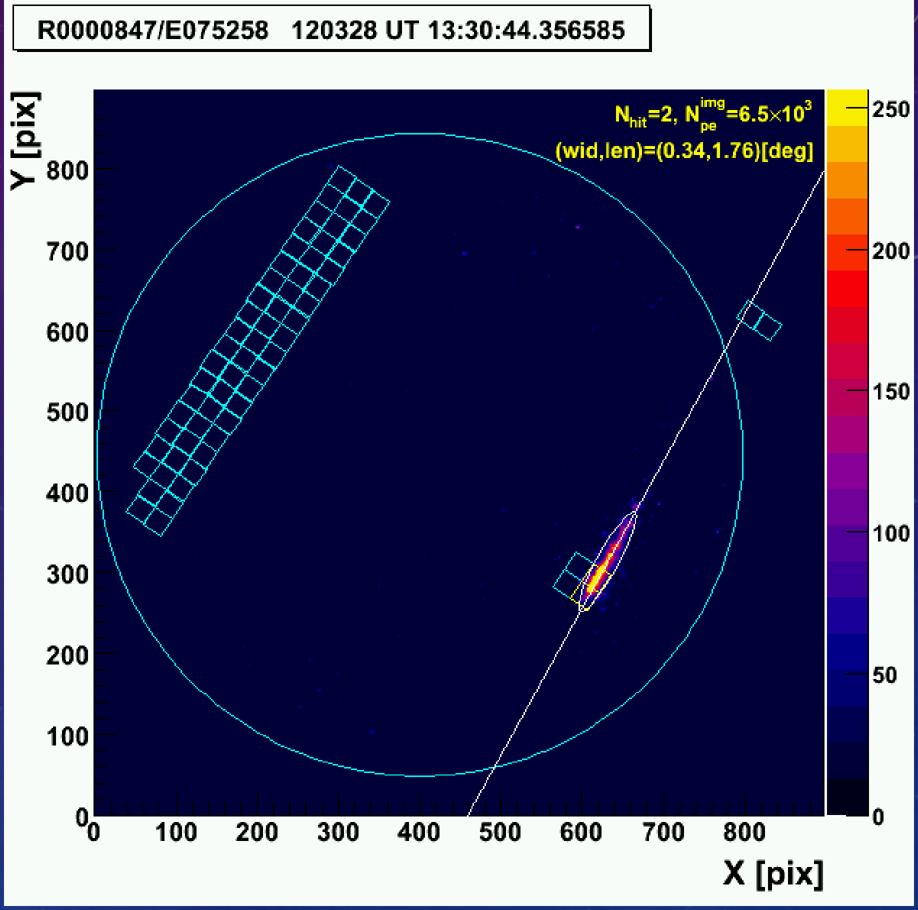






Real Shower Images

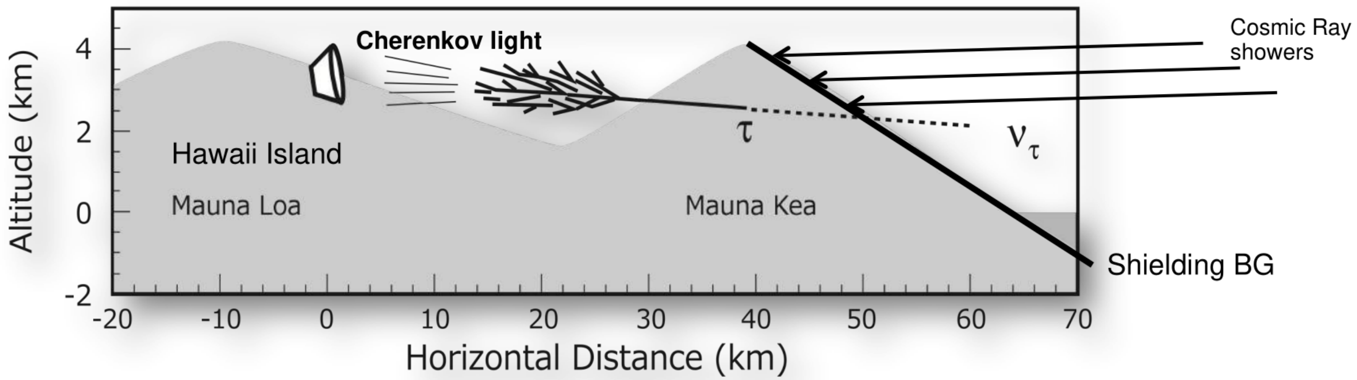




- All AS images -> Hillas image parameters, i.e. Width, Length, …
- Same threshold and cluster cuts are applied as ν_τ search.

Proof of Concept by Ashra-1

Earth-skimming technique of imaging Cherenkov showers



> Ashra-1 already demonstrated this mehod (APJ 736 L12; Astropart. Phys. 41 (2013) 7)!

Proof of concept

The Astrophysical Journal Letters, 736:L12 (5pp), 2011 July 20
doi:10.1088/2041-8205/736/1/L12

OBSERVATIONAL SEARCH FOR PeV–EeV TAU NEUTRINO FROM GRB081203A

Y. Aita[1], T. Aoki[1], Y. Asaoka[1], T. Chonan[1], M. Jobashi[1], M. Masuda[1], Y. Morimoto[1], K. Noda[1], M. Sasaki[1], J. Asoh[2], N. Ishikawa[2], S. Ogawa[2], J. G. Learned[3], S. Matsuno[3], S. Olsen[3], P.-M. Binder[4], J. Hamilton[4], N. Sugiyama[5], and Y. Watanabe[6]
(Ashra-1 Collaboration)
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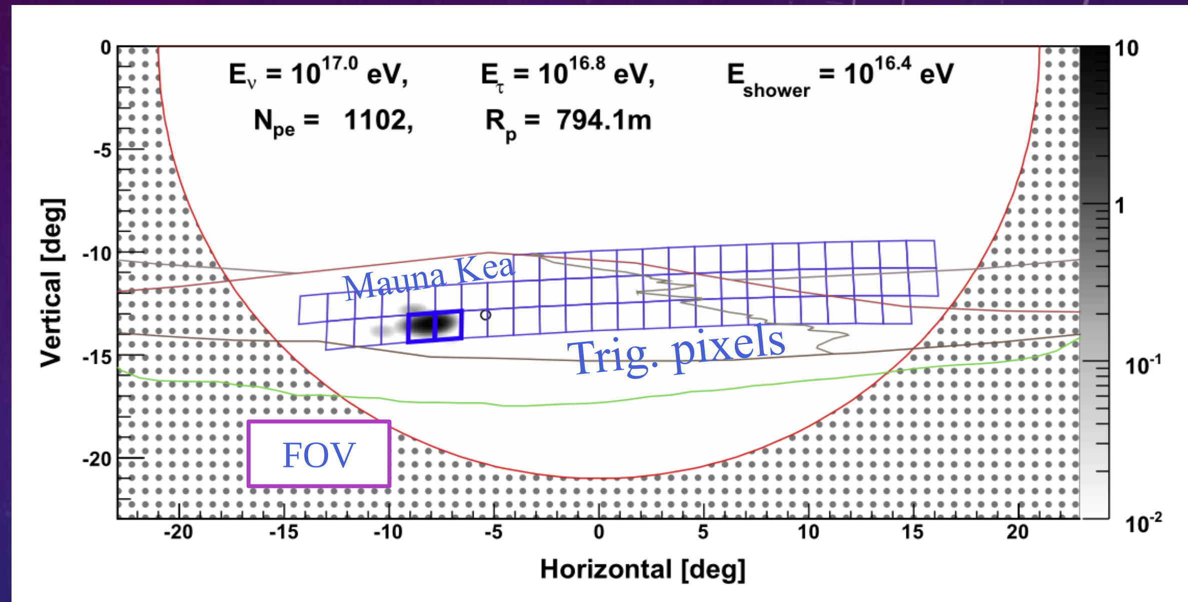
Received 2011 April 29; accepted 2011 June 10; published 2011 June 28

ABSTRACT

We report the first observational search for tau neutrinos (ν_τ) from gamma-ray bursts (GRBs) using one of the Ashra light collectors. The Earth-skimming ν_τ technique of imaging Cherenkov τ showers was applied as a detection method. We set stringent upper limits on the ν_τ fluence in PeV–EeV region for 3780 s (between 2.83 and 1.78 hr before) and another 3780 s (between 21.2 and 22.2 hr after) surrounding GRB081203A triggered by the *Swift* satellite. This first search for PeV–EeV ν_τ complements other experiments in energy range and methodology, and suggests the prologue of "multi-particle astronomy" with a precise determination of time and location.

NTA Simulated Images of ES-ν_τ Air-showers

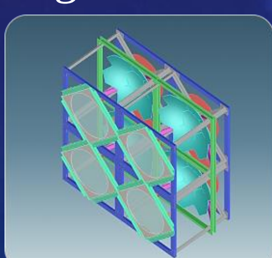
Ashra-1

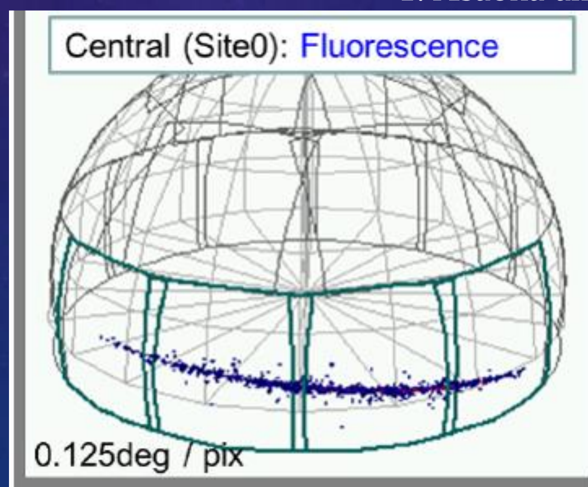


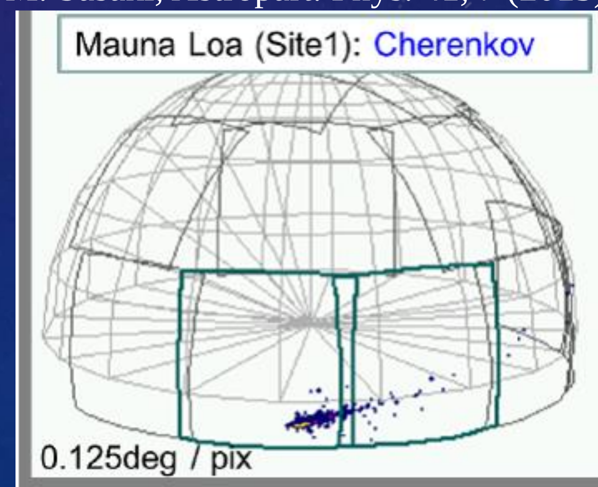
Y. Asaoka and M. Sasaki, Astropart. Phys. 41, 7 (2013).

NTA

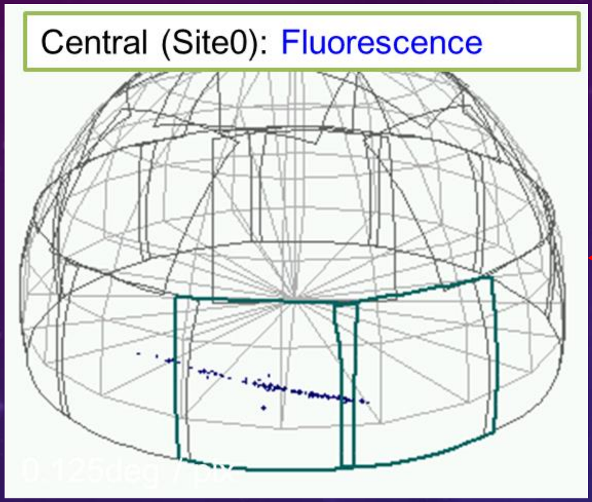
light gather. eff. = 10 x Ashra-1
⇒ Triggerable enough @1PeV

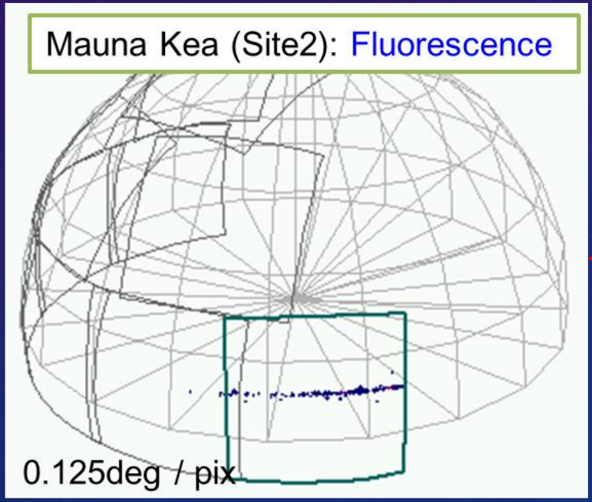


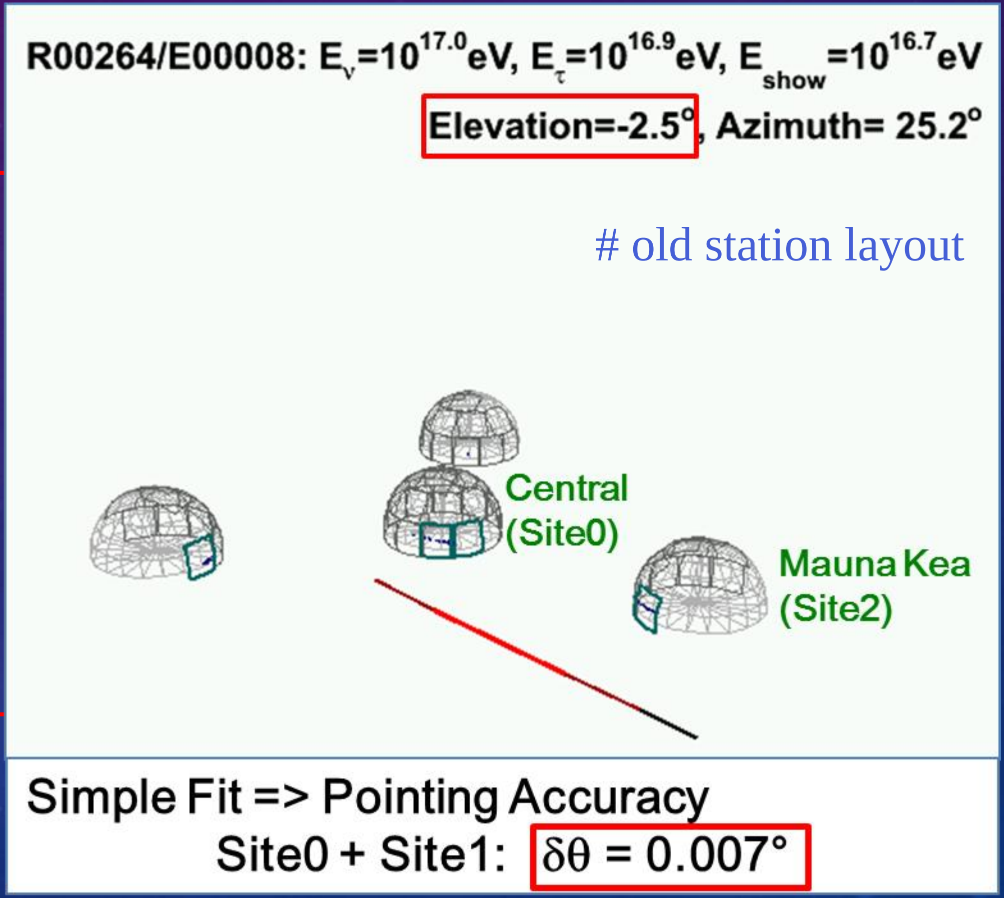




NTA Simulated Event





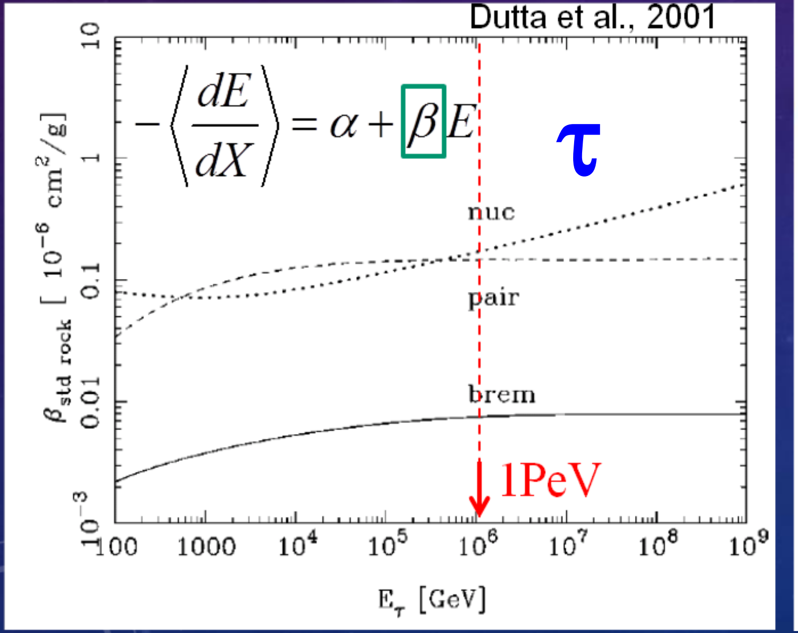


Even a low photon-stat. event has good point-back resolution.

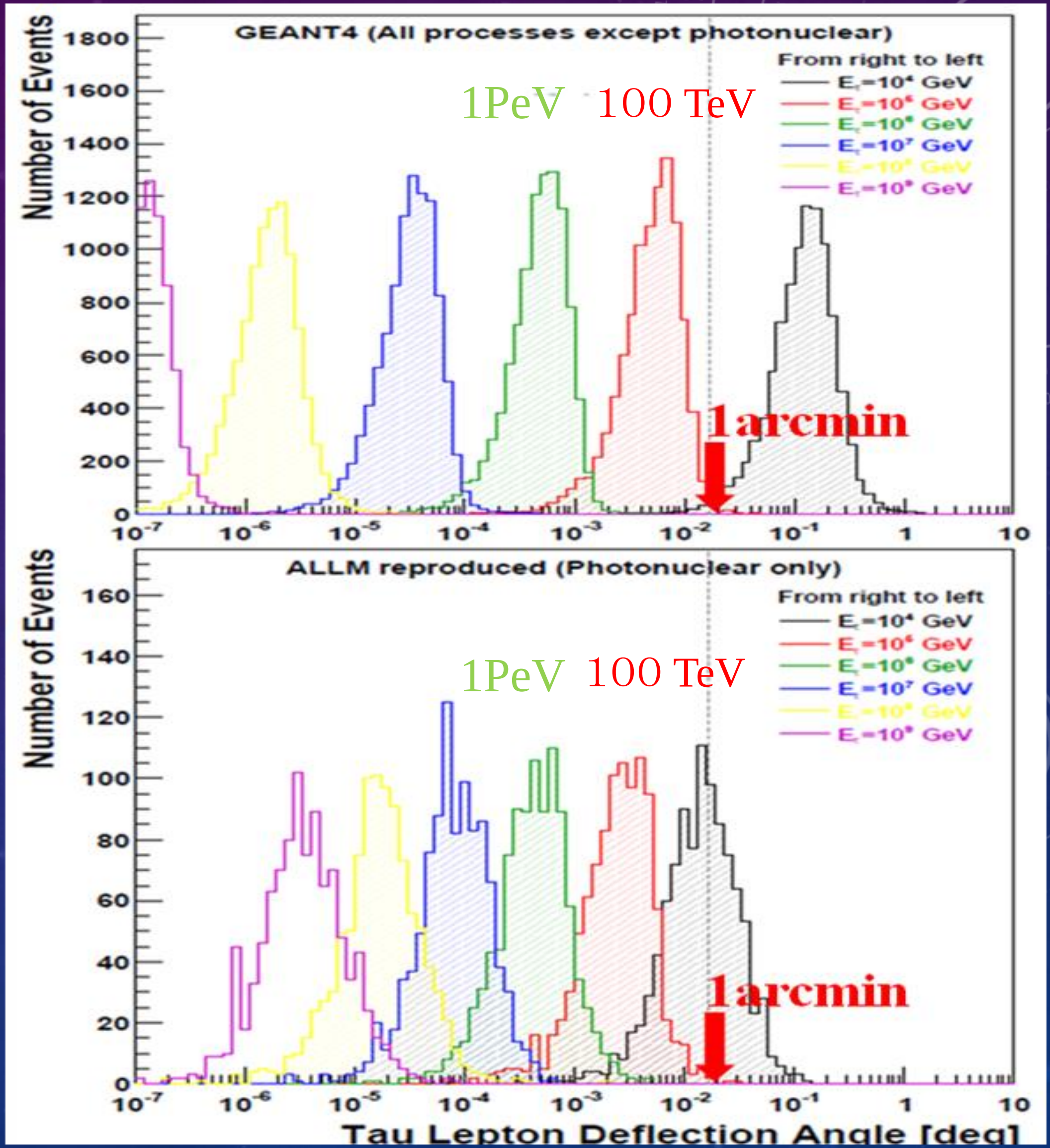
NTA

τ Propagation in Rock

Can point back to Pevatron within 0.1 arcmin with ES-ν_τ



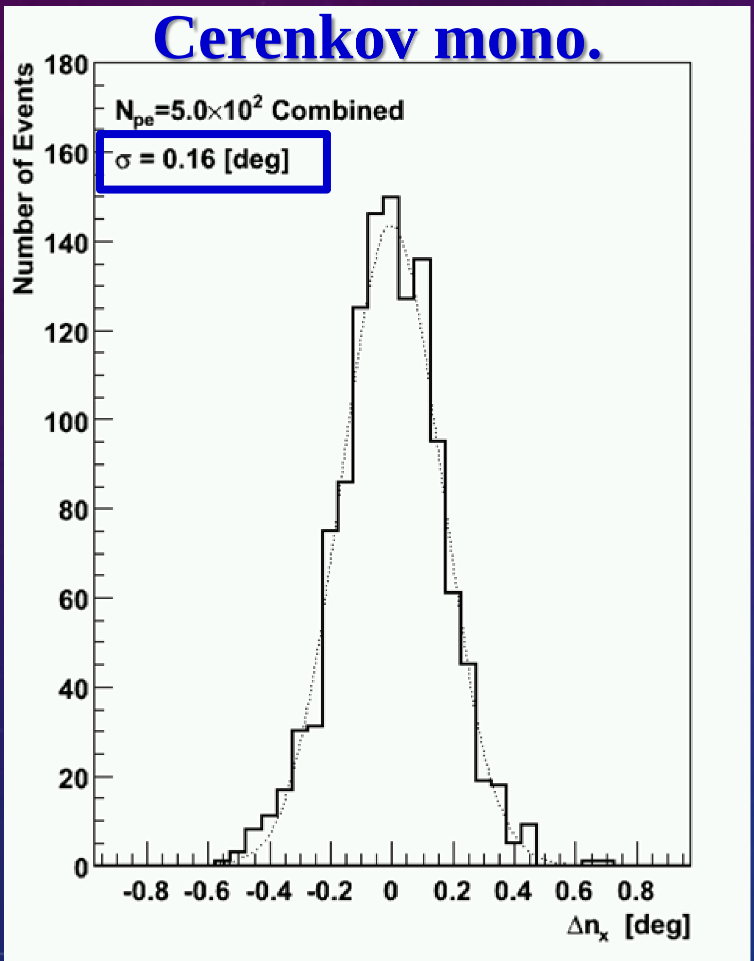
Y. Asaoka and M. Sasaki, Astropart. Phys. 41, 7 (2013).

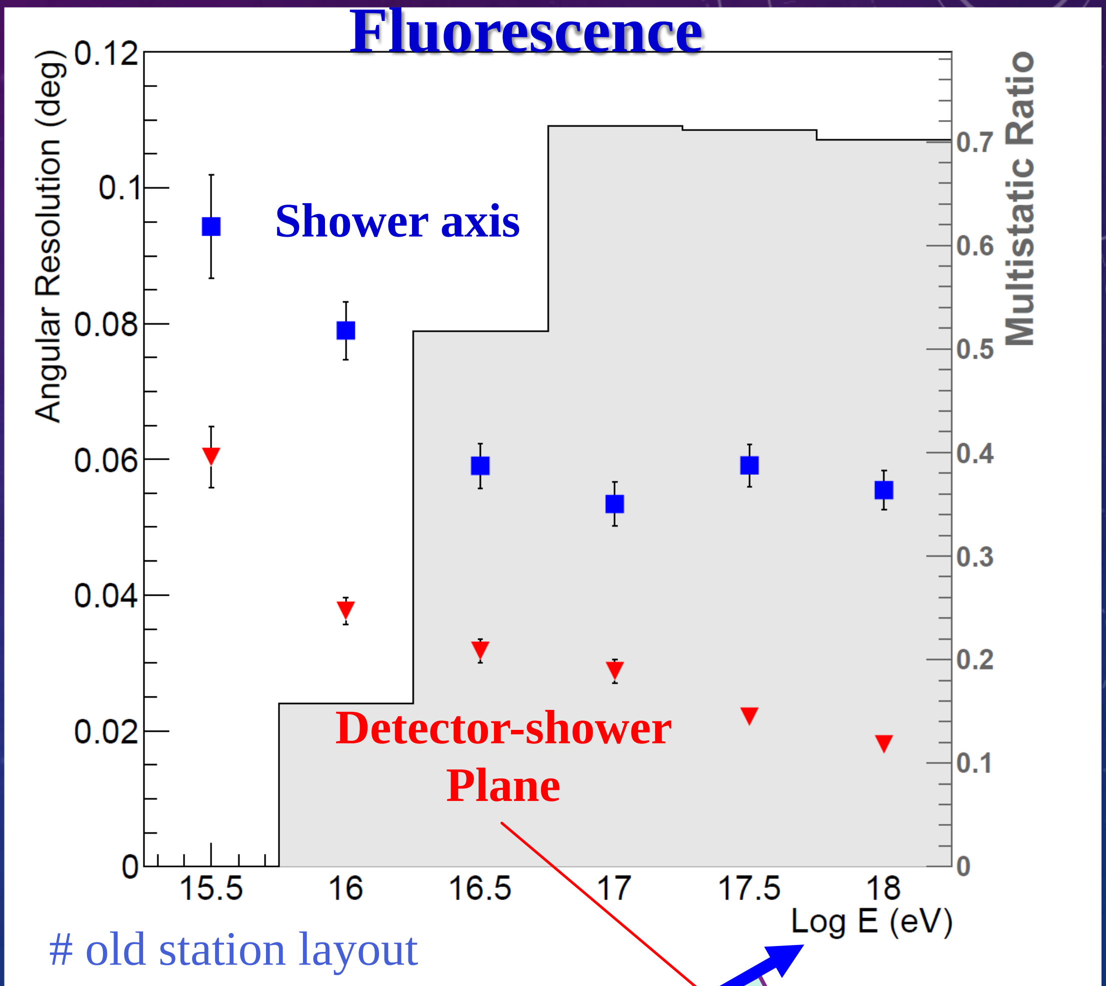


Reconstructed Angular Resolution

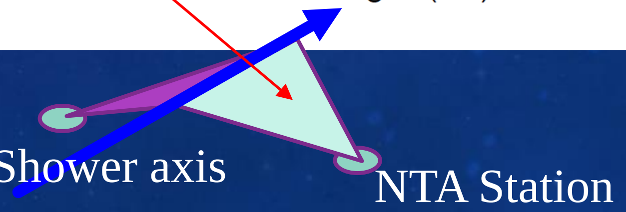
Y. Asaoka & M. Sasaki, Astropart. Phys. 41 (2013) 7–16

M. Sasaki & G. Hou, NTA LOI





⇒ **Point-back resolution <u>< 0.2 deg.</u>**
i.e. Cherenkov monostatic case



NTA

ES+DP-ν Sensitivities

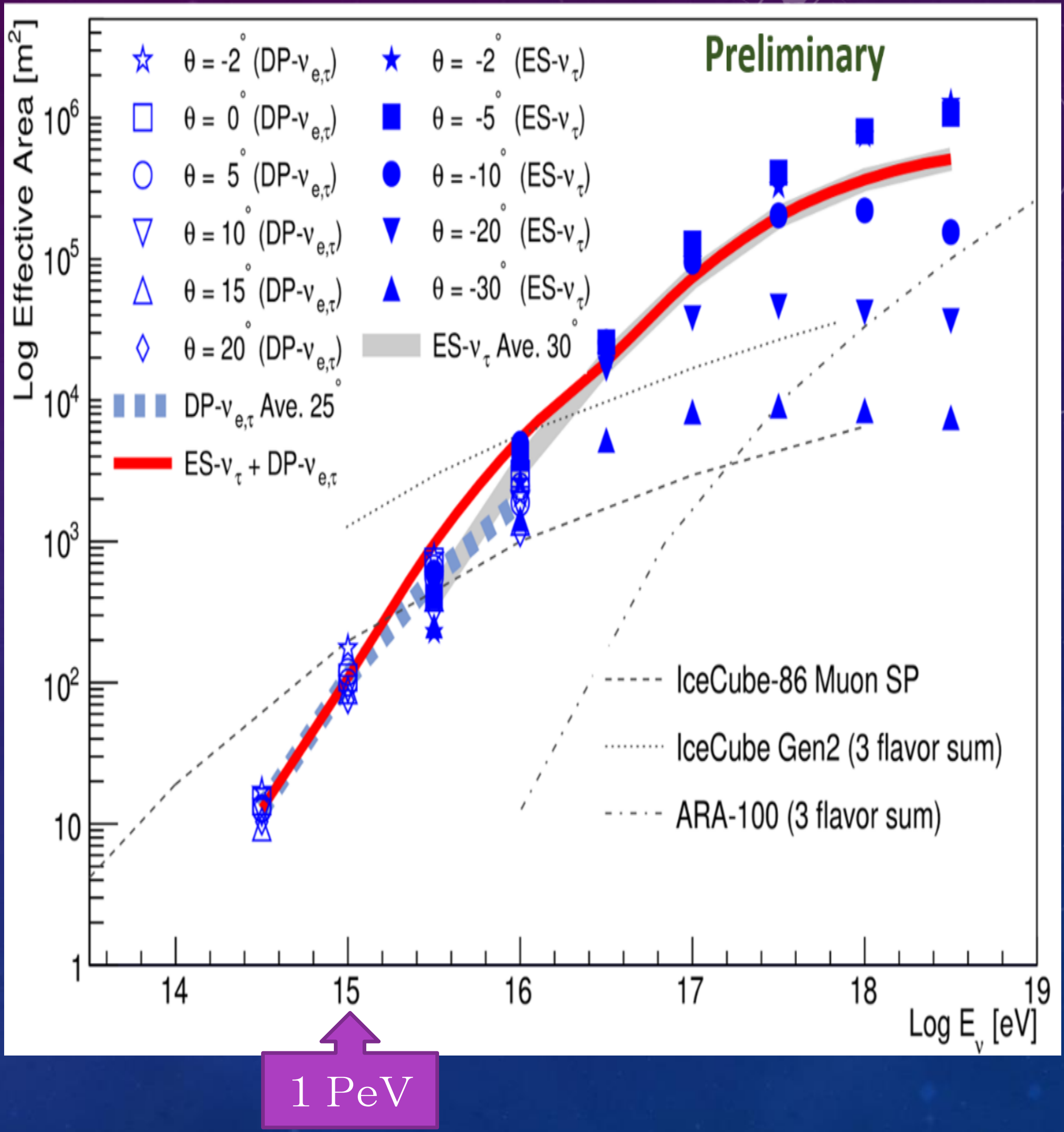
Tau decay length proglem for ES-ν_τ is recovered at E_ν = 300 TeV - 10 PeV

Note)

DP-ν_μ not yet implemented in the simulation.

Definition of A_{eff} :

$$N_{evt} = \Phi_\nu \cdot A_{eff} \cdot \Omega_{FOV} \cdot T_{obs}$$



NTA

Glashow共鳴

$\bar{\nu}_e e^- \rightarrow W \rightarrow X$ @ E = 6.3PeV

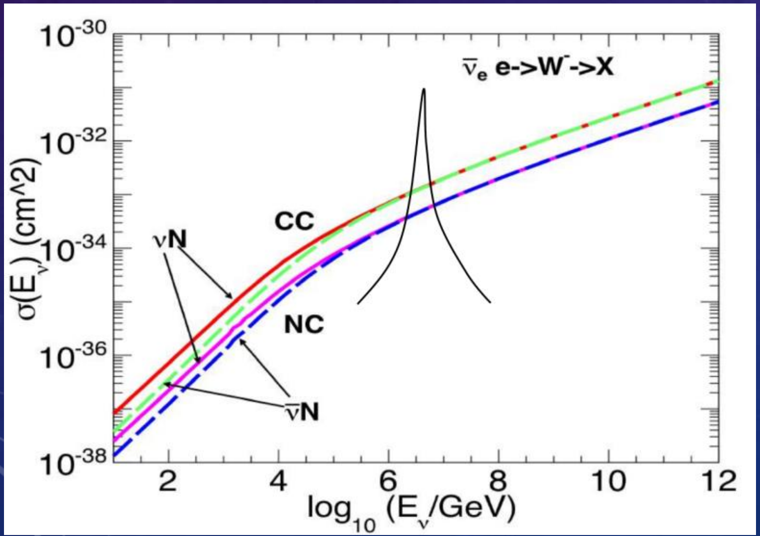
⇒ 崩壊 ハドロン70%、レプトン30%

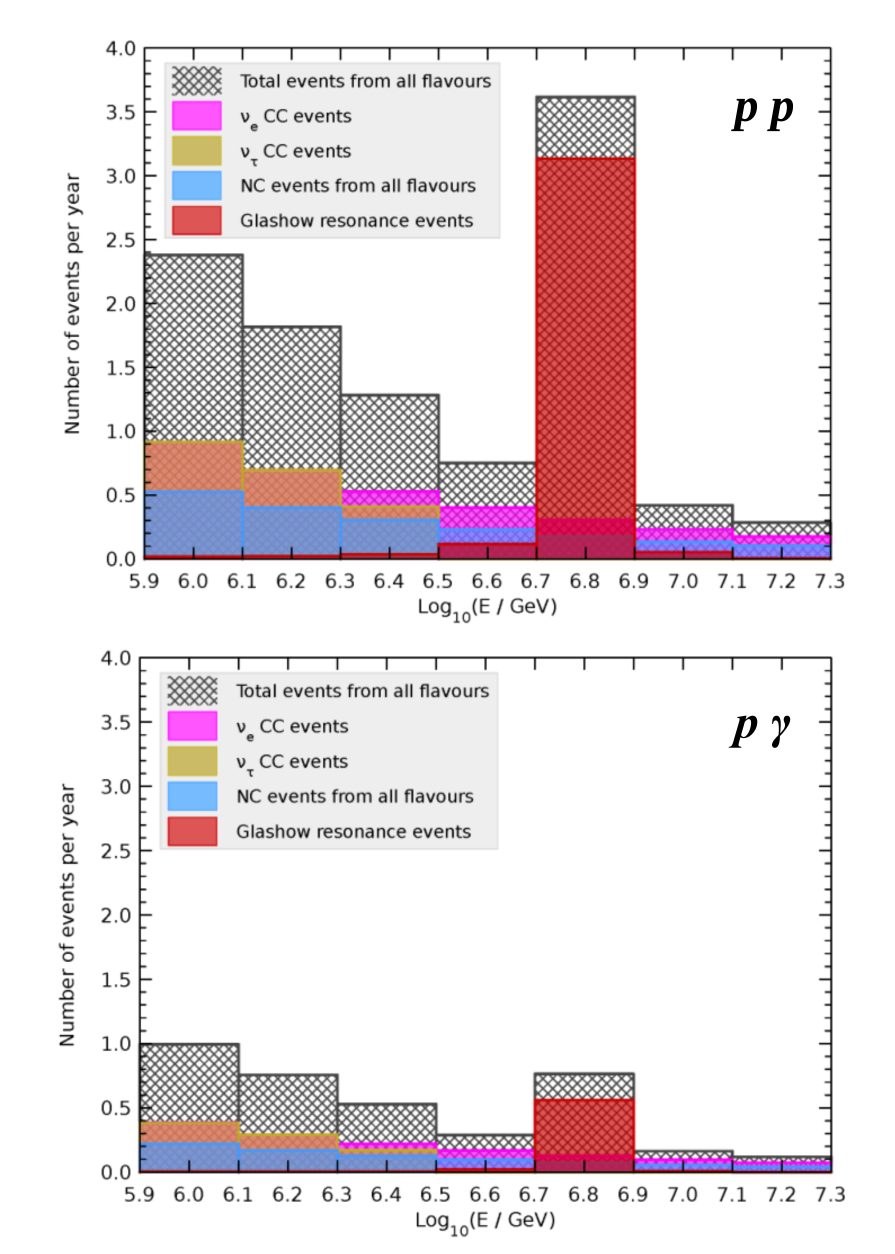
WB流束仮定 IceCubeで3, 4例/年 期待

NTA DP- $\bar{\nu}_e$ 空気シャワーで検定

DPではほぼ ν_e のみ、他フレーバBGなし

ES比べエネルギー決定も容易





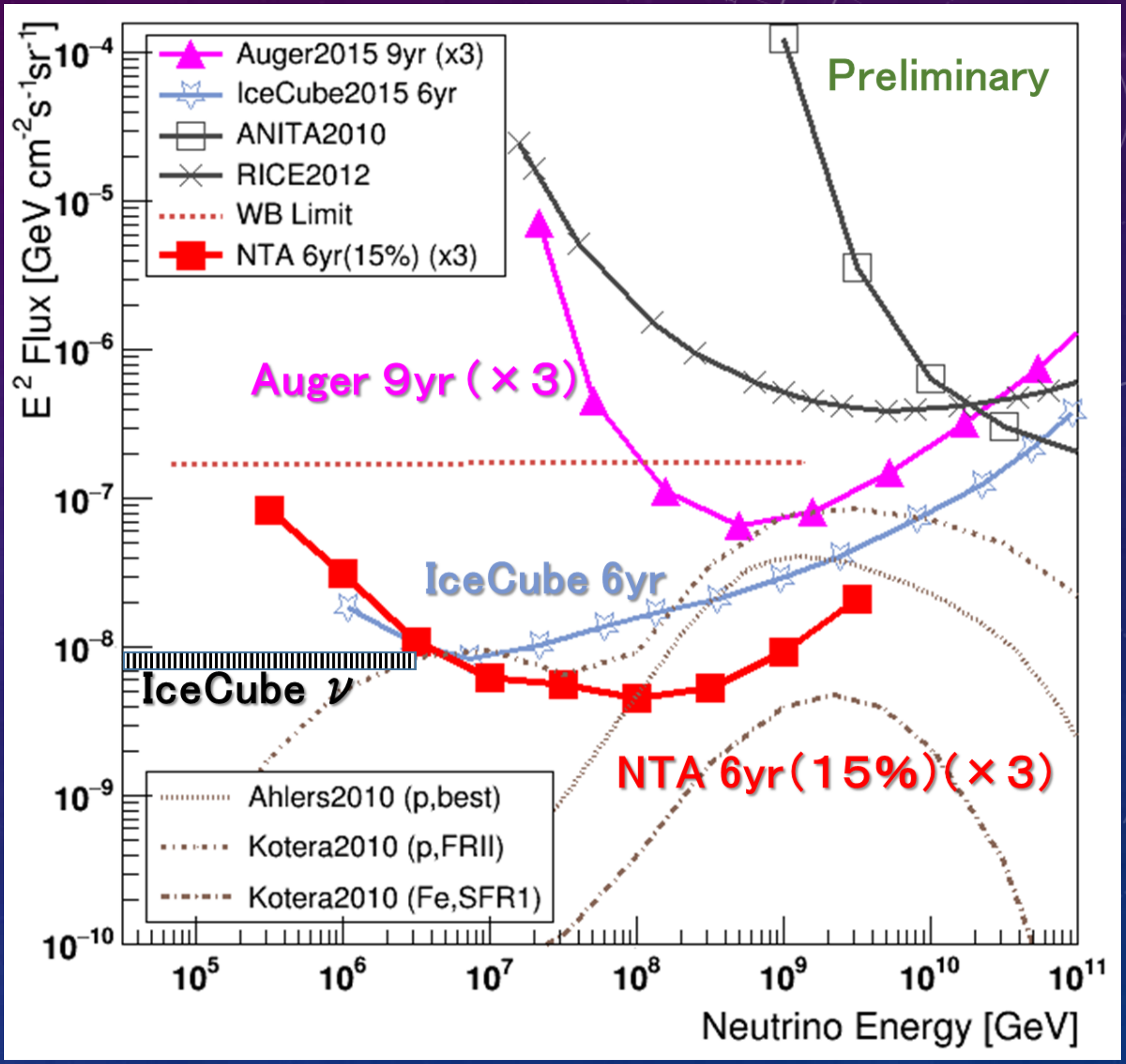
NTA

Diffuse ν Sensitivities

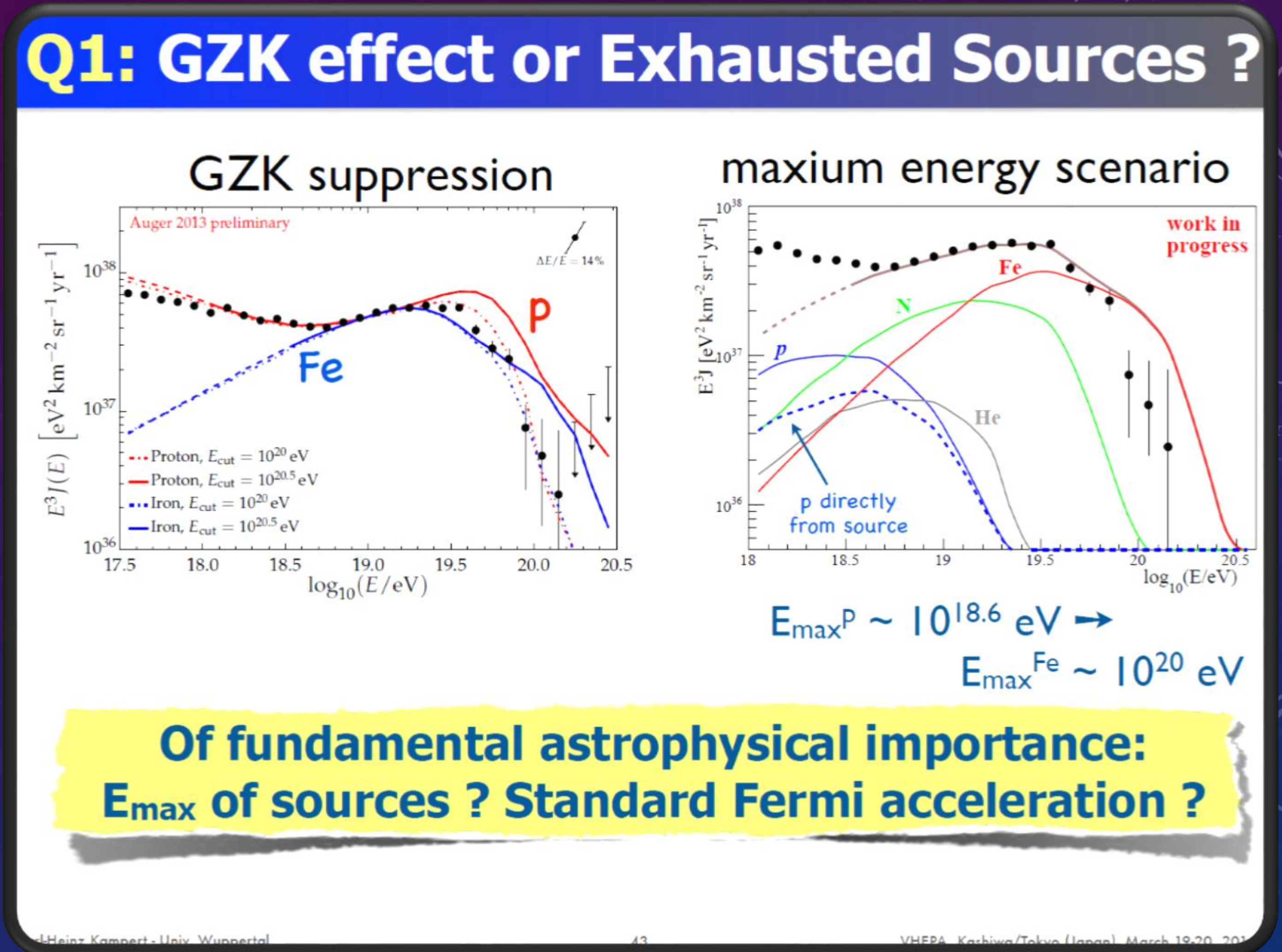
Best sensitivity above 1PeV but suffered by the duty factor (15%)

NTA FOV is nearly horizontal
⇒ Possible obs. under the Moon (Moon Run)

After successful R&D
duty factor 15% => 30%



NTA

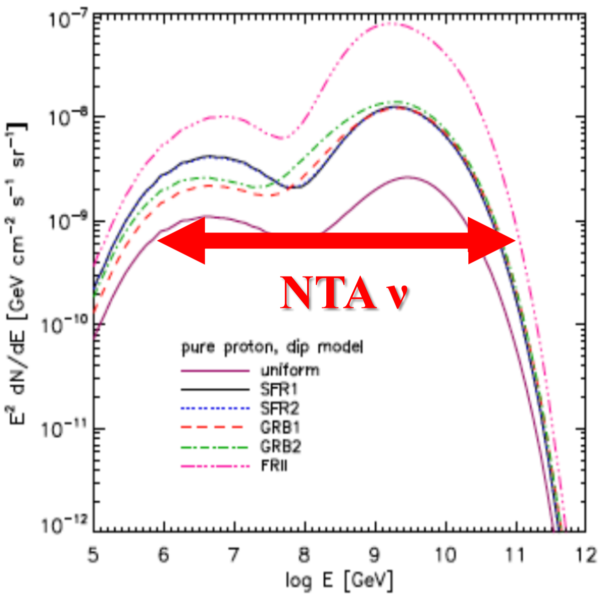


Karl-Heinz Kampert, VHEPA2014

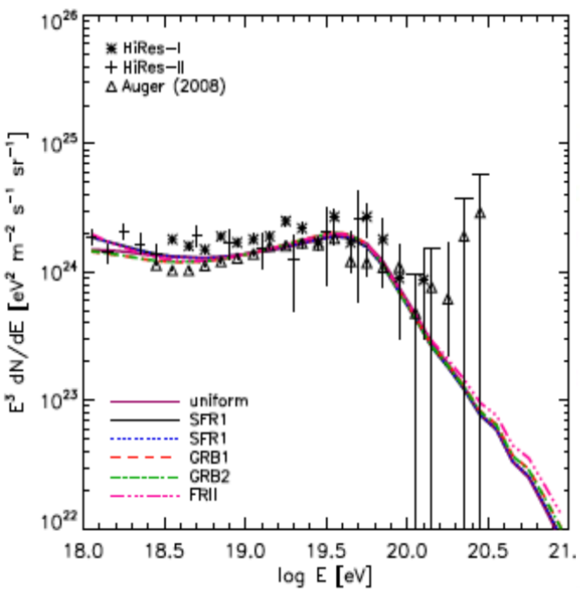
NTA

Resolve "GZK Effect/Exhausted Source" Problem

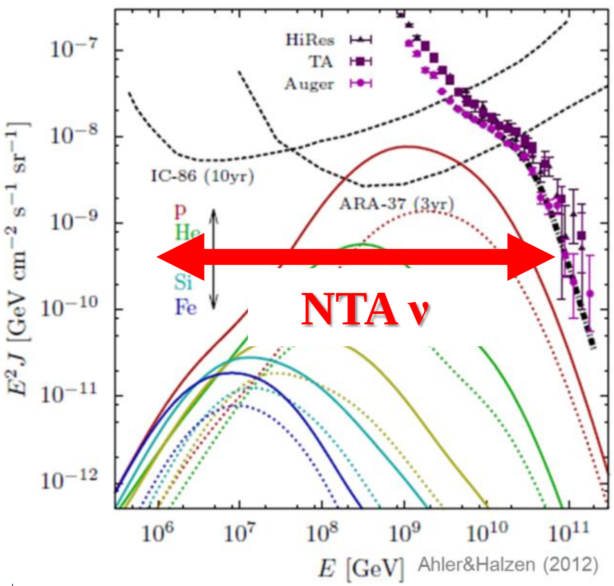
neutrinos



cosmic rays



neutrinos



Kotera, Allard & Olinto, JCAP 1010 (2010) 013.

Pure proton evolution, dip model

Ahler & Halzen (2012)

Composision dependence

Test the hypothesis by searching for the GZK-ν flux

⇒ NTA can rule it out completely

NTA

New γ-ray Imaging Method with PeV γ-ray Air Fluorescence Light

Air depth 690g/cm^2 @ 3300m asl. ~

Air-shower X_{max} = 600g/cm^2 at E_γ = 1 PeV

=>

NTA can image X_{max}

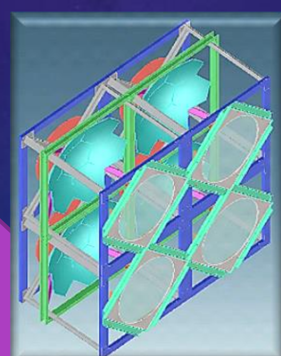
of PeV γ-ray air-shower in the FOV.

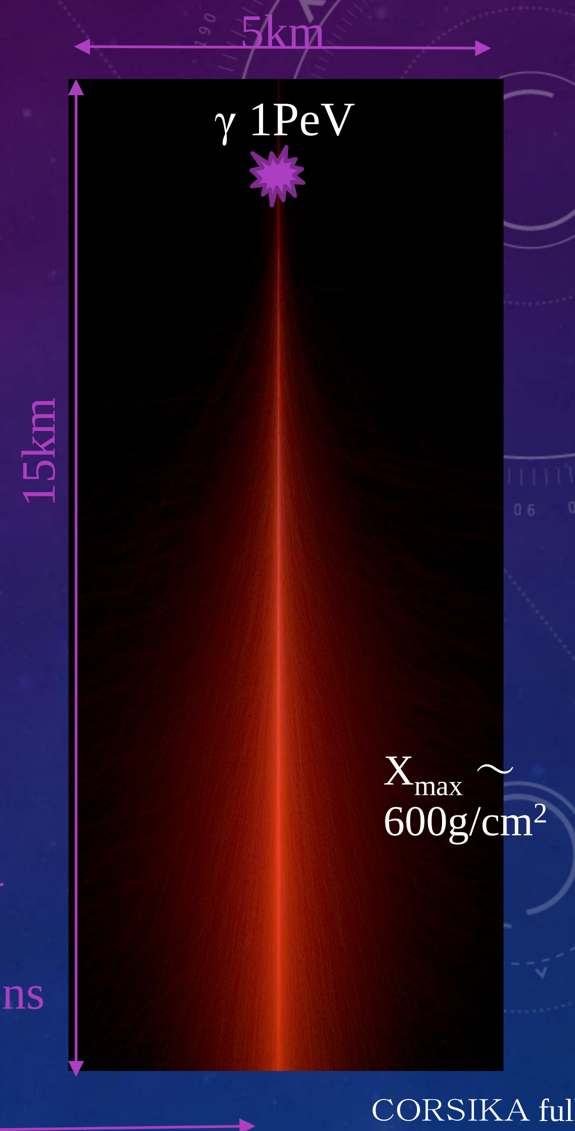
=>

NTA γ effective area is equivalent to

an grand array detector at ~3000m asl.

with the area of R_p < 2km @ 1 PeV





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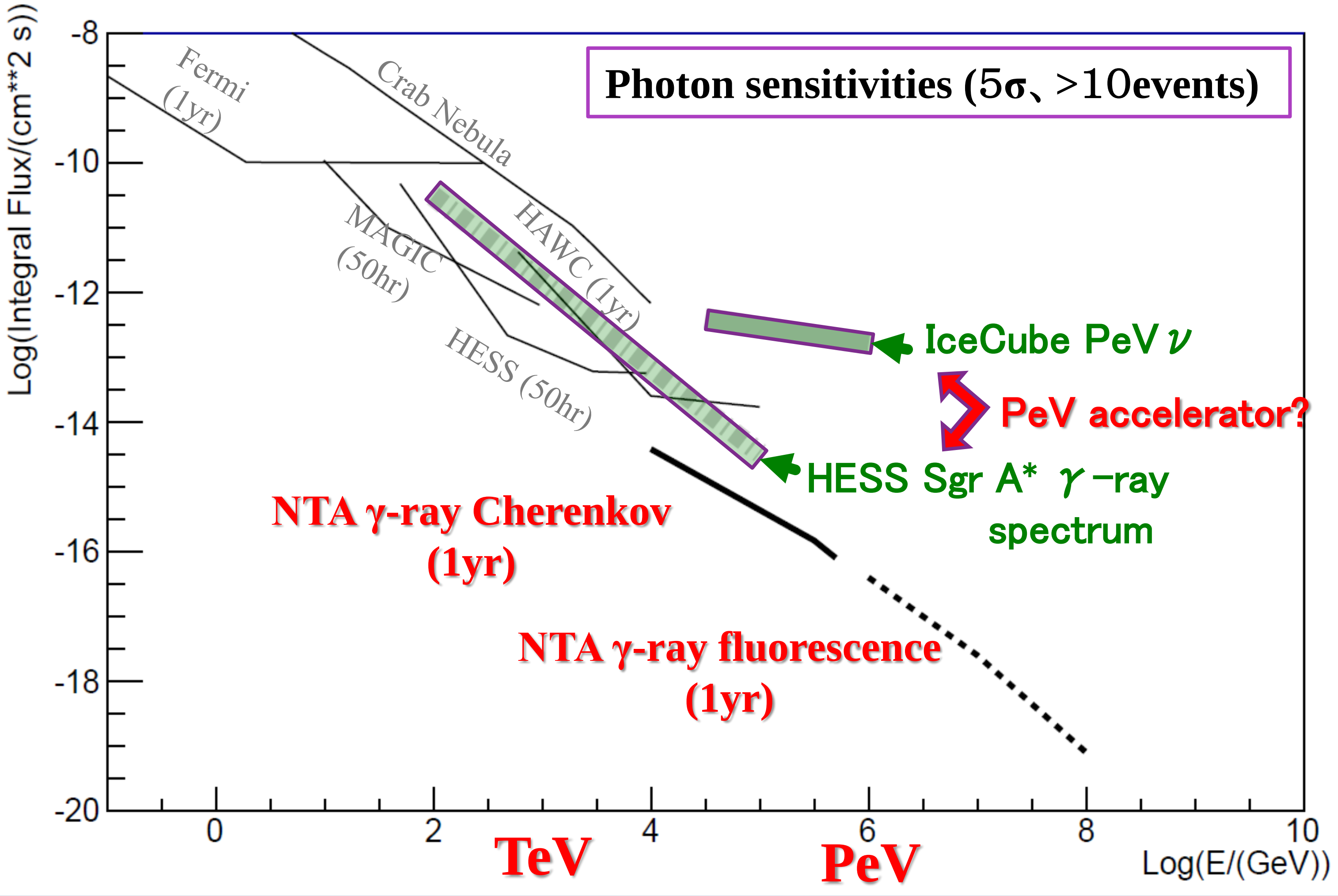
Integrated γ-ray Flux Sensitivities



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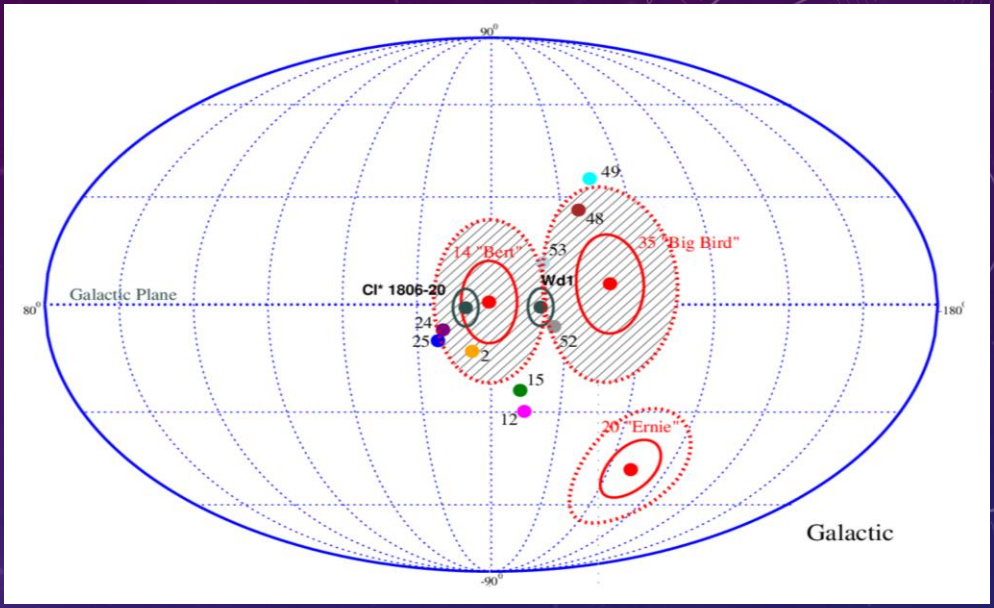
Compact Star Clusters in GP SNR γ-ray &ν Emissions

1σ, 2σ error circles from the center position of the IceCube PeVν

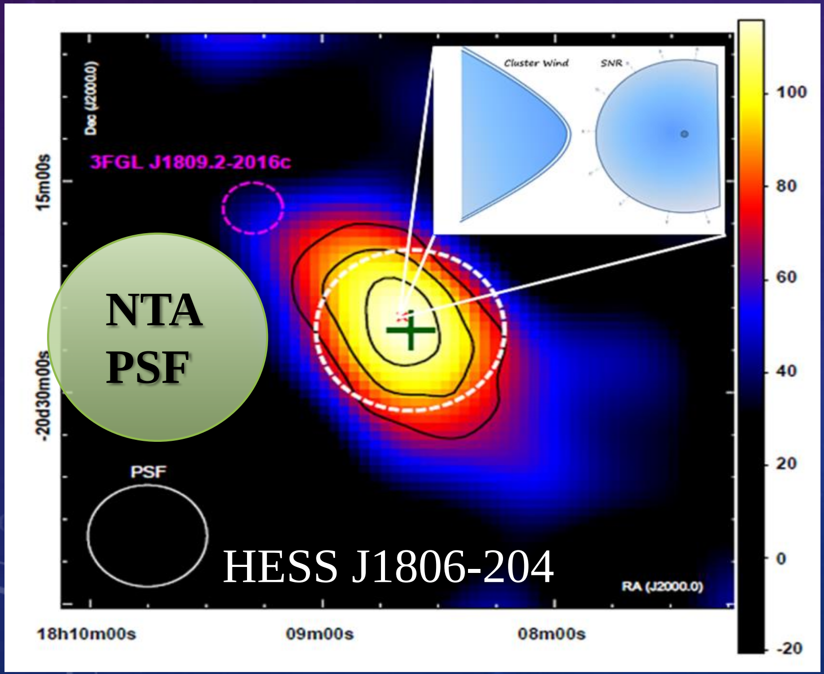
Evoluting young SNR:

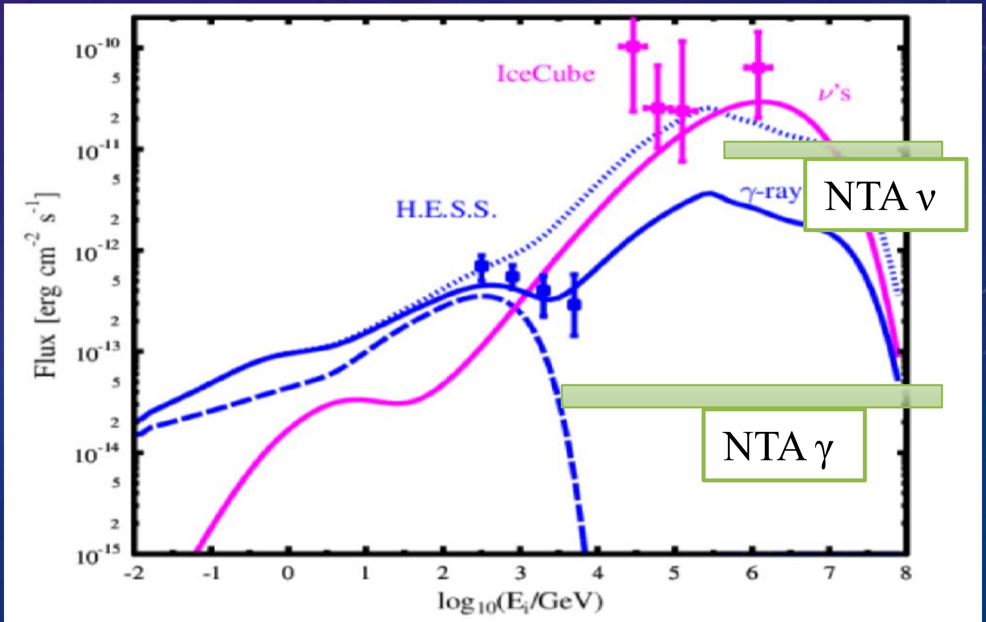
Westerlund 1 and HESS J1806-204

Colliding steller flow (CSF) model

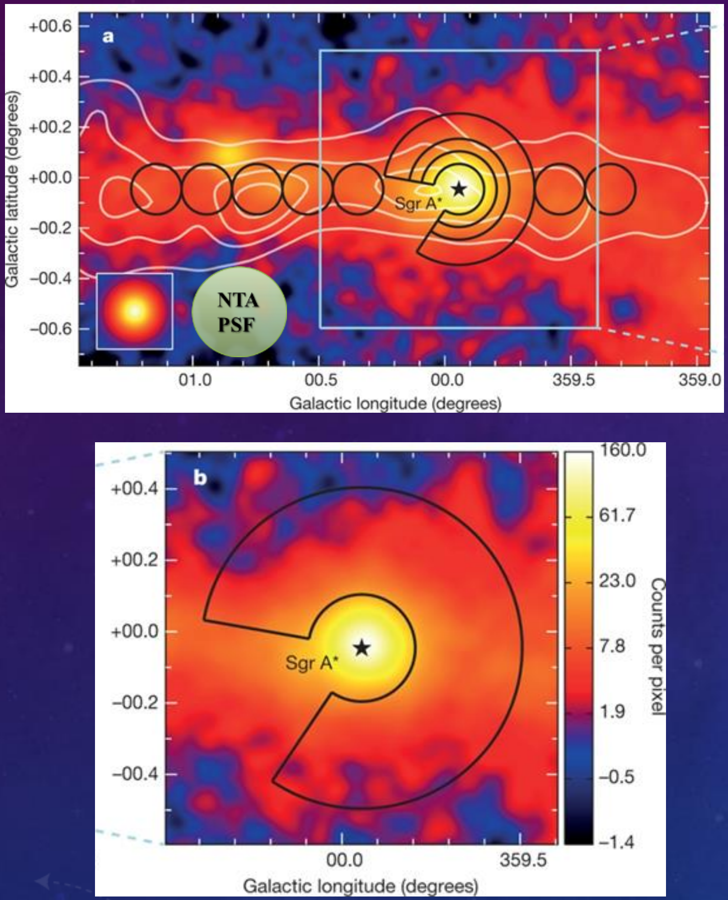


Bykov et al., AIP Conference Proceedings 1792, 020003 (2017)

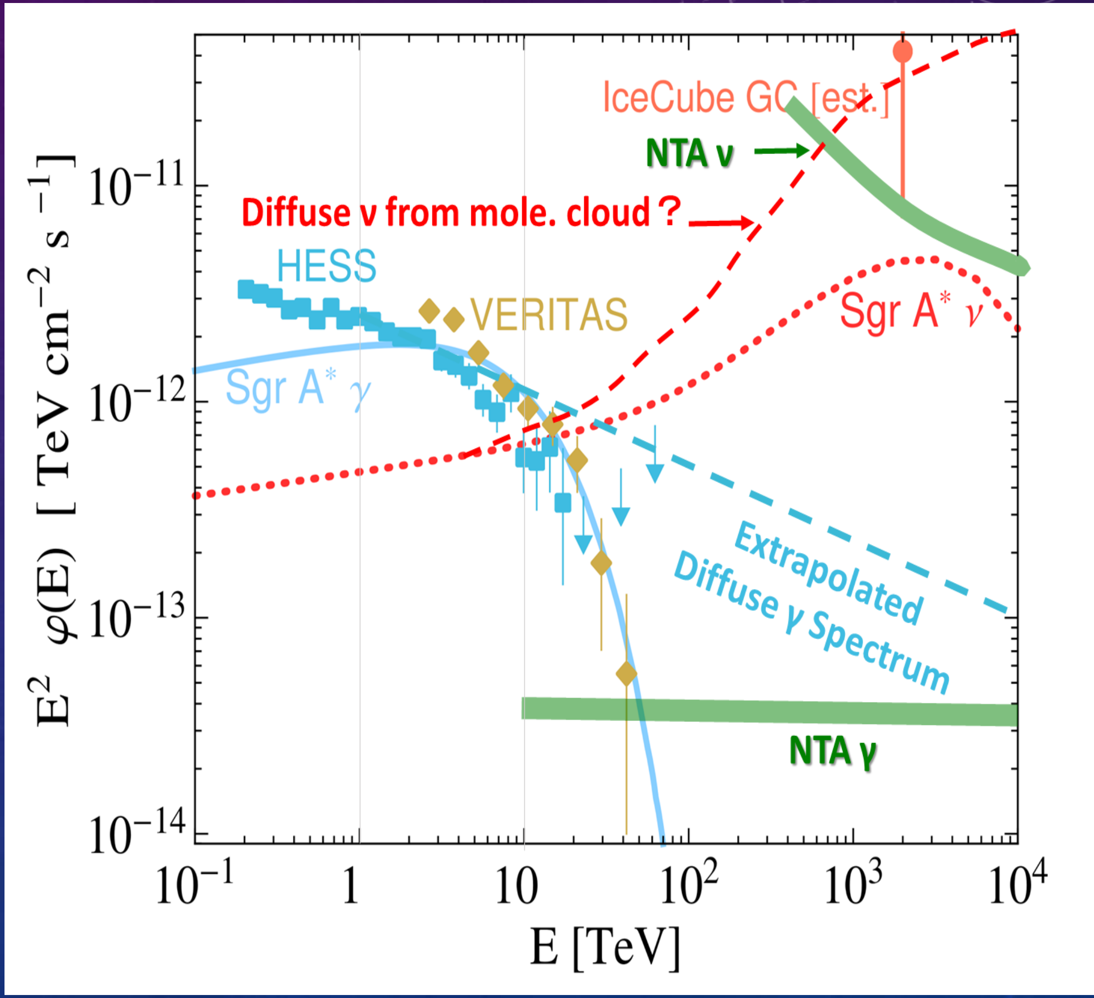




Pevatron Candidate Sgr A*
Combined Observation of PeV ν & γ-ray



HESS Image GC (Nature 531, 476)



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Possible Confirmation with NTA for HESS GC γ-rays

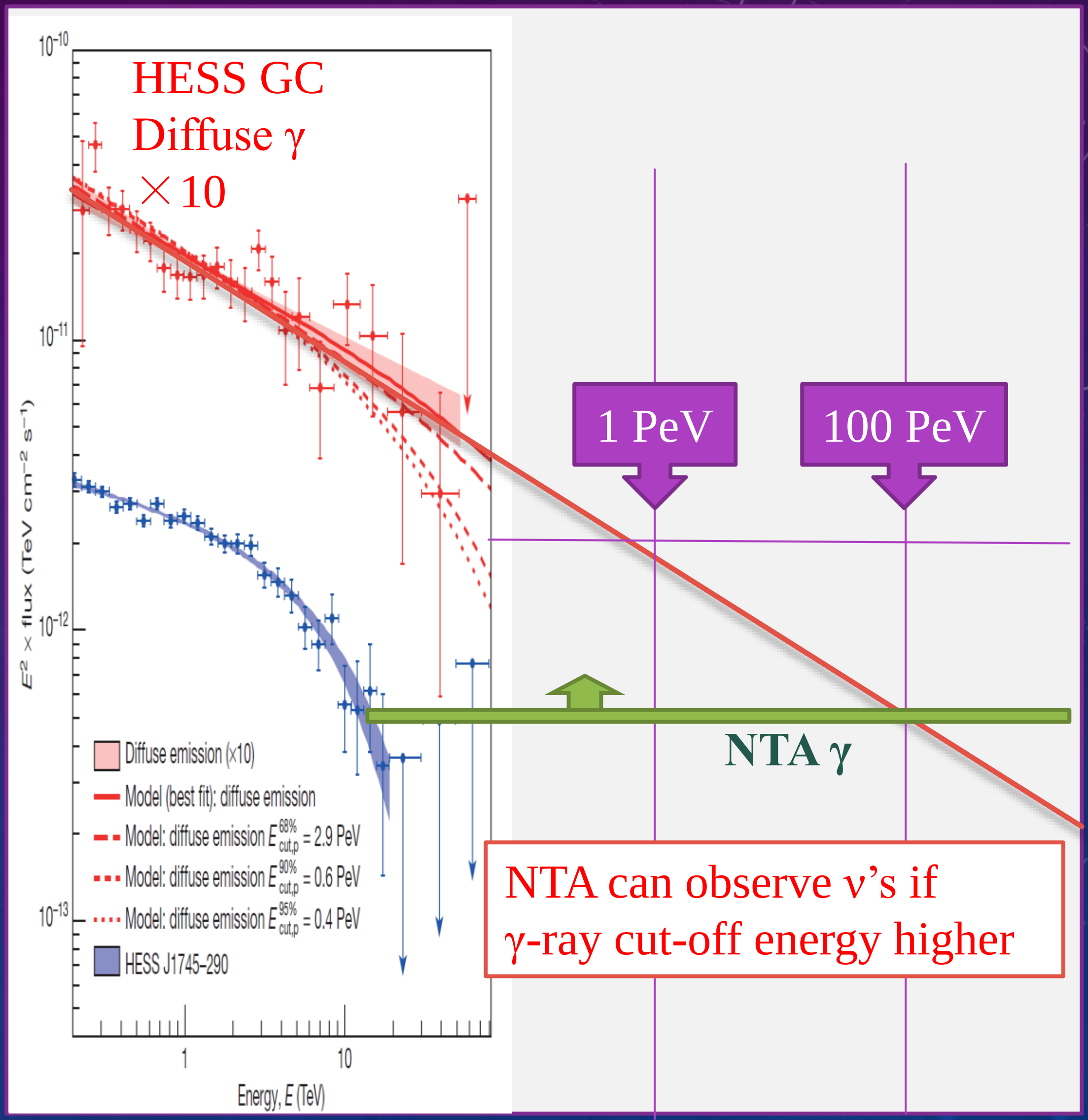
If NTA γ confirm no cut-off below 100 PeV

⇒ NTA must observe ν flux from GC

NTA γ confirm no cut-off below 100 PeV

and no ν flux

=> Non-standard accel. scenario or



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PRD 90 (2014):023010

Galactic Plane
TeV-PeV Diffuse γ-rays
Hypernova

Galactic Plane：

~1200 SNRs

~20個 Hypernova

加速された核子が滞在

星間物質と*pp*散乱⇒

拡散γ線やνを放出が期待される

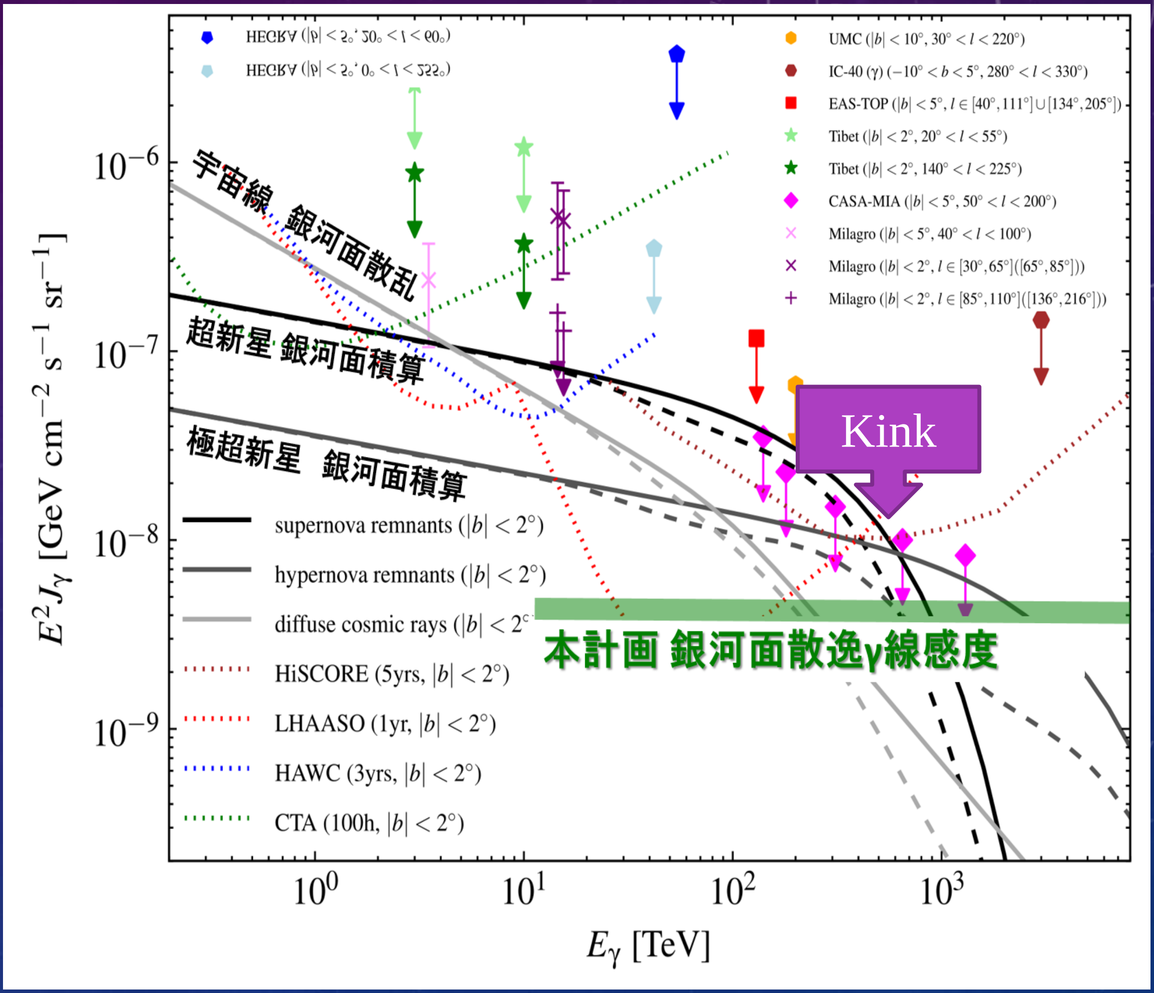
TeV-PeV γ-ray Observation：

GC (α= 266.4° , δ= -28.9°)

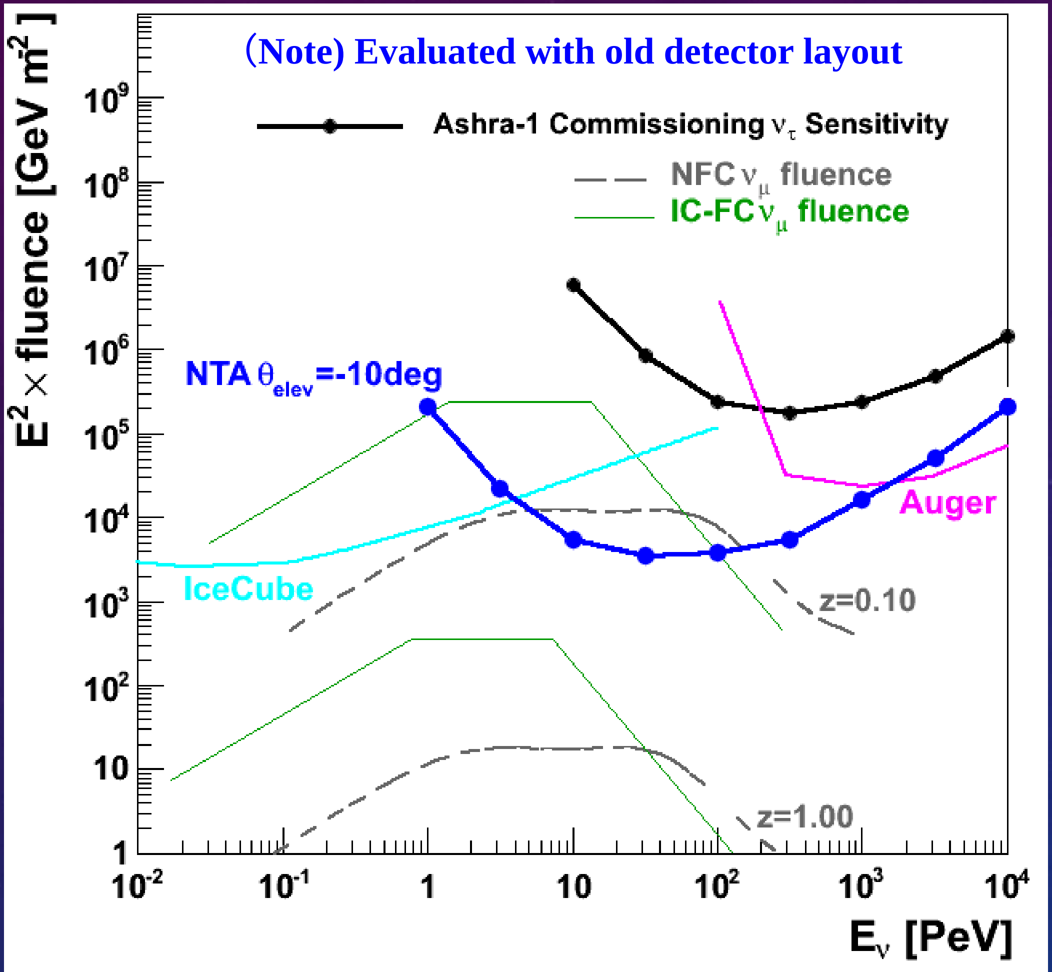
GP (|b|<2°)

are not included in FOV efficiently

Powerful NTA γ-ray imaging observation with wide FOV



GRB Neutrino Search Comparison



Complement IceCube:
- Methodology
- Energy
- Self-trigger for Tau Neutrino

0. Auger, PRD 79 (2009) 102001

1. IceCube, Nature 484 (2012) 351
- IC40+IC59 stacked 117+181GRBs
- Very strong bias for time window (28s) around Satellite Triggers to suppress huge BG

2. Murase et al. ApJ 651 (2006) L5
- Nearby Low luminosity (LL) GRB (ex. GRB 060218/SN 2006aj) dominate total neutrino fluxes at Earth
- X or γ Satellites cannot detect

3. Hummer et al. PRL 108 (2012) 231101
- Recalculated neutrino flux => Ashra Energy Region more important

NTA Survey Depth: z ~ 0.15 (600Mpc) for GRBν flux (by Hummer et al.)

LIGO等とのクロス観測 重要 ← NTAν GRB探査領域はLIGOと大きく重なる

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NASA： https://www.nasa.gov/feature/goddard/nasa-goddard-scientist-gives-outlaw-particles-less-room-to-hide

Lorentz Invariance Violation

PeV-EeV ν を使えば基本物理を探れる

- 超光速ニュートリノ

⇒ 他の粒子放出

⇒ スペクトルに鋭い切断

⇒ IceCube PeV ν から制限？

⇒ **高エネルギー側の高統計が必要**

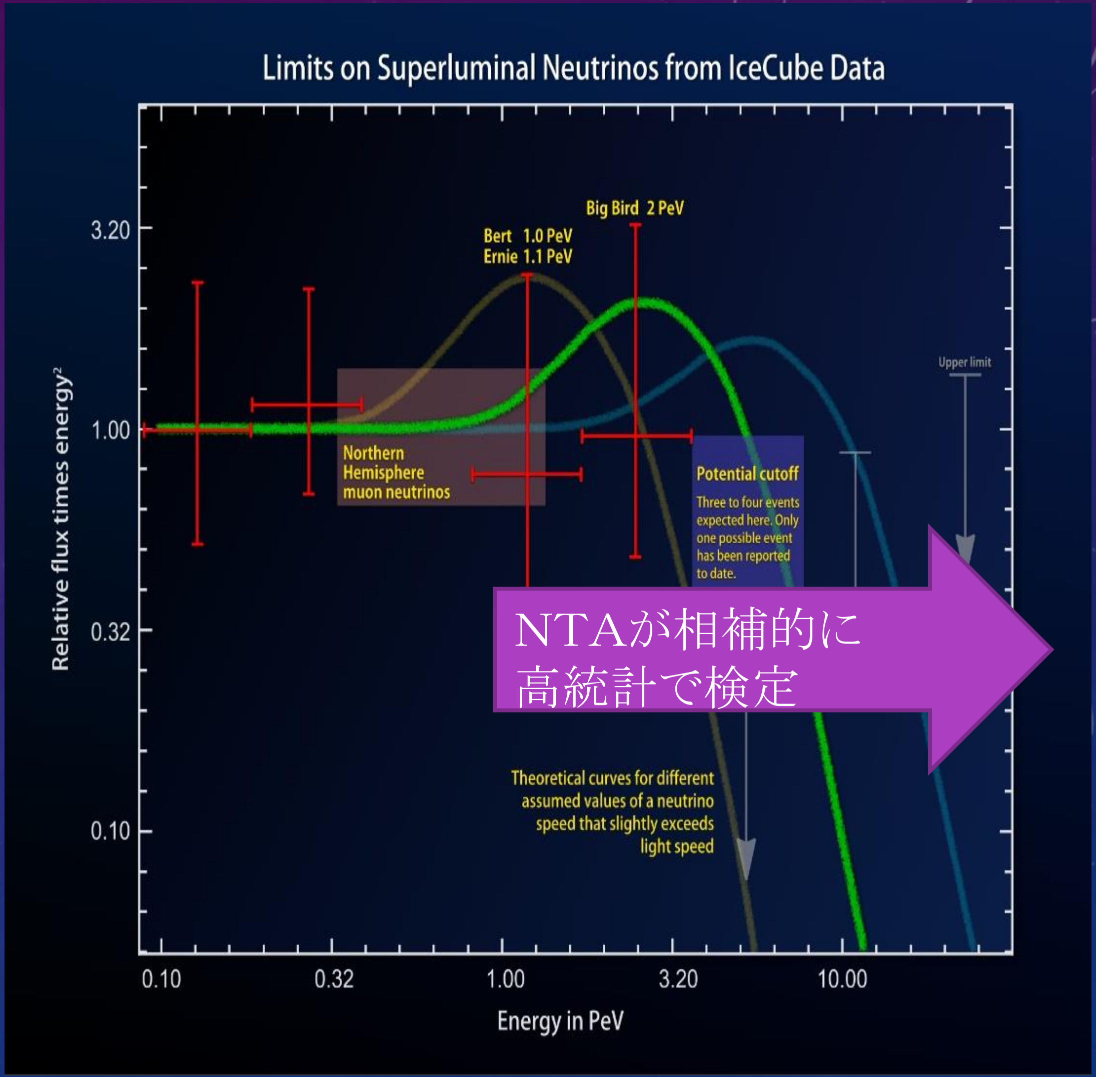
- 突発天体からν速度への制限：

例）PKS B1424–418 とHESE-35 PeVν　一致？

⇒ $(v - c)/c < O(10^{-11})$

⇒ 対応天体との一致の信頼度が重要

⇒ **NTA ν**



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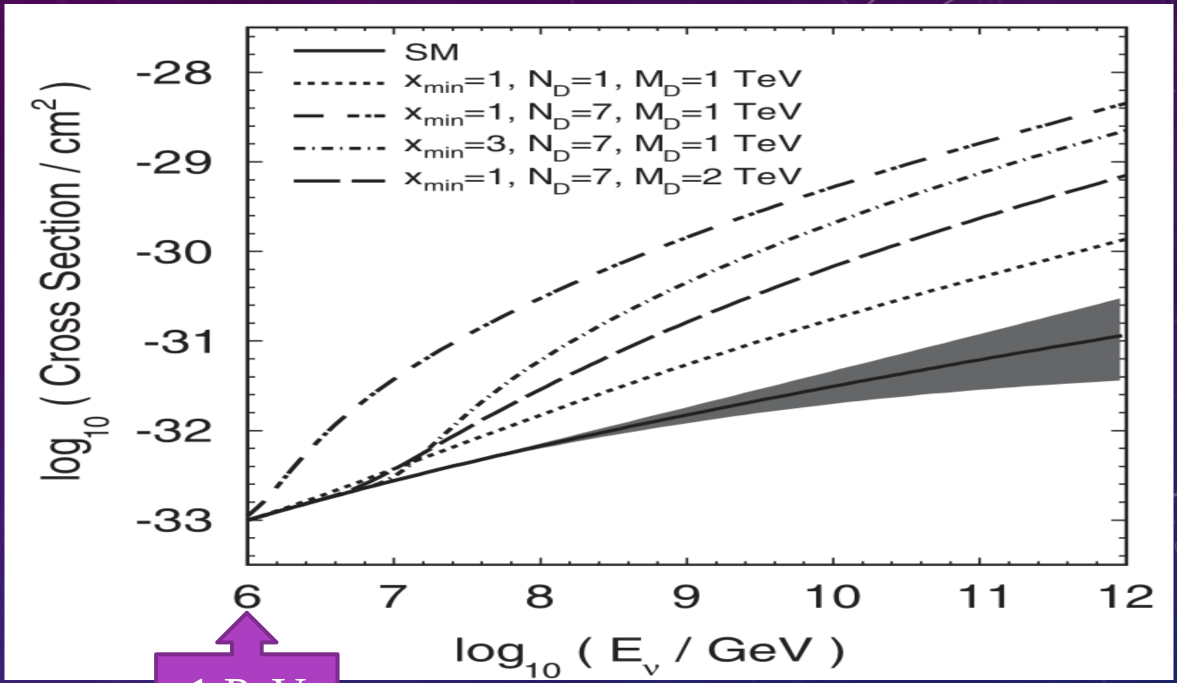
Extra Dimension Search



1 PeV

A.Connolly et al., PRD 83, 113009 (2011)

重力が3+1次元で弱いのは他次元に伝達したため

減少Planck質量以上でマイクロBHの生成

⇒ νN散乱断面積の増加

もしくは、散乱長の変化による、

地球との散乱角度分布の変化

LHC(7TeV)でも探査、μBH質量制限

NTA ES-ν では：

地球かすり角(θ)分布異常

NTA ES-ν / DP-ν の事例数の比

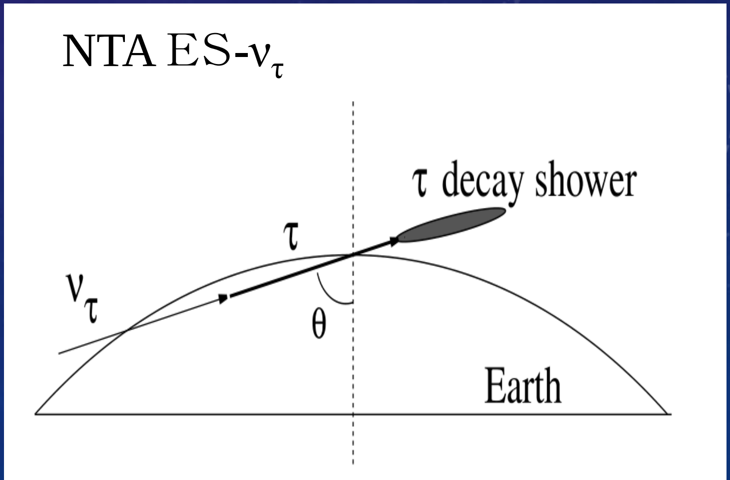
に反映される

検定に高統計と高い角度分解能が必要

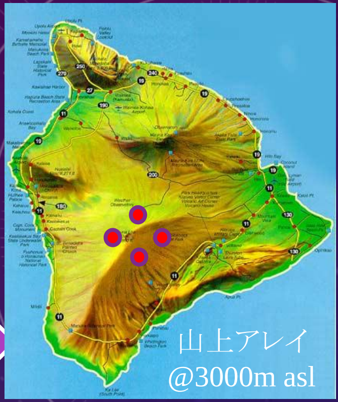
⇒ NTA ν

E_ν (PeV)	L_{CC}^{ν} (10^7g/cm^2)	$-\theta_{elev}$ (deg)
1	270	32
10	94	16
100	35	5.9
1000	14	2.3

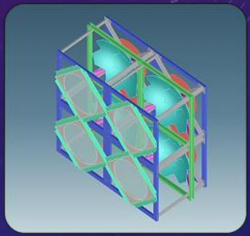
[M.Sasaki et al., Astropart. Phys. 19 (2003) 37]



NTA 観測に向けて

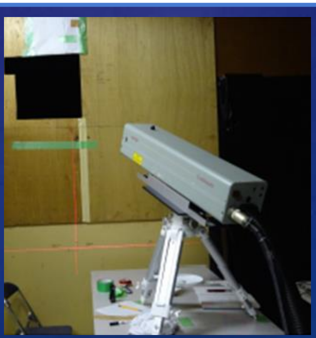


	2016	2017	2018	2019	2020	2021	2022	2023
NTA 国際共同観測拠点	予算請求		建設/部分的観測					完全観測
Ashra- 国際実証開発拠点	実地試験観測/ 多粒子観測/ 自動化・データ流・解析技法の確立							
Akeno 国内開発拠点	アセンブリ/統合化/レーザー観測/長期安定性・試験							



国内外のラボ

要素開発・試験



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Summary

Open a new chapter of physics with NTA

ν & γ telescope with < 0.2° resolution, > π sr FOV,
and high sensitivity in subPeV-EeV.

- ν & γ cross detection with IceCube around 1 PeV
- Check ν & γ wide range spectra in subPeV-EeV
- ν & γ survey of GP including GC

=> Clear ID of position and mechanism of Pevatrons

- Search for ν & γ short burst with LIGO and others

=> Significant & complementary contributions to Time Domain Astronomy
=> NTA can also issue ν & γ burst alerts rapidly

- Probing astroparticles propagating in BG photons

=> Solving out GZK-problem with testing diffuse-ν flux
=> ν & γ combination to reveal BG photon density more precisely

- Probing non-standard physics at energy frontier

=> Highest energy ν particle physics
Extra dimension, Lorentz invariance violation, ...
=> Highest energy γ-ray observation
New “Super-Cutoff Problem” a la Super-GZK

Toward Comprehensive Understandings for VHE Particle Universe