Sensitivity for tau neutrinos at PeV energies and beyond with the MAGIC telescopes

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Outline:
1) Introduction
2) Identification of tau neutrino induced showers
3) Results (acceptance, event rate, sensitivity)

Introduction

> **UHE Neutrinos arise from decays of charged pions:**

Hadronic model:

$$p + p(\gamma) \rightarrow \pi^{\pm} + X$$
$$\hookrightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$
$$\hookrightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_e(\bar{\nu}_e)$$

$$p + p(\gamma) \rightarrow \pi^{0} + X$$
$$\hookrightarrow 2\gamma$$

> Sources: AGNs,GRBs, Supernova ...

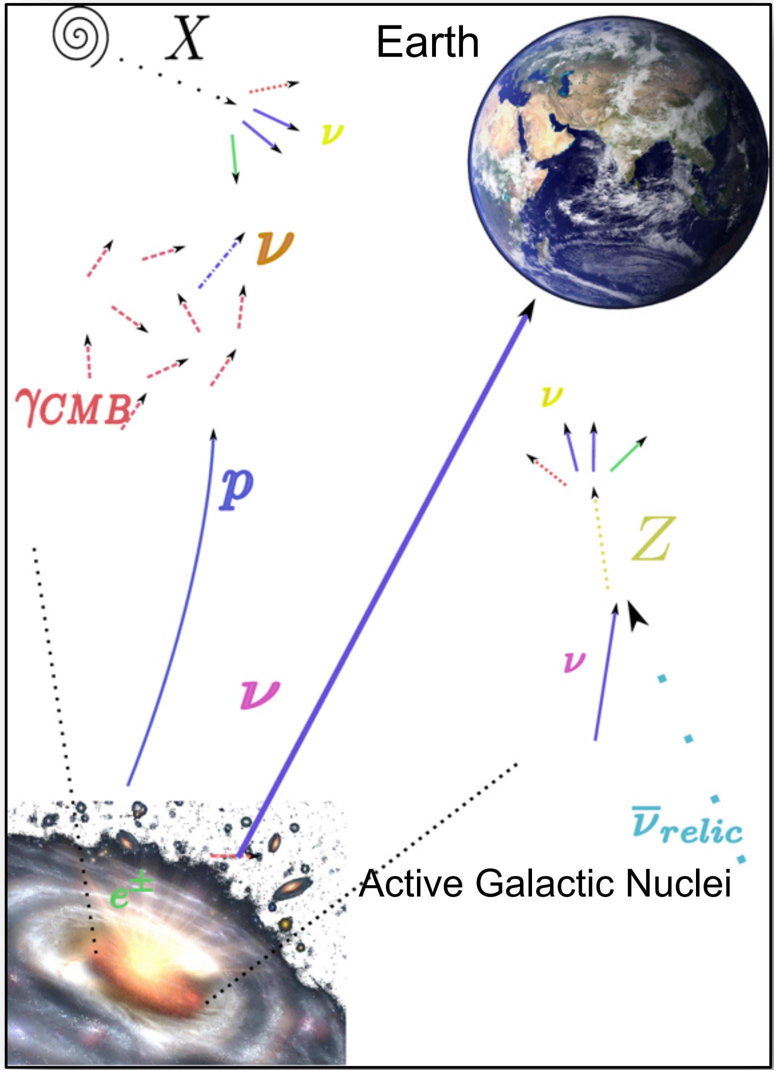
$$\nu_{\mathbf{e}} : \nu_{\mu} : \nu_{\tau} = \mathbf{1} : \mathbf{2} : \mathbf{0}$$

> Flavour oscilations over cosmological distances:

$$\nu_{\mathbf{e}} : \nu_{\mu} : \nu_{\tau} \sim \mathbf{1} : \mathbf{1} : \mathbf{1}$$

In this scenario we expect tau neutrinos at Earth

> **Neutrinos are also produced from interaction of Cosmic-rays with Microwave Background (GZK or cosmogenic neutrinos)**



> **Present status:**

IceCube: 82 HE neutrino candidates (30 – 2000 TeV) PoS(icrc2017)981
Fermi: evidence from pions of proton acceleration from Supernova Remnamts (60 MeV – 2 GeV) (Science,15 Feb 2013)

Choked Jets and Low-Luminosity GRBs

> **AGNs,GRBs, Star-form./burst galaxies do not explain the IceCube neutrino signal**
...IceCube neutrinos are also not traced by extragalactic γ-emitters (VERITAS, MAGIC, Fermi) ➔ IceCube neutrinos could originate from environments with high γ-ray opacity

> **Choked jets and Low Luminosity GRBs as hidden neutrino sources**

N. Senno, K. Murase, P. Meszaros Phys. Rev. D 93, 083003 (2016); E. Nakar, The Astrophysical Journal, 807 2 (2015) ->LL GRB 060218/SN 2006 AJ

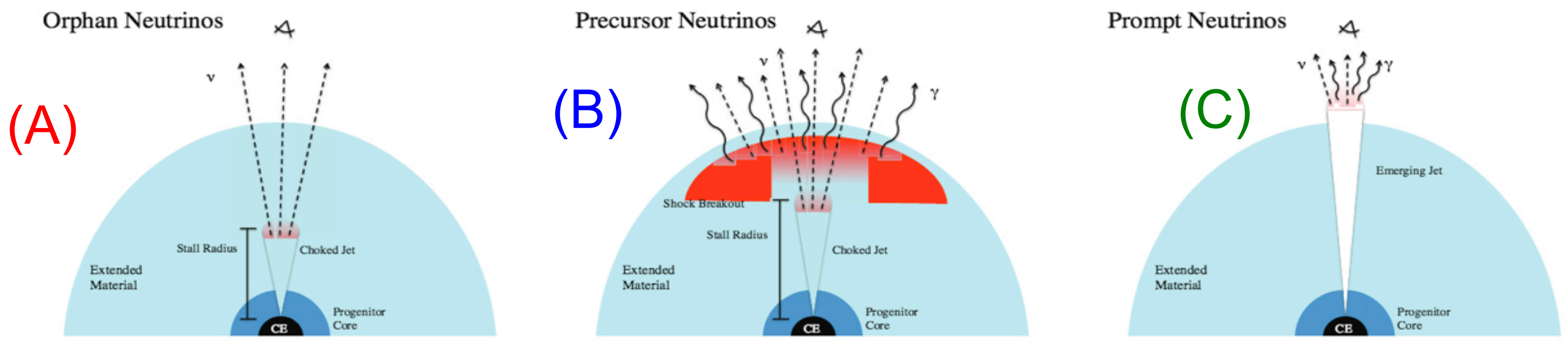


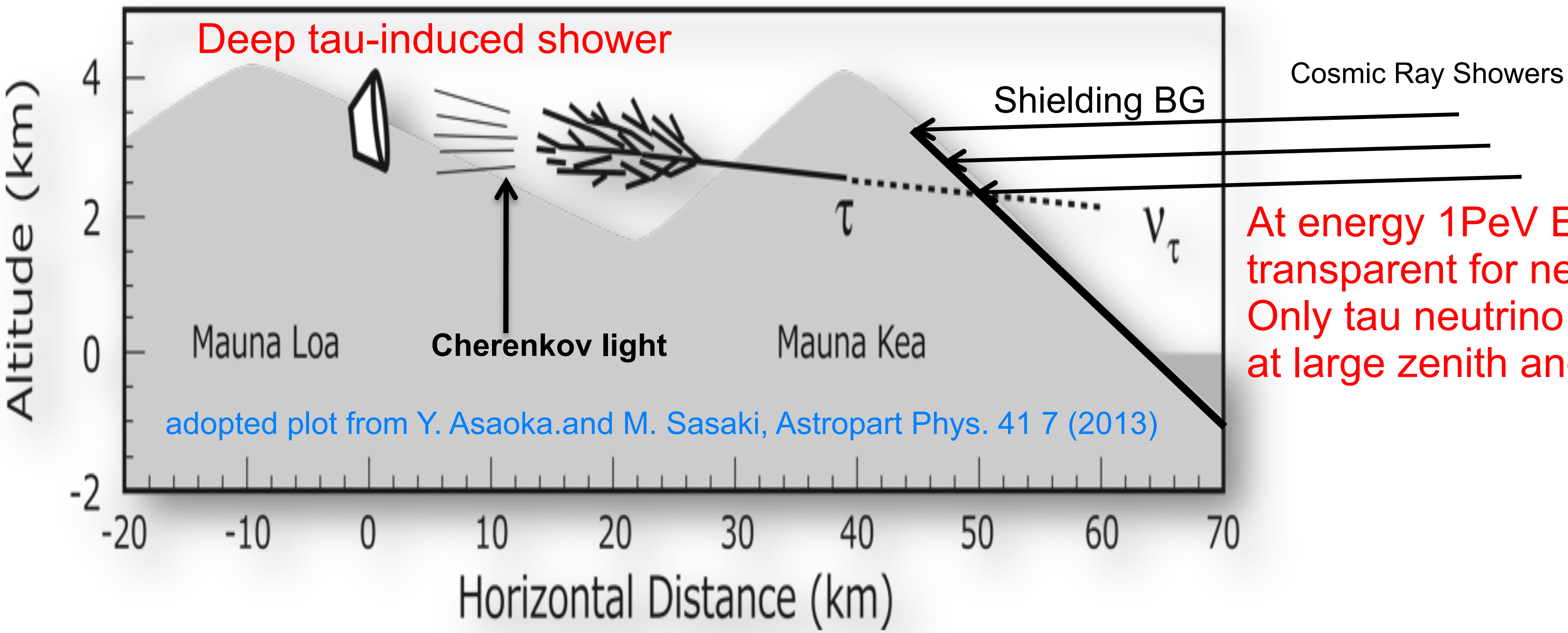
FIG. 1: **Left panel:** The choked jet model for jet-driven SNe. Orphan neutrinos are expected since electromagnetic emission from the jet is hidden, and such objects may be observed as hypernovae. **Middle panel:** The shock breakout model for LL GRBs, where transrelativistic SNe are driven by choked jets. Choked jets produce precursor neutrinos since the gamma-ray emission comes from the SN shock breakout later than the neutrinos (e.g., [25]). **Right panel:** The emerging jet model for GRBs and LL GRBs. Both neutrinos and gamma rays are produced by the successful jet, and both messengers can be observed as prompt emission.

(A)	(B)	(C)
- Neutrinos - γ-ray absorbed - Time scale: $10^{1.5}$ - $10^{2.5}$ s	- neutrino precursor - Later γ-ray counterpart - Time scale: 10 - 1000 s	- neutrinos - γ-ray emission - Time scale: $10^{3.5}$ s

Earth-skimming technique

- **Up to now, NO detection of high energy tau neutrino, so detection would:**
  - *confirm astrophysical origin of IceCube events*
  - *shed light on the emission mechanisms at the source (hadronic vs leptonic)*
  - *better constrain new physics models which predict deviation from equal fraction of all flavours.*
- **Challenge: identify neutrino showers in dominant background of nucleonic showers**
  - *The discrimination power is enhanced when looking at inclined showers*

Earth-skimming technique: D. Fargion, Astrophys.J. 570, 909 (2002).
X. Bertou et al., Astropart.Phys. 17, 183 (2002).



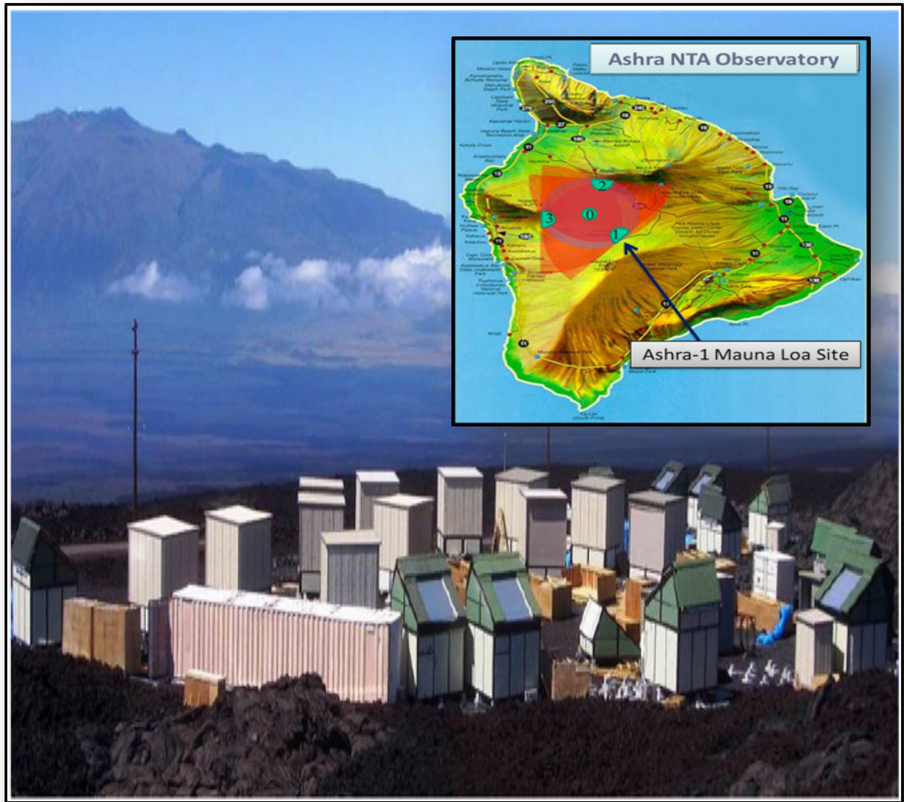
At energy 1PeV Earth is not transparent for neutrinos. Only tau neutrino can survive at large zenith angles 90°-95°

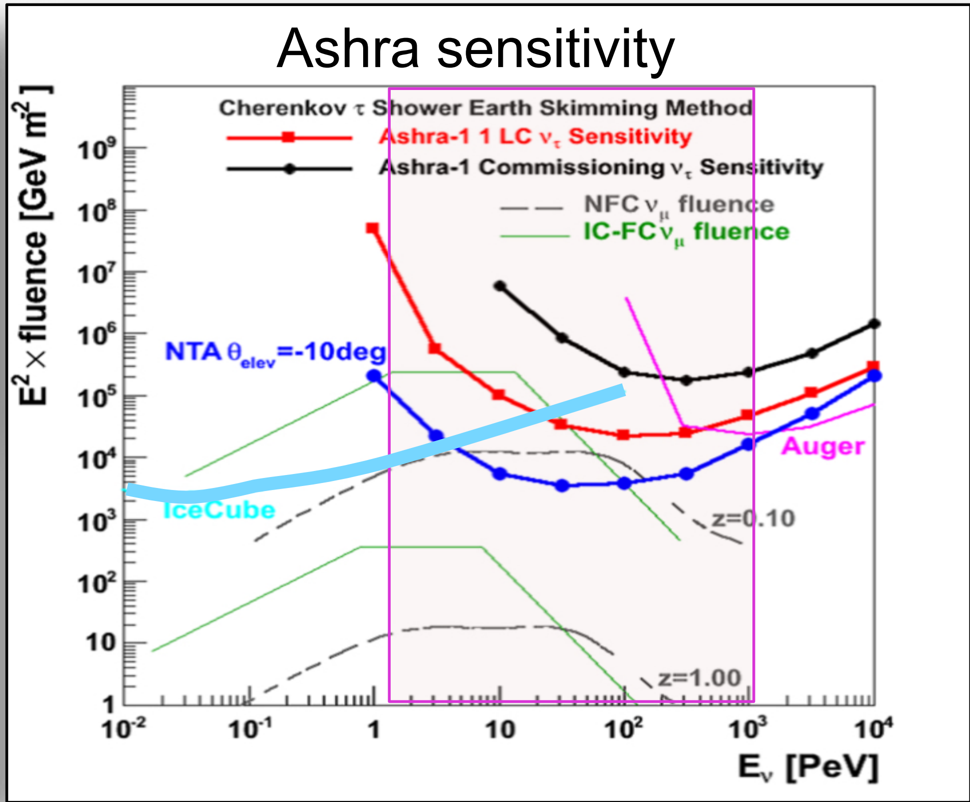
Ashra and its extension

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

*-12 light collection detectors **covering 77% of entire night sky**, the wide optical **field-of-view (42 deg)**, high resolution imaging system with trigger **(arcminute res.)***

- planned extension, so called Neutrino Telescope Array (NTA) *(astro-ph:1409.0477)*



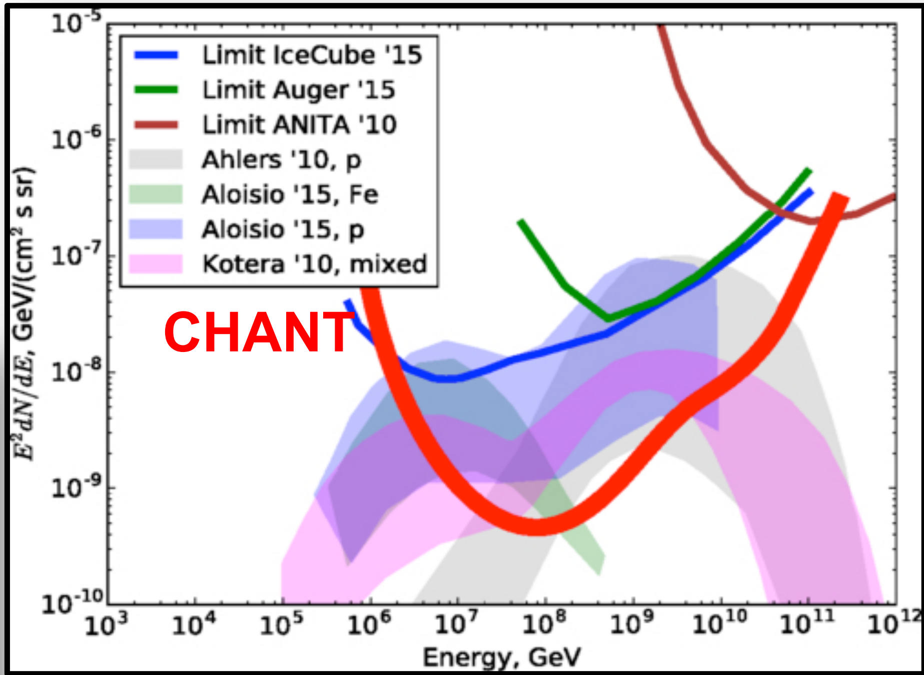


> Better sensitivity than IceCube or Auger in 5 PeV - 1000 PeV energy range, possible to constrain neutrino emission for close GRBs

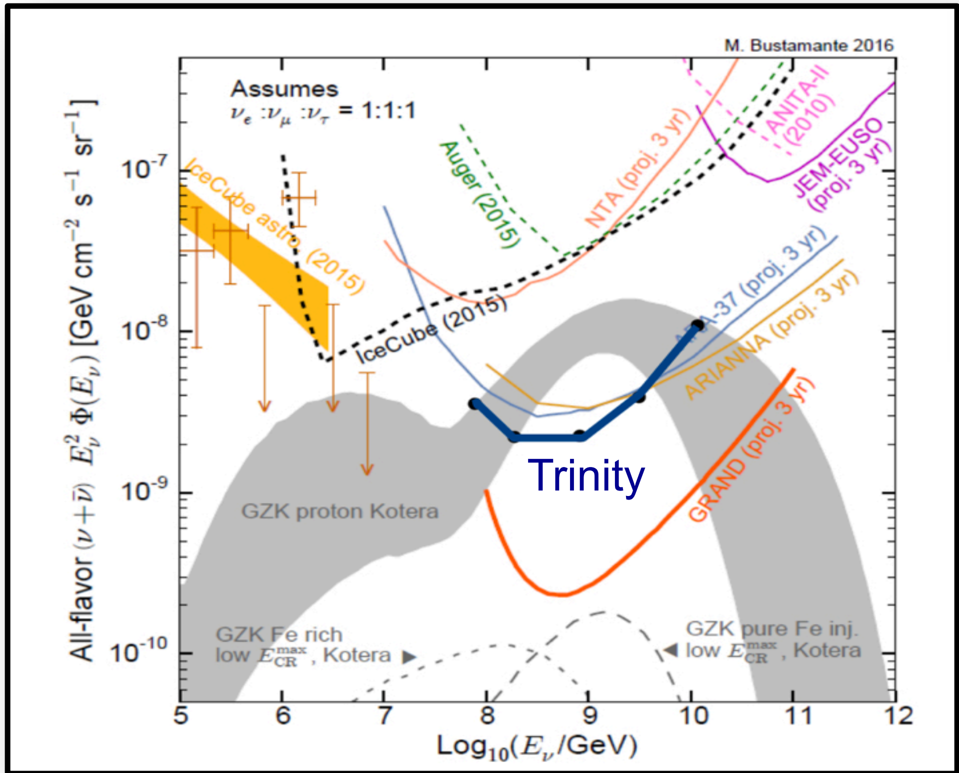
Future approach

> **Conventional approach (Antares, IceCube) low statistics in 1 – 100 PeV,**
new detection technique is needed, see for example:

A.Neronov, D. Semikoz, L. Anchordoqui, J. Adams, A. Olinto,
"Sensitivity of space-based Cherenkov from Astrophysical Neutrinos Telescope (CHANT)",
Phys. Rev. D 95, 023004 (2017)



For a space or balloon borne CHANT system with the telescope modules providing 360 deg overview of the strip below the Earth limb.



A. Nepomuk Otte

"Trinity: An experiment to detect cosmogenic neutrinos with the Earth skimming technique"

- 1-2 km above ground
- 360 degrees azimuthal acceptance
- 1 m^2 effective mirror area

(M)ajor (A)tmospheric (G)amma (I)maging (C)herenkov

> **MAGIC, La Palma, Spain**

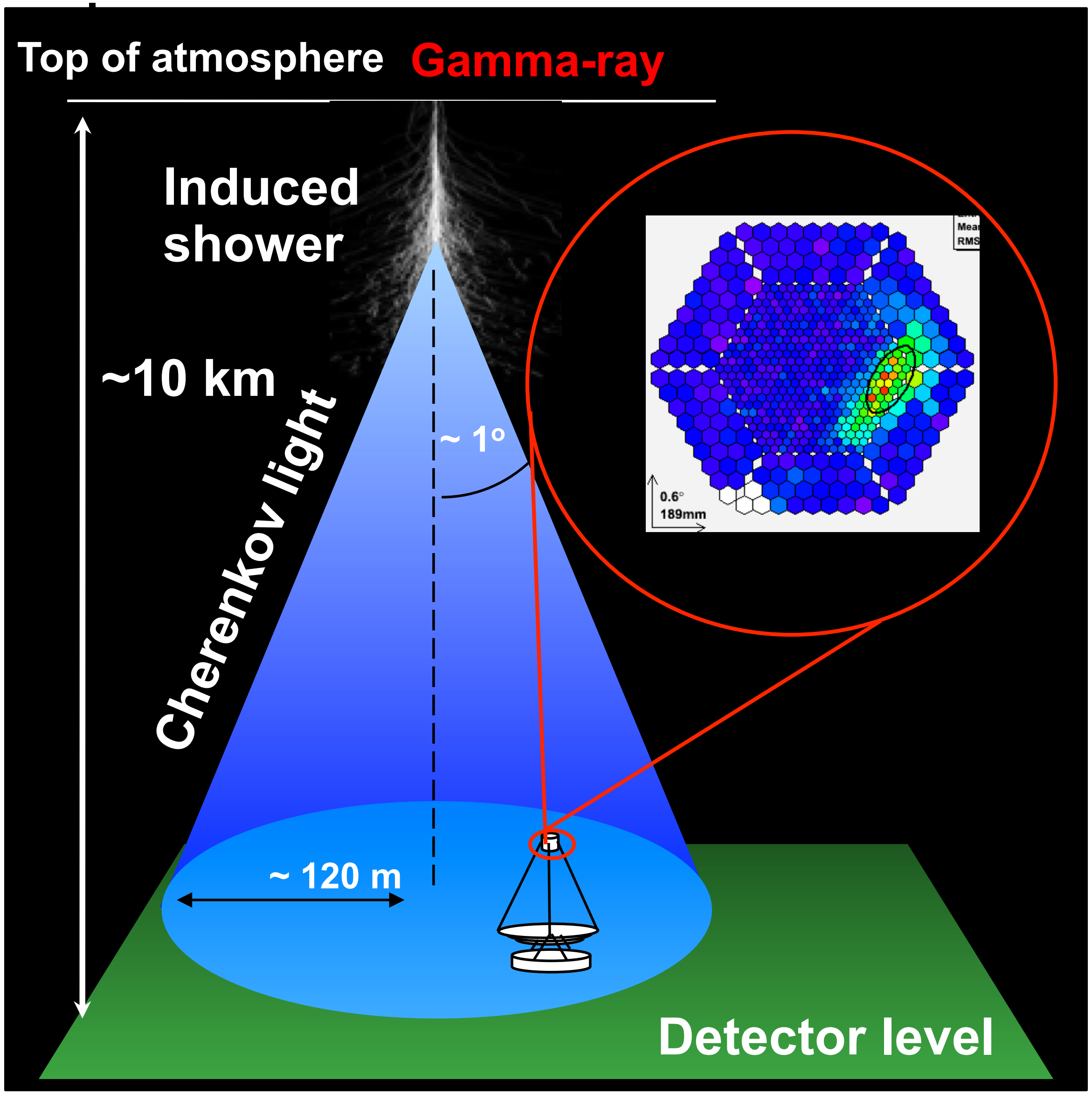
Two telescopes, 2200 a.s.l
each telescope mirror diameter: 17m

© Daniel Lopez, IAC

- *Field of view of 3.5 degrees*
- *Angular resolution 0.1 deg*
- **Cosmic gamma-rays with energy range from 50 GeV to 50 TeV**

Basic detection principle of IACTs

> **Detection of high energies gamma-rays**



> **Image on camera**

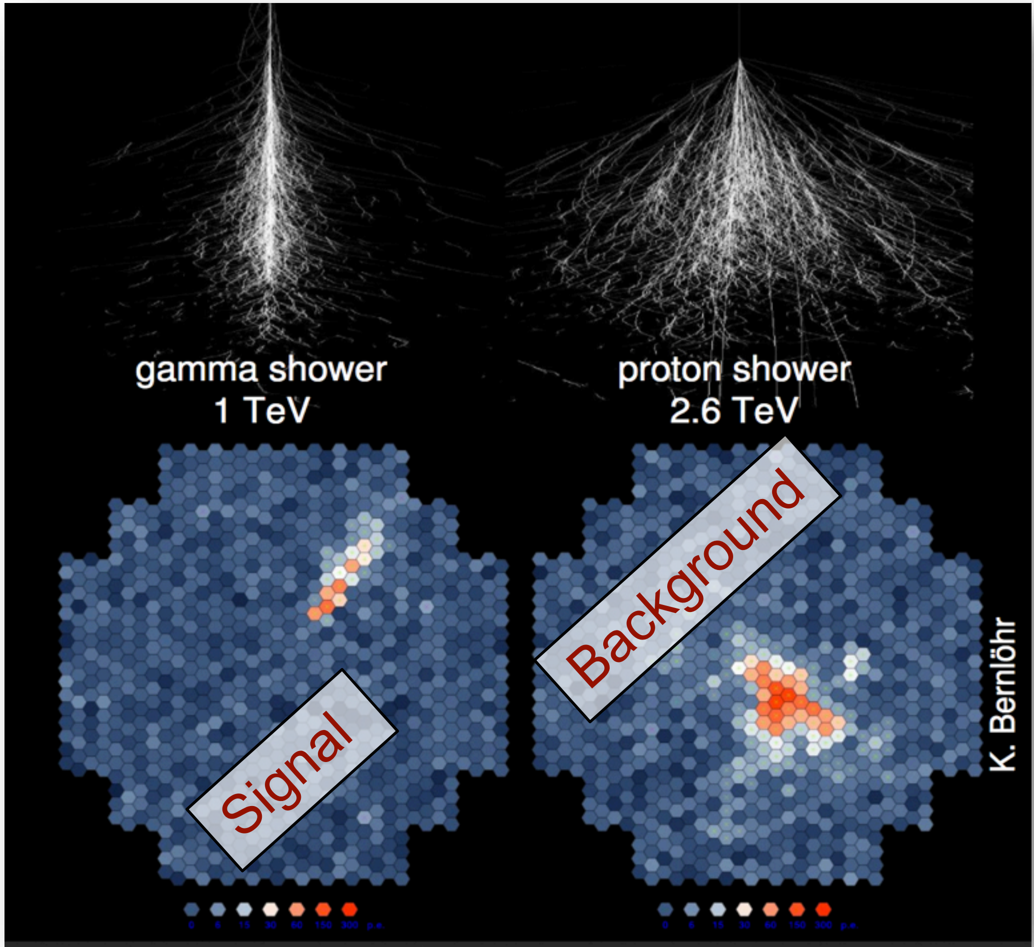
- Image intensity ➔ gamma-ray energy
- Image form ➔ background reduction
- Image orientation ➔ gamma-ray direction

> **Stereo reconstruction**

- *improved direction*
- *background reduction*
- *low energy threshold*

Gamma-hadron separation

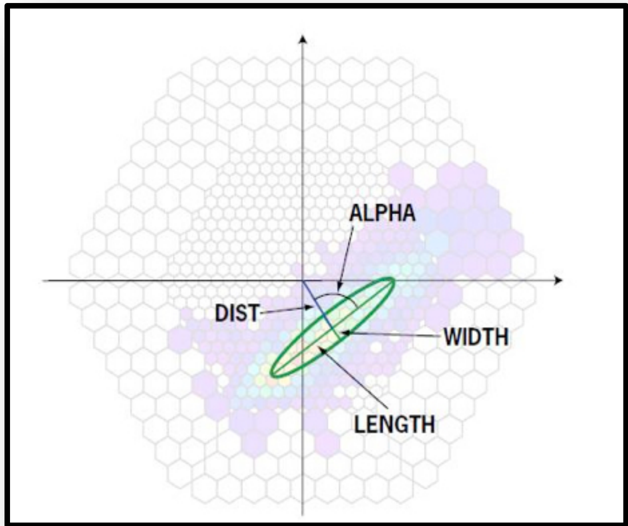
> **Background reduction by image shape analysis**
... Cosmic Rays main background for Cherenkov astronomy



> *Protons create hadronic showers with irregular images*

> *Electrons, positrons, gammas produce electro-magnetic shower, shower image is elongated ellipse*

> Hillas parameters:

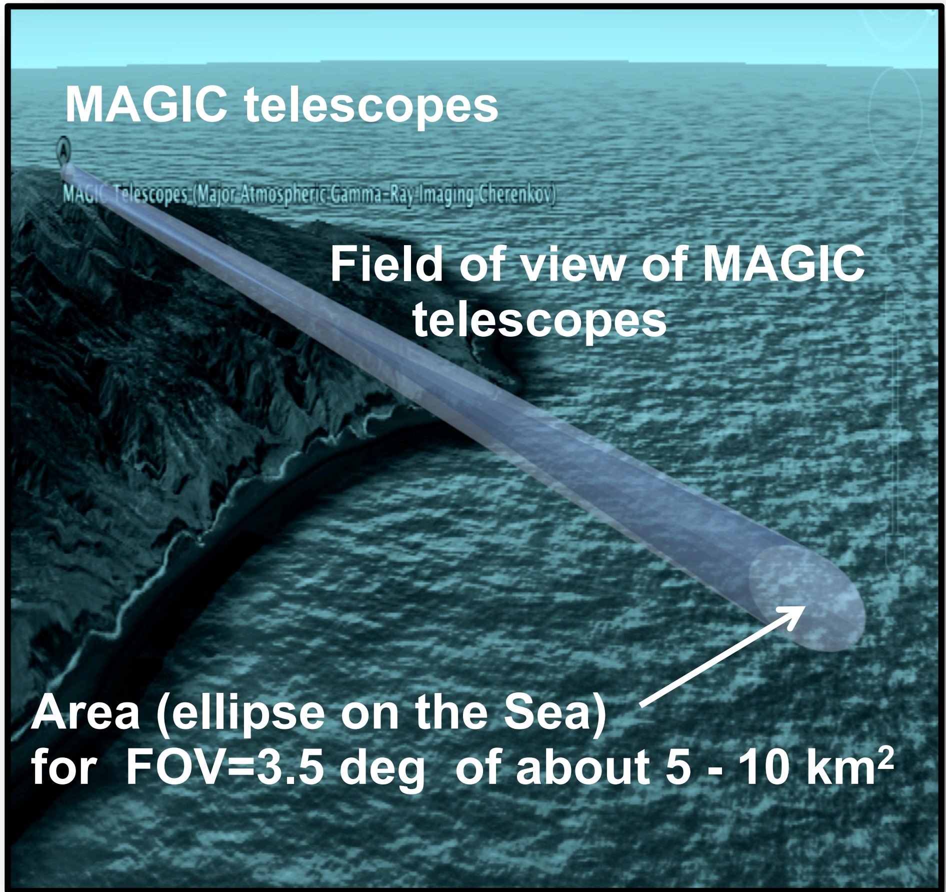


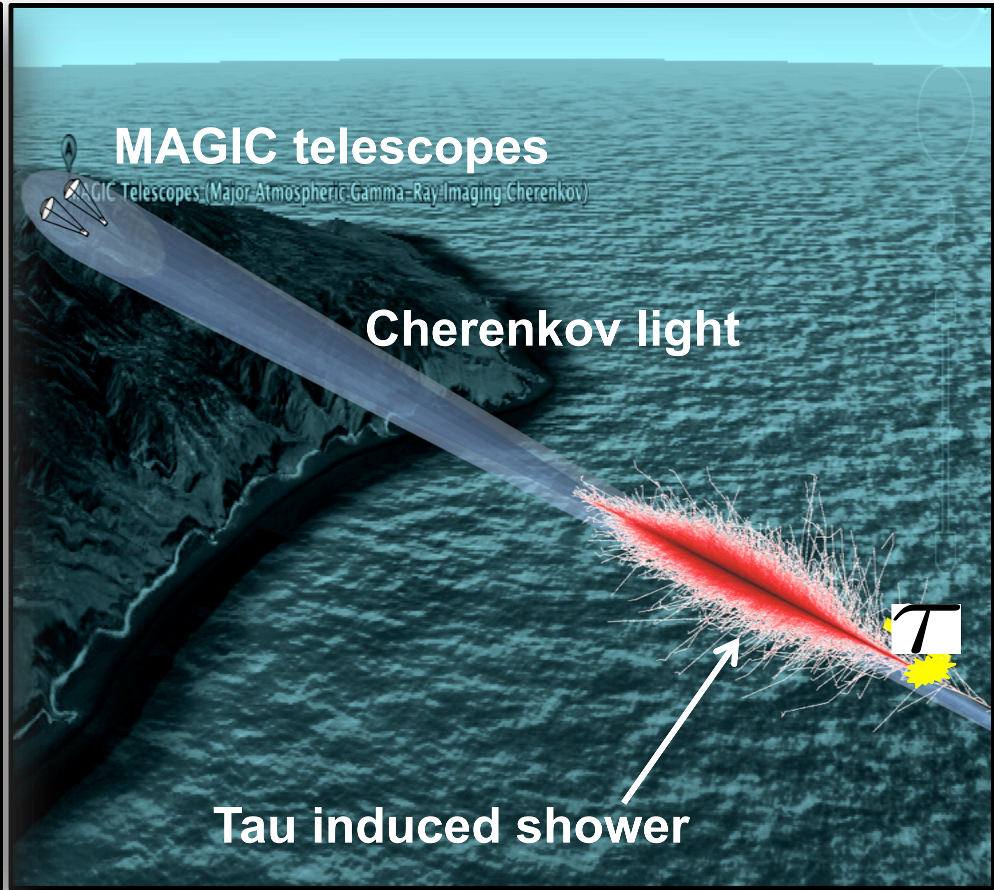
A.M. Hillas,Nucl. Phys. Proc. Suppl.52B (1997) 29

SIZE parameter: the total amount of detected light (in p.e.) in all camera pixels

MAGIC as neutrino detector

> **MAGIC telescopes can point down to the Sea**,
  …The large volume can be monitored: moving down MAGIC telescope to 91.5 deg the surface of the Sea is 165 km away.





> **Sometimes nights with high clouds prevent observation of γ-ray sources**,
  for MAGIC of about ~ 60 - 100 hours/year. Possibility to collect large amounts of data while not wasting "expensive dark time" of MAGIC

MAGIC as neutrino detector

> **Analytical calculations:** M. Gaug et al., ICRC 2007 arXiv:0709.1462

- **sensitivity [100 TeV – 1 EeV]**
- **~10^{-4} events/year** for diffusse neutrino flux given by Engel, Stanev & Stecker (GZK neutrinos)
- **~10^{-2} events/year** are predicted for the Waxmann & Bahcall neutrino model from GRBs, for an average GRB located at z=1
- some data (a few minutes) were taken, but at that time no Monte Carlo to interpret these data

> **Monte Carlo simulation chain**

(1) Propagation of neutrino through the Earth

ANIS ➔

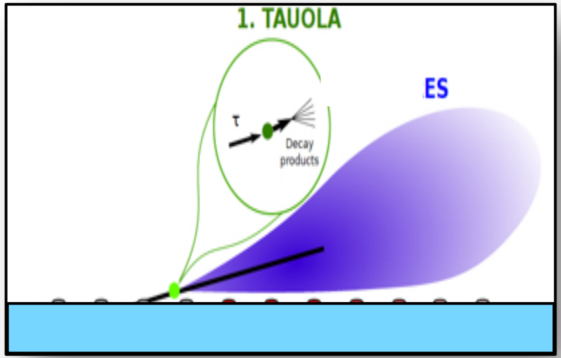
A. Gazizov, M.P. Kowalski
Comput.Phys.Commun. 172 (2005) 203

Adopted version: DG, M. Roth, A.Tamburro
Astropat. Physic. 26 (2007) 402

(2) Simulation of tau-induced shower in air at high zenith angles

CORSIKA ➔

D. Heck, et al.,
Report FZKA 6019 (1998) 3



Compiled: with **CURVED-EARTH**, **TAULEP, CHERENKOV/IACT, THIN** option

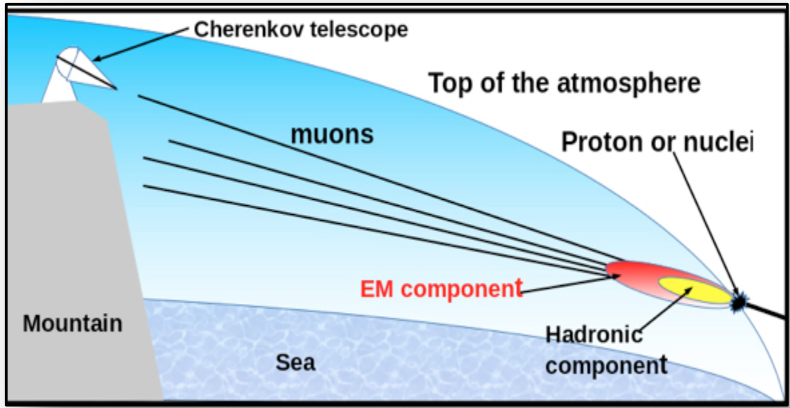
(3) Simulation of MAGIC response

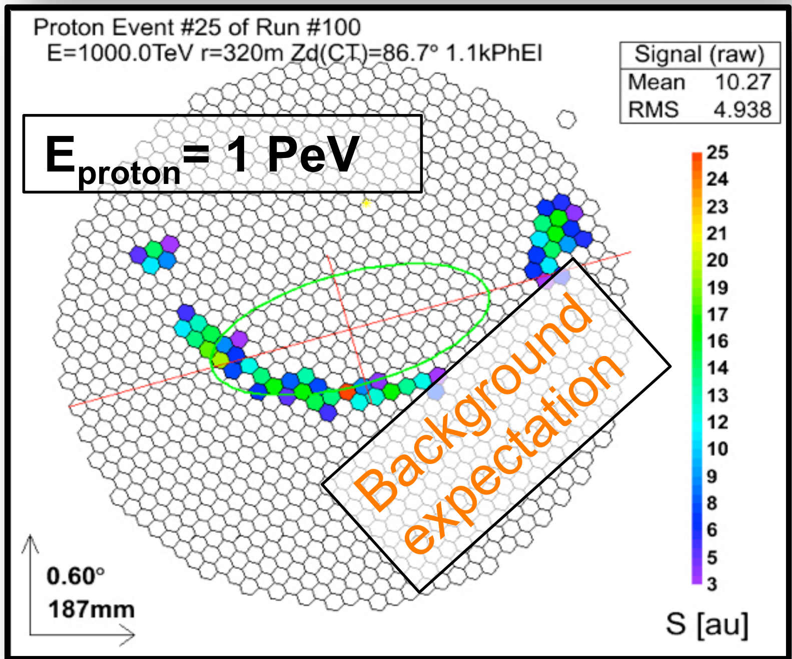
MARS

R. Zanin, et al.. 2013. MARS,
the MAGIC analysis and reconstruction software, ICRC 2013

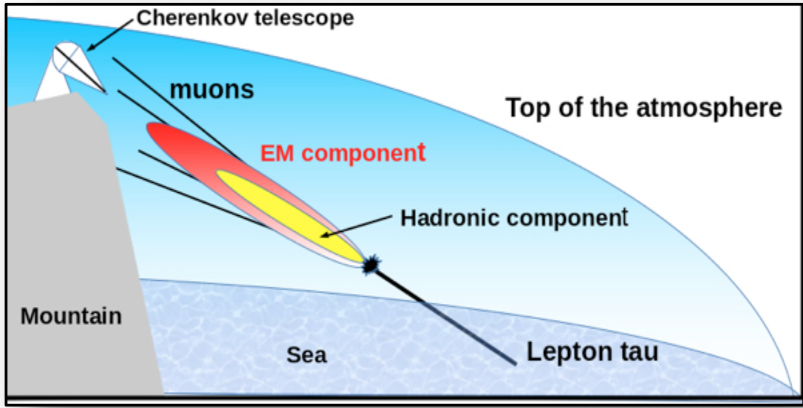
Monte Carlo simulation chain

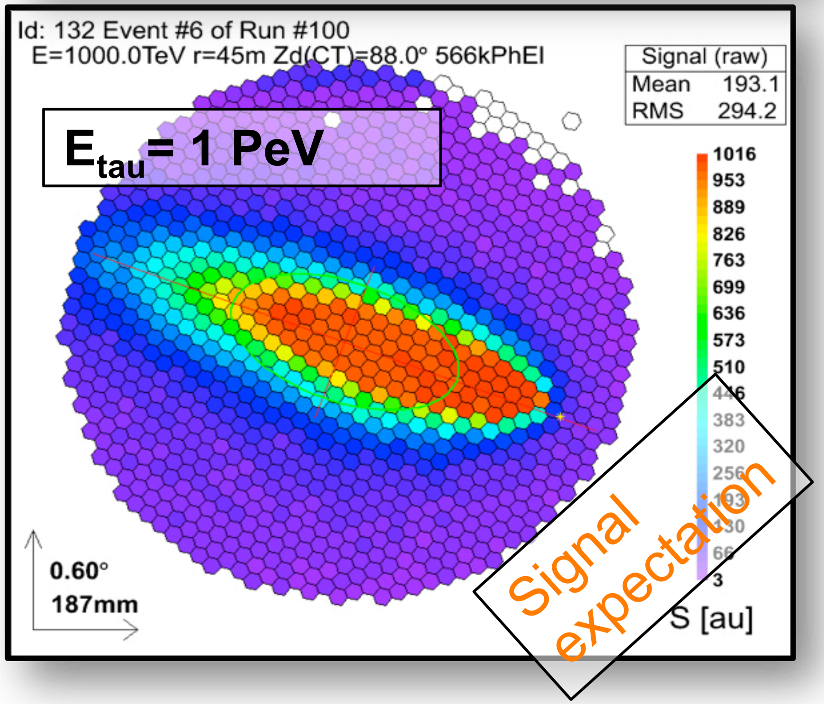
Proton injected at the top of the atmosphere
(~800 km to the detector for 87°)





Deep tau-induced shower
(~50 km to the detector)



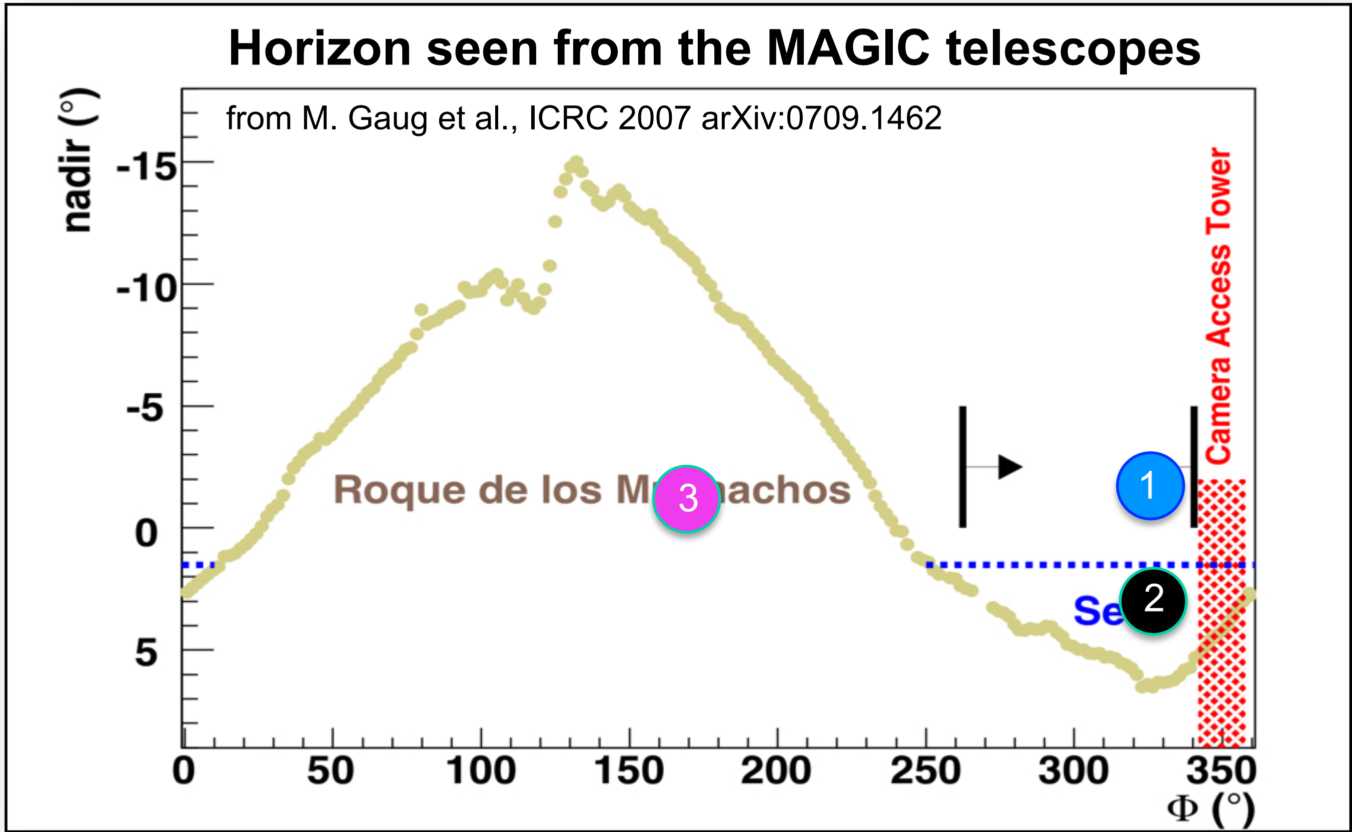


MAGIC data at very high zenith angles (ZA > 85°)

(1) Data: direction slightly above the sea (seaOFF), ZA=87.5°, AZ=330°, **Time= 9.2 hrs**

(2) Data: direction of the sea (seaON), ZA=92.5°, AZ=330°, **Time= 29 hrs**

(3) Data: towards the Roque de los Muchachos mountain, ZA= 89.5 AZ=170, **Time=7.5 hrs**



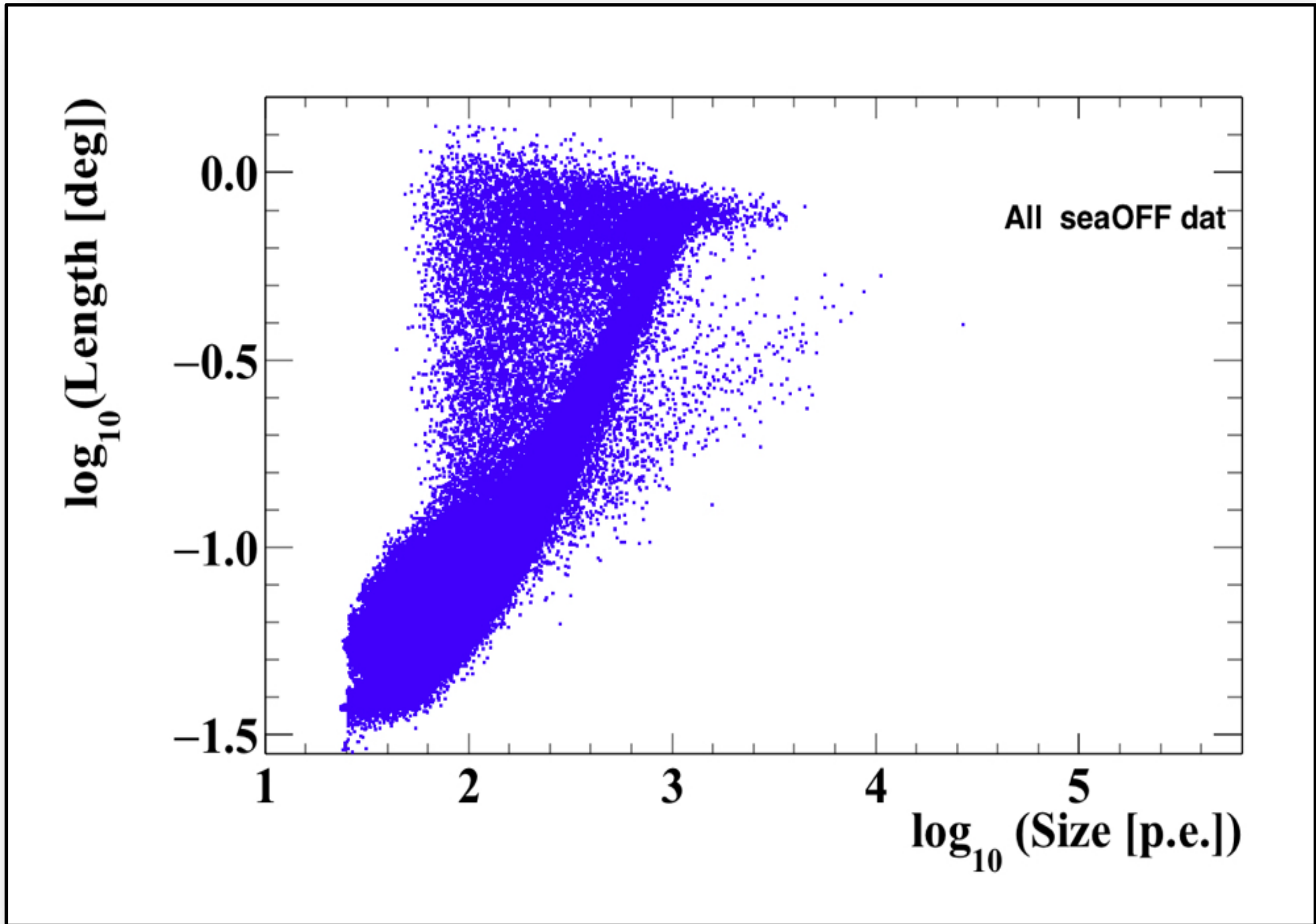
> About 91% of data were taken during nights characterized by optically thick high cumulus clouds, when normal gamma-ray observations are usually unfeasible.

Background measured at high zenith angles

Measured background at very high zenith angles

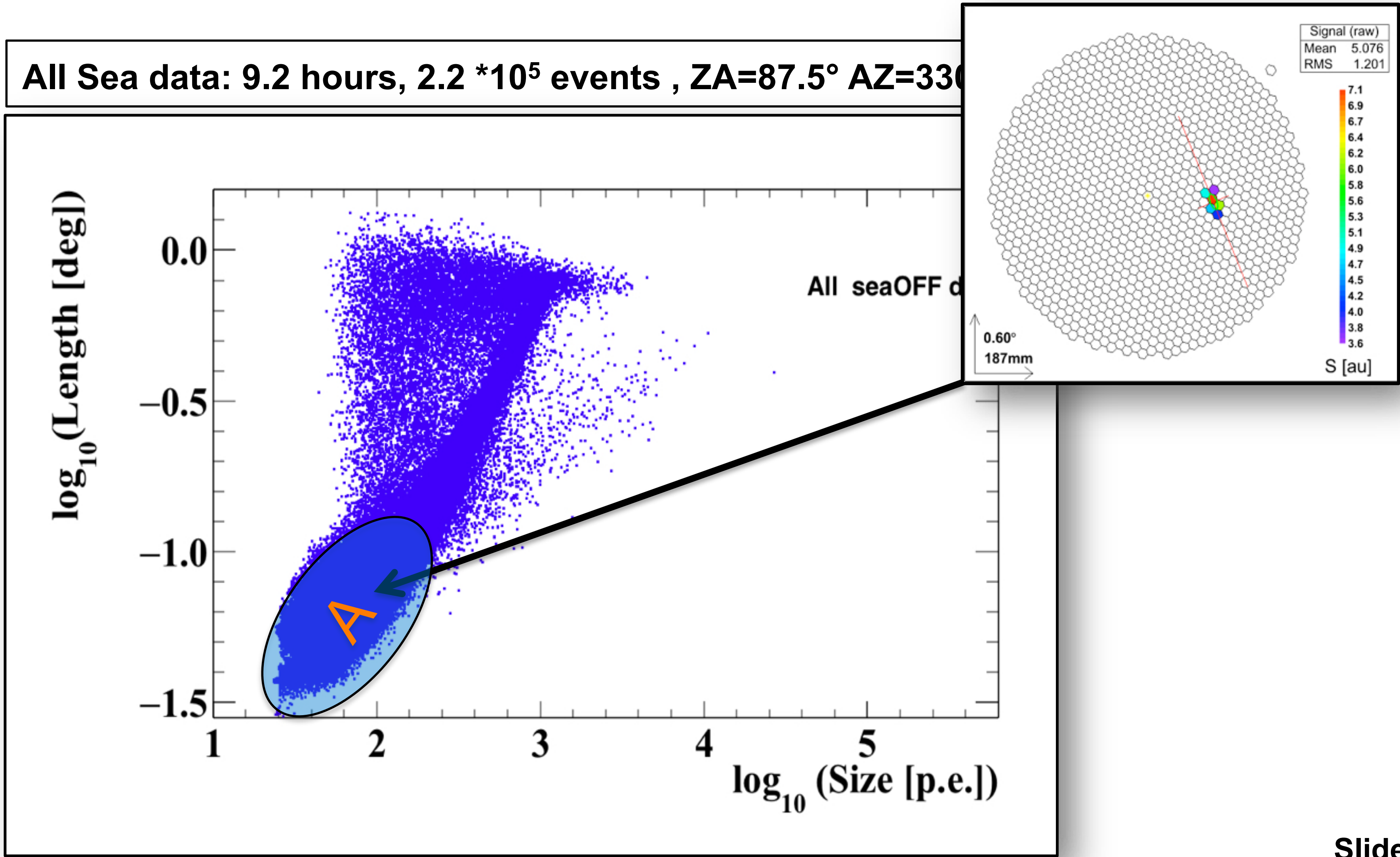
- The rate of stereo seaOFF events is about 27 times larger (~4.6 Hz) than for seaON (~0.17 Hz) observations.
- seaOFF observations provide high-statistics background estimate for about 30 hrs of seaON data, in the region with negligible signal contribution. Thus seaOFF data were used to estimate the background and construct the selection criterion to identify tau-neutrino showers.

All Sea data: 9.2 hours, 2.2 *10^5 events , ZA=87.5° AZ=330°

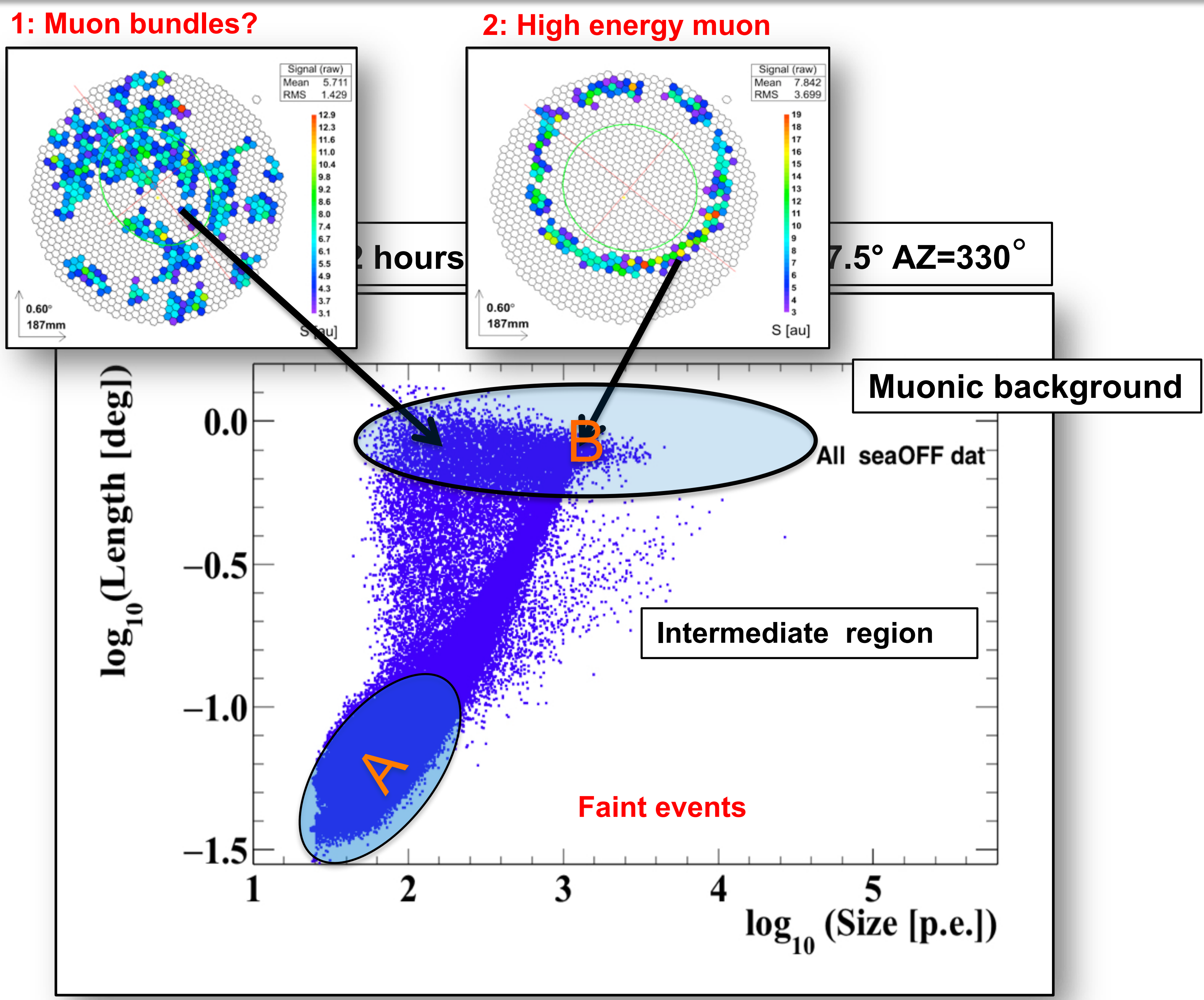


Measured background at very high zenith angles

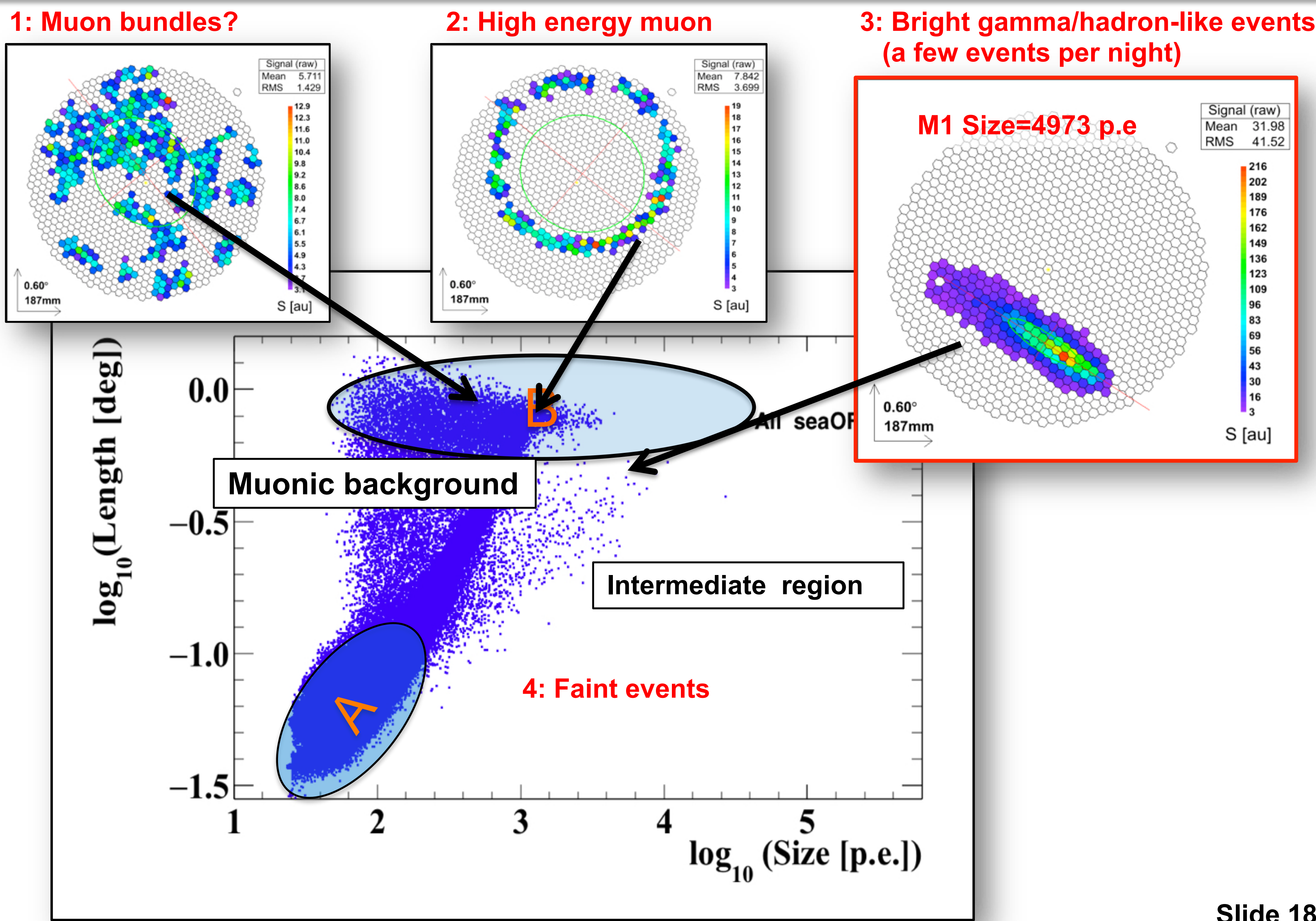
Many faint events: rate 5 Hz



Measured background at very high zenith angles



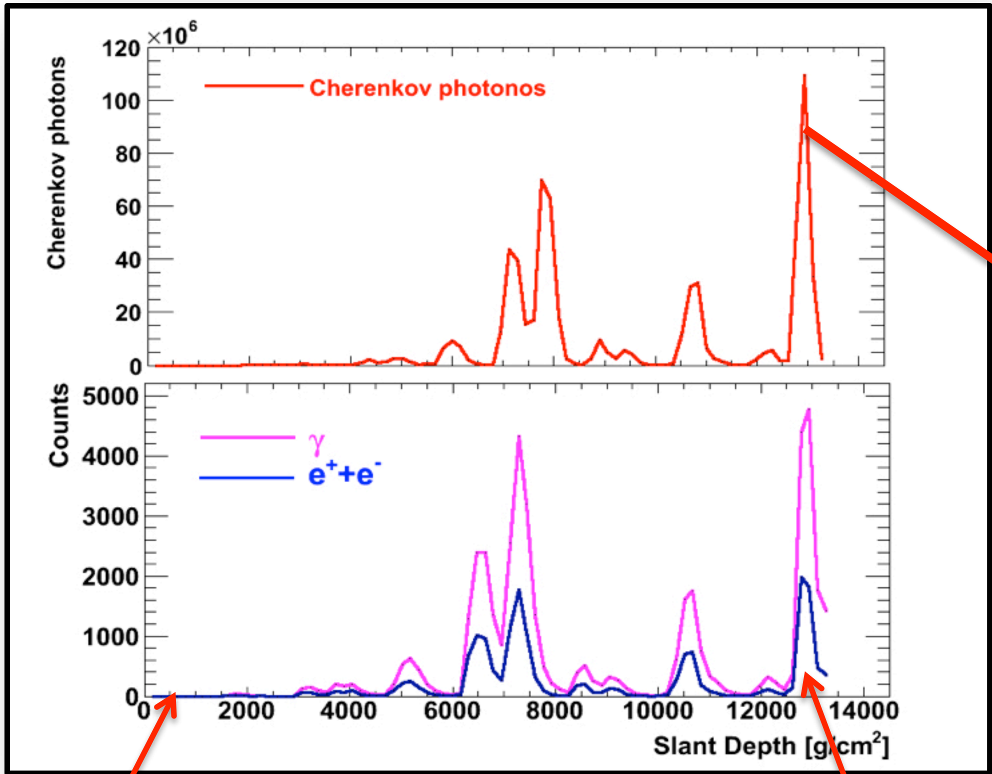
Measured background at very high zenith angles



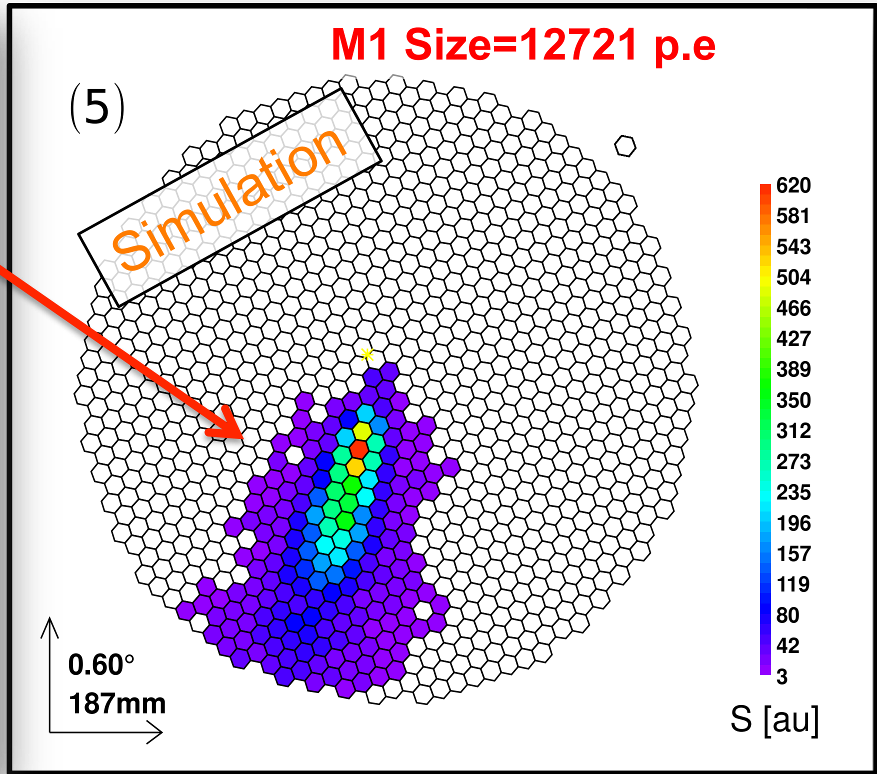
Bright events at horizontal direction: bremsstrahlung muon

> At high zenith angles and for a few TeV muon events the mean free path for *radiative processes* (**Bremsstrahlung**, **Pair-Production** and **Photo-Nuclear interactions**) are comparable to the thickness of atmosphere
…results many electromagnetic sub-showers can be created along the muon track.

CORSIKA longitudal profile



Injected single muon E_{muon}=1 PeV, ZA = 86.5°



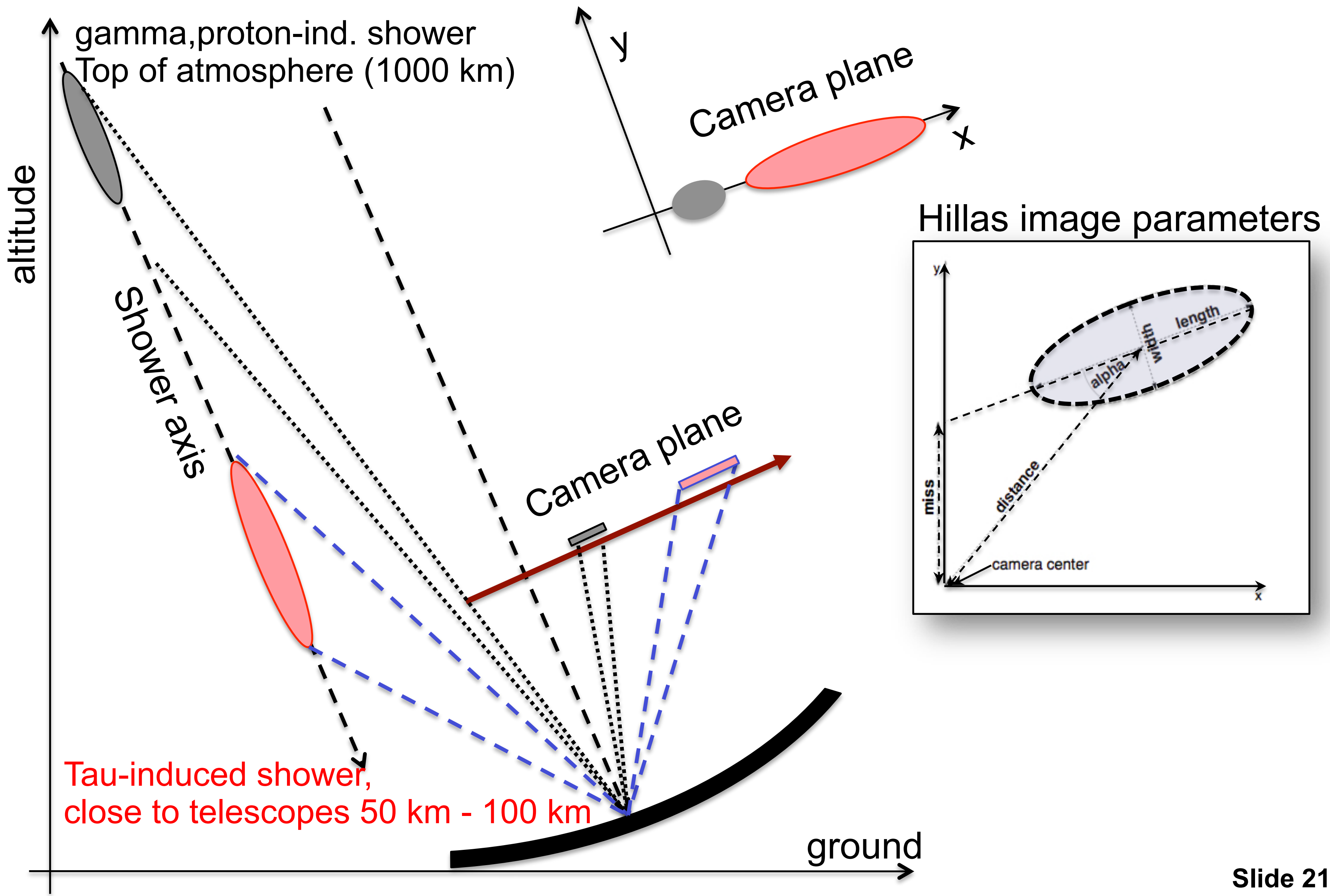
Top of the atmosphere

Detector level

Caveat: *This kind of background can mimimic the neutrino signal.*

Identification of tau neutrino induced shower

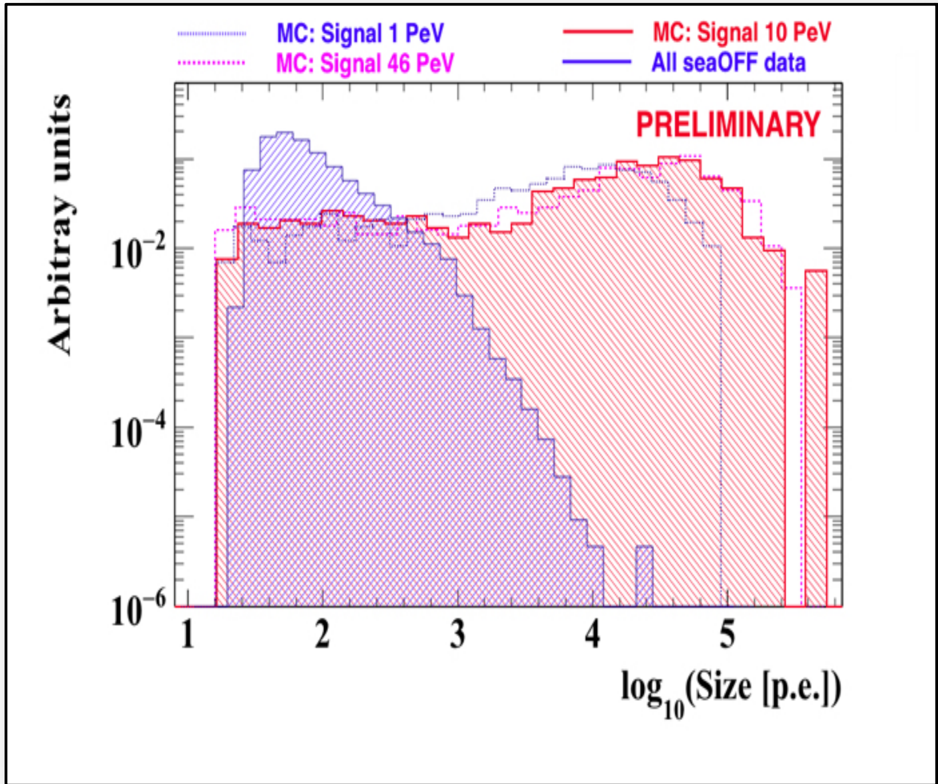
Towards tau neutrino identification

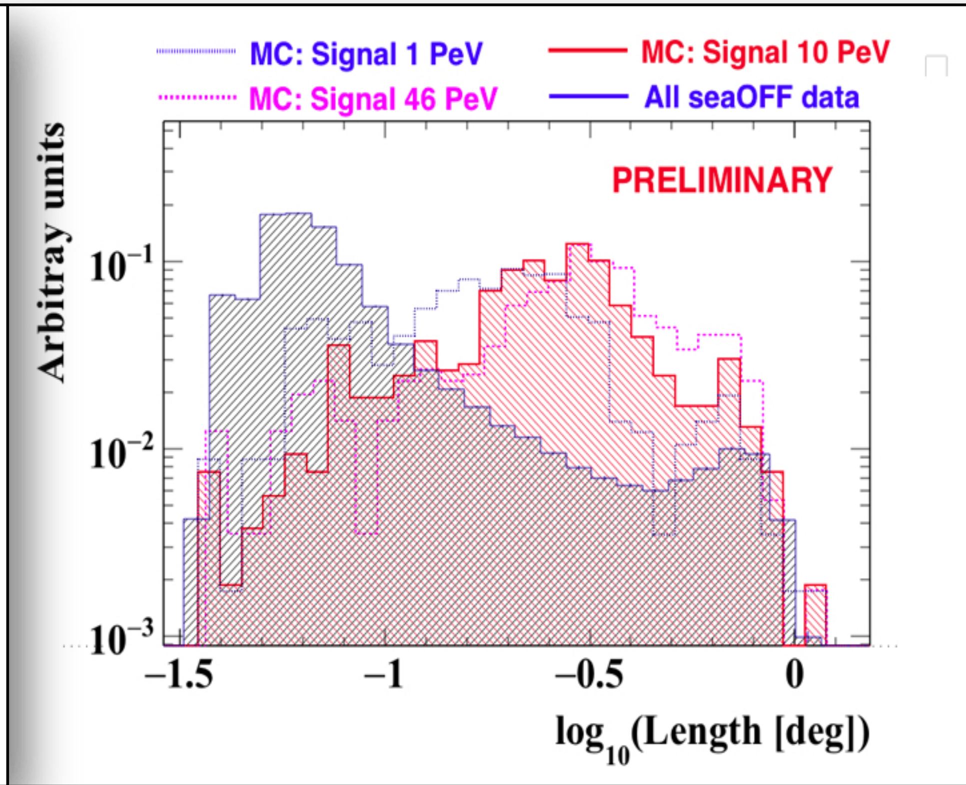


Distribution of Hillas variables at high zenith angles

SIGNAL MC simulations:
- *deep tau-induced shower*
- *distance to the detector < 100 km,*
- *tau-decay branching ratio included in MC*

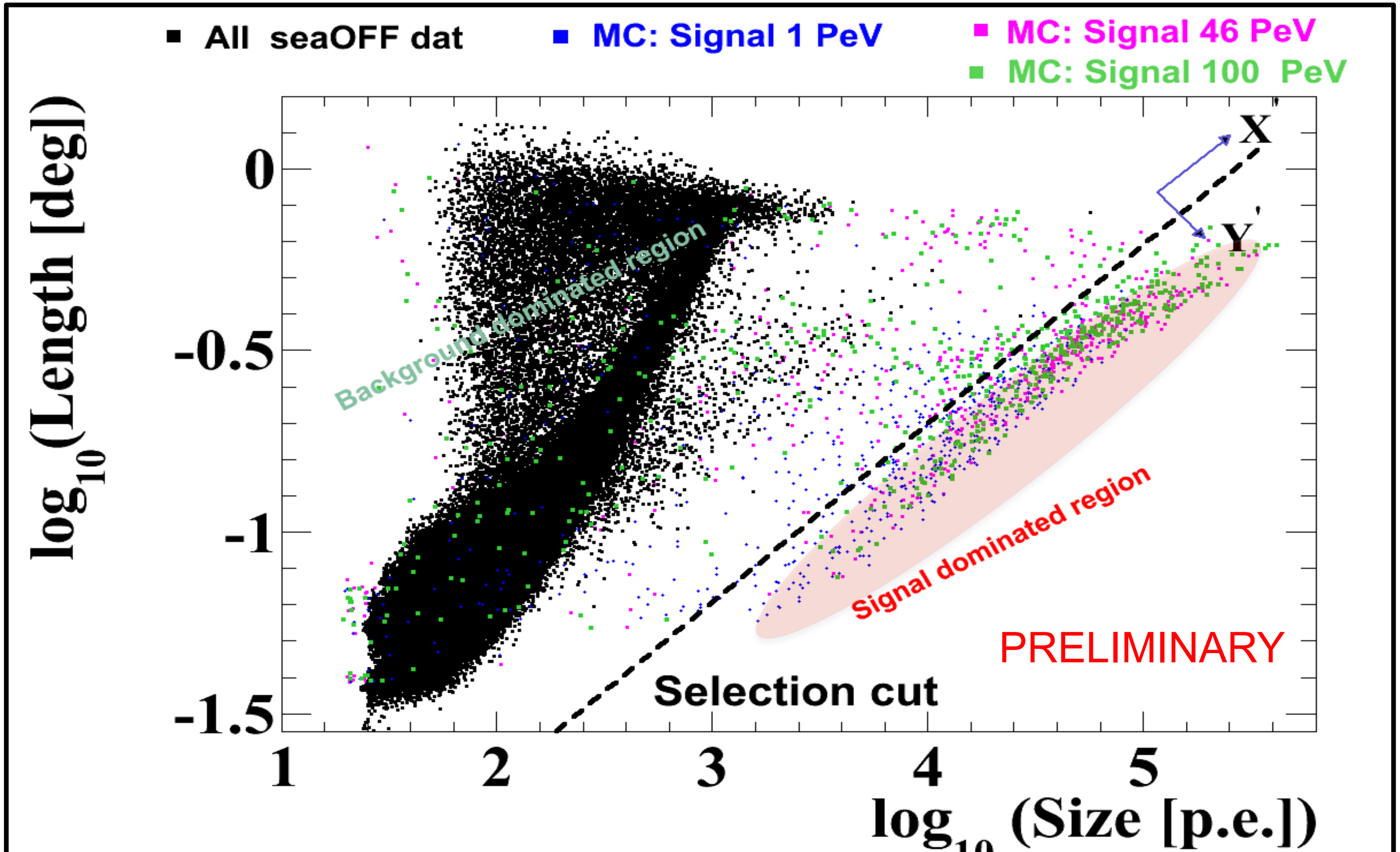
BACKGROUND:
- *seaOFF data (9.2 hours)*





> Very nice separation between data and simulated signal in Hillas parameters phase-space

Selection criterion



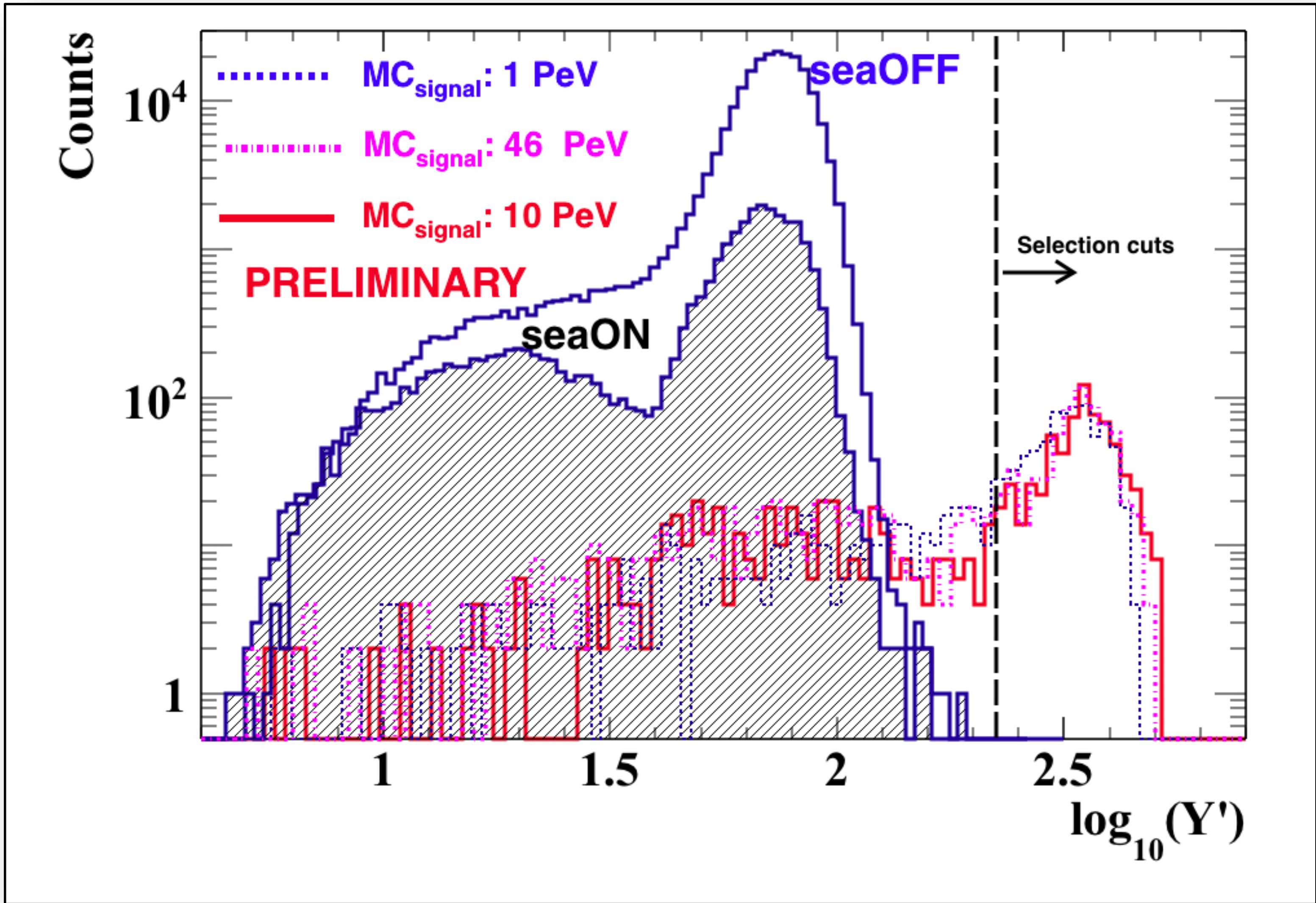
Selection criterion:

$$\log_{10}(Y') = \log_{10}(\text{Size}[\text{p.e.}]) * \cos(\alpha) - \log_{10}(\text{Length}[\text{deg}]) * \sin(\alpha),$$

where $\alpha = 63.435°$

> This plot shows that MAGIC can discriminate tau neutrinos from background of hadronic showers.

Selection criterion

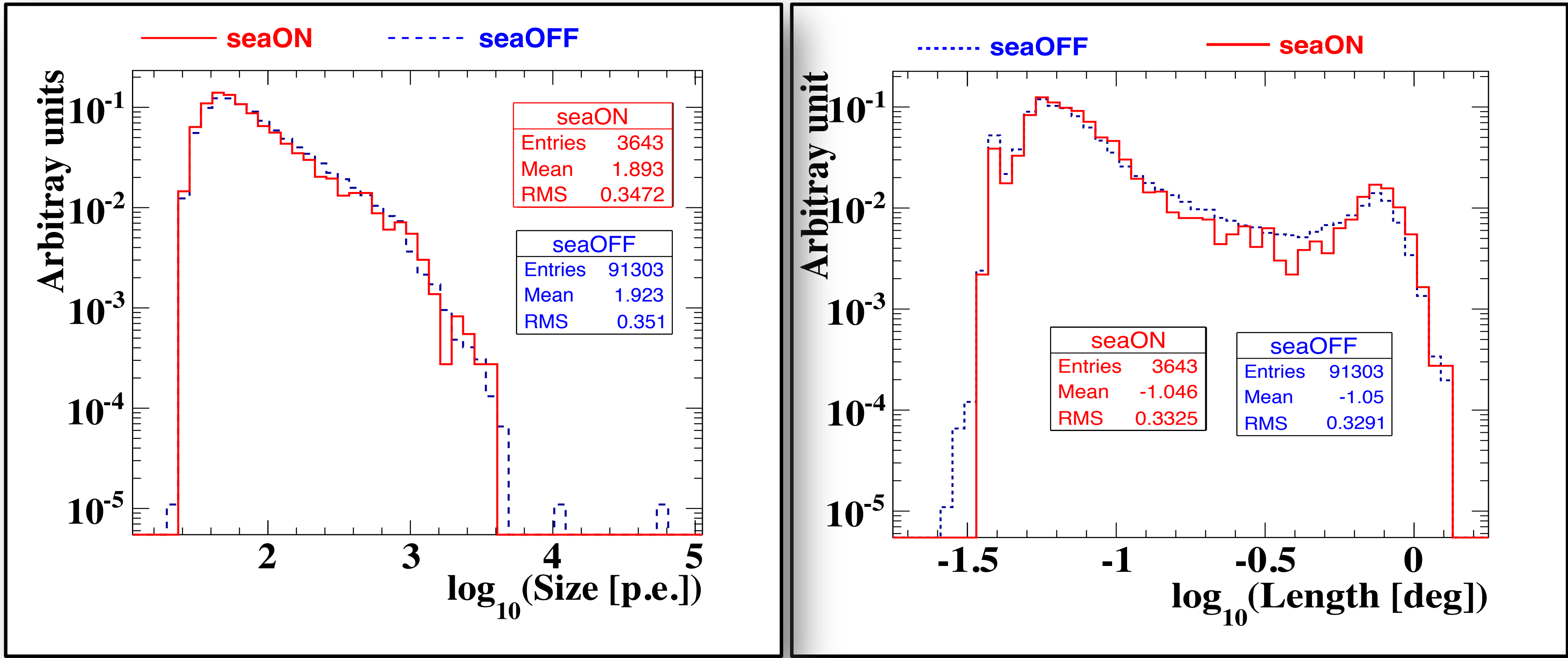


> NO neutrino candiate is found, if the selection cut is applied to all seeON data

Signal efficiency after the cut $\log_{10}(Y') > 2.35$ about 20-25 % for shower with impact distances smaller than 0.3 km, otherwise $\log_{10}(Y') > 2.10$ was used.

Measured background at very high zenith angles

> Normalized distribution of Hillas parameters at these zenith angles



REMARK: The data were taken during one night (17.01.2016), under similar weather conditions.

> The shape of these distributions for seaOFF and seaON data is very similar, indicating a universal behaviour of Hillas distributions at these zenith angles

Aperture and event rate calculations

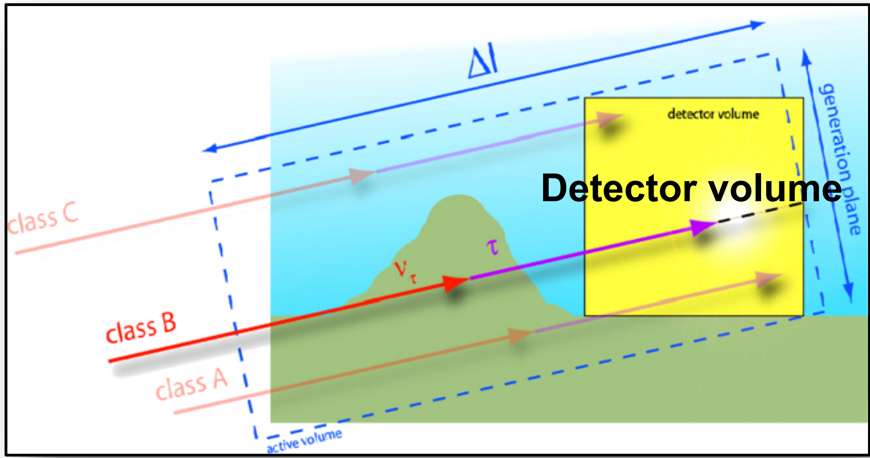
Acceptance calculation

(1) Neutrino propagation in Earth: All Neutrino Interaction Simulation (ANIS)

A. Gazizov, M.P. Kowalski
Comput.Phys.Commun. 172 (2005) 203

- *In the adopted ANIS version the local topography of site can be included*

- *The detector volume: cylinder with radius **50 km** and **10 km** height*



RESULTS: distribution of decay vertexes of lepton tau in detector volume (E_{tau}, x_{decay}, y_{decay}, h_{decay})

(2) Acceptance calculations

Simulated zenith and azimuth pointing angles of MAGIC
.

The number of tau leptons with estimated position of the shower max, in FOV and impact distances < 1.3 km

The physical cross-section of the interaction volume seen by the neutrino.

$$A^{\rm PS}(E_{\nu_\tau},\theta,\phi) = N_{\rm gen}^{-1} \times \sum_{i=1}^{N_{FOV cut}} P_i(E_{\nu_\tau},E_\tau,\theta) \times A_i(\theta) \times T_{{\rm eff},i}(E_\tau,r,d,\theta)$$

The number of generated neutrino events.

The conversion probability that a neutrino with energy $\boldsymbol{E_{\nu\tau}}$ *and zenith angle θ produces a lepton with energy* $\boldsymbol{E_\tau}$ *(used as the weight of event)*

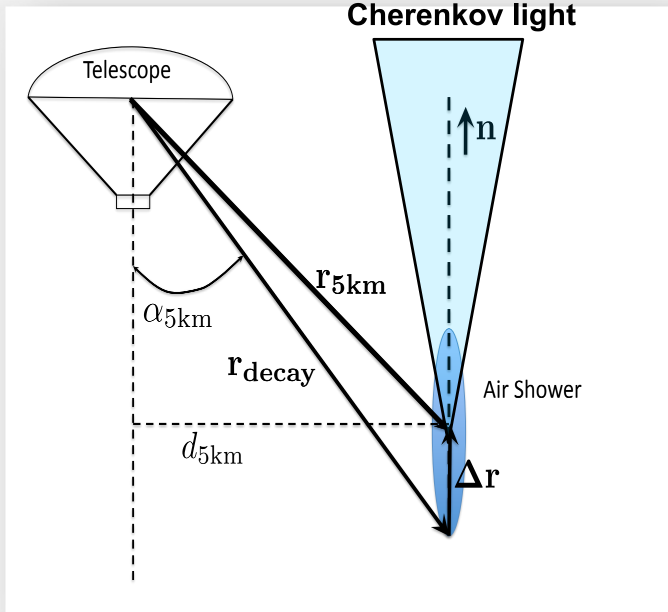
$T_{{\rm eff},i}(E_\tau,r,d,\theta)$ *- the trigger efficiency for tau-lepton induced showers with estimated position of shower maximum at distance **r** and the impact distance **d**.*

Acceptance calculation: FOV cut

> We accept MC events with the estimated position of the shower max in MAGIC FOV and for shower impact distances d < 1.3 km

$$\vec{r}_{5\mathrm{km}} = \vec{r}_{\mathrm{decay}} + \Delta r \cdot \vec{n}$$

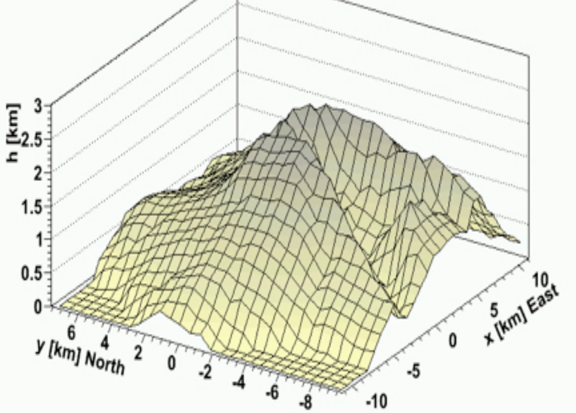
$$\alpha_{5\mathrm{km}} = ((180^\circ/\pi) \times \arcsin(d_{5\mathrm{km}}/r_{5\mathrm{km}})) < (\alpha_{FOV}/2 + \alpha_{\mathrm{Cher.}}) \approx 3.10^\circ$$

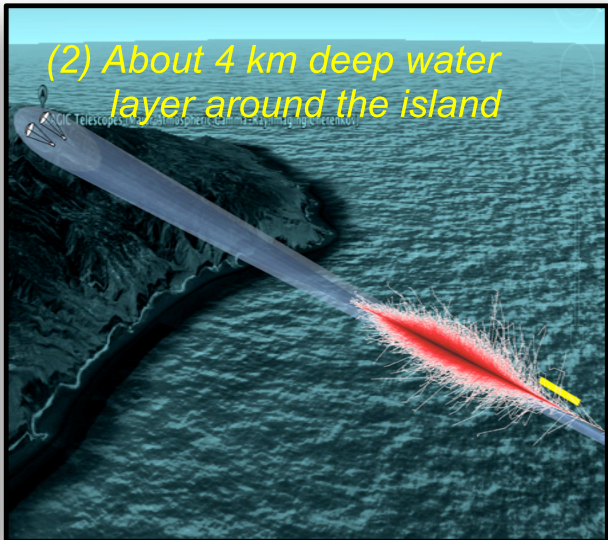


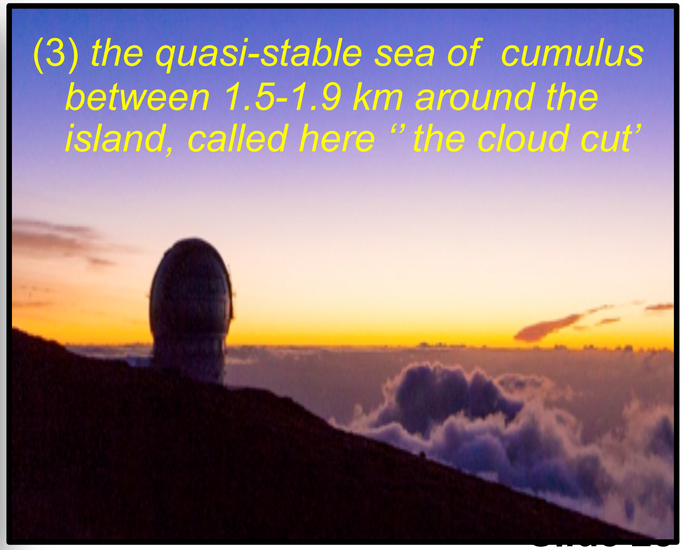
For shower energies relevant for this analysis i.e.1-1000 PeV, the largest lateral extension of the shower is reached approximately after 600 g/cm^2. For the near ground density of air (ρ=0.0012 g/cm^3), this depth interval corresponds to about Δr=5 km

> In aperture simulations we also included:

(1) topography of the La Palma



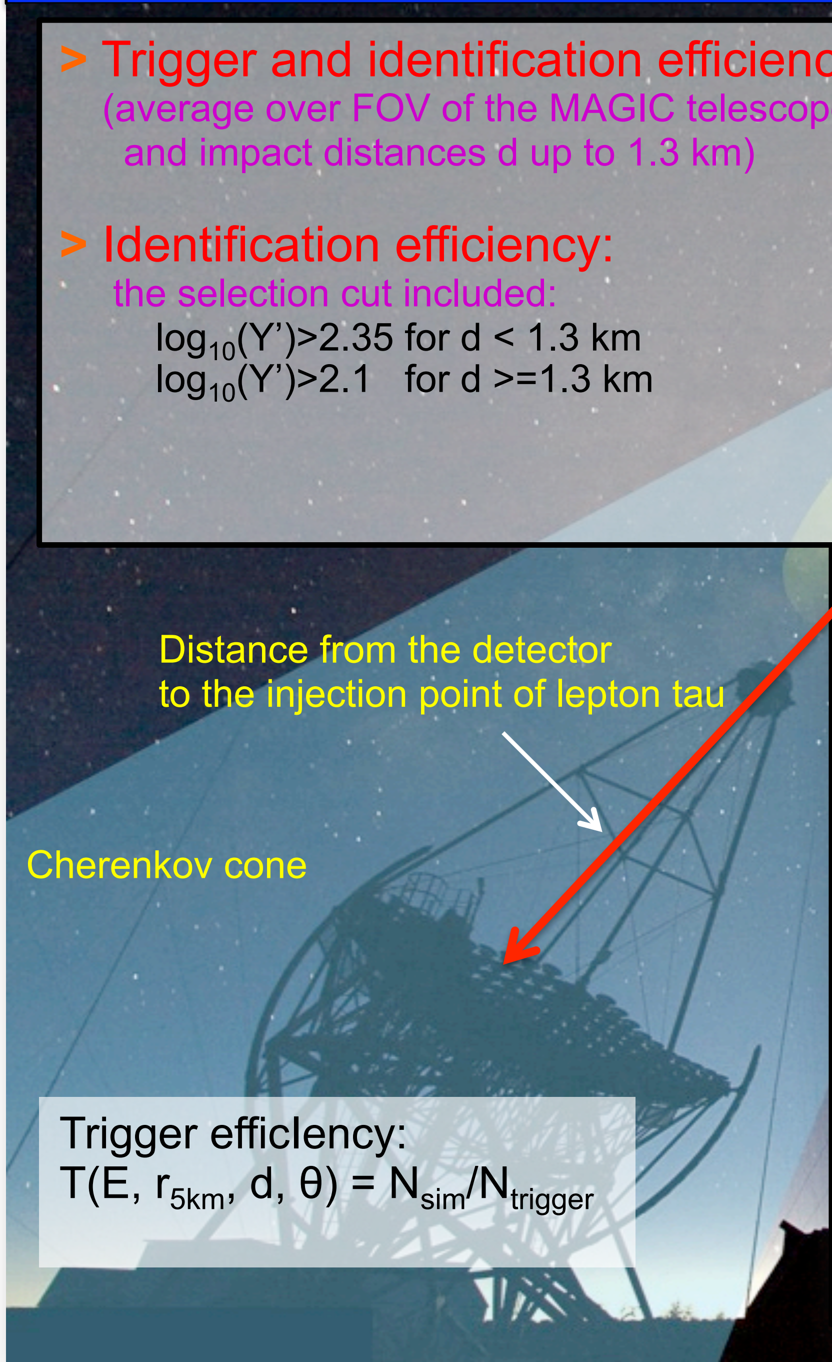


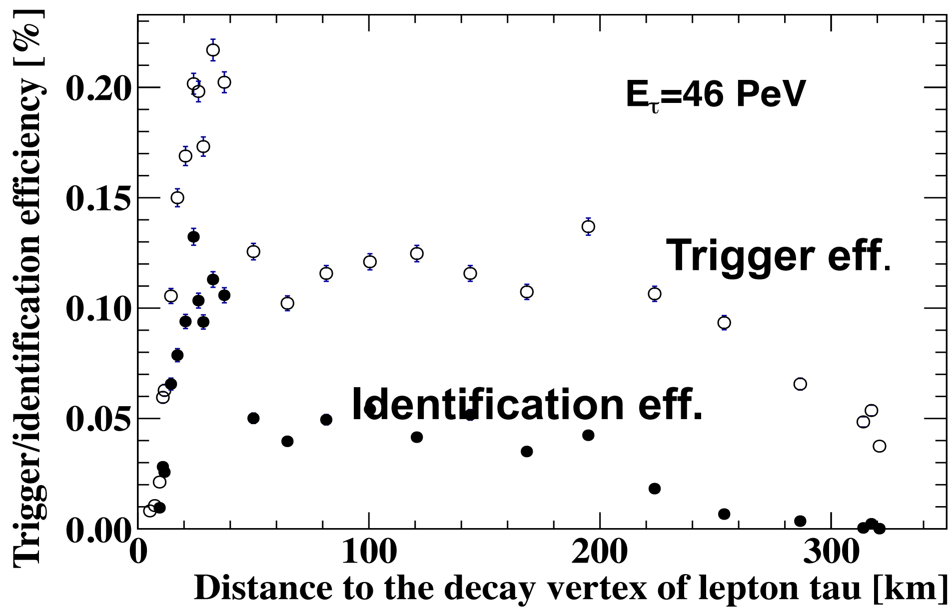


MC simulations of trigger efficiency $T(E_{tau}, r_{5km}, d, \theta)$

> Trigger and identification efficiency
(average over FOV of the MAGIC telescopes
and impact distances d up to 1.3 km)

> Identification efficiency:
the selection cut included:
$\log_{10}(Y')>2.35$ for d < 1.3 km
$\log_{10}(Y')>2.1$ for d >=1.3 km

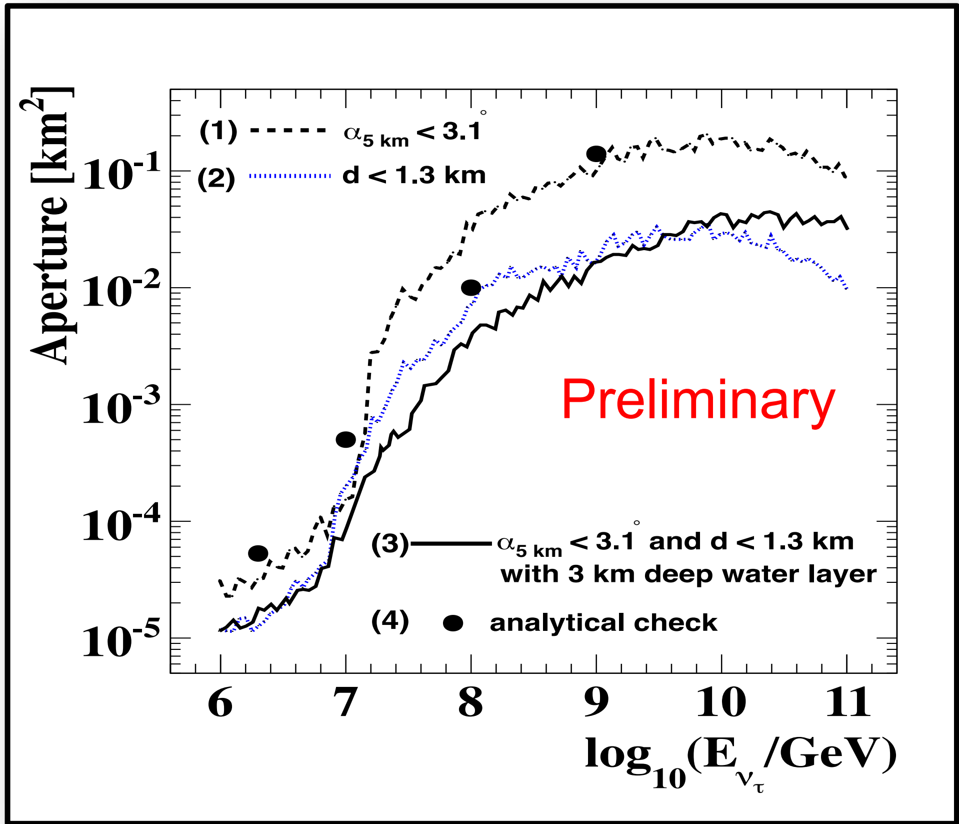


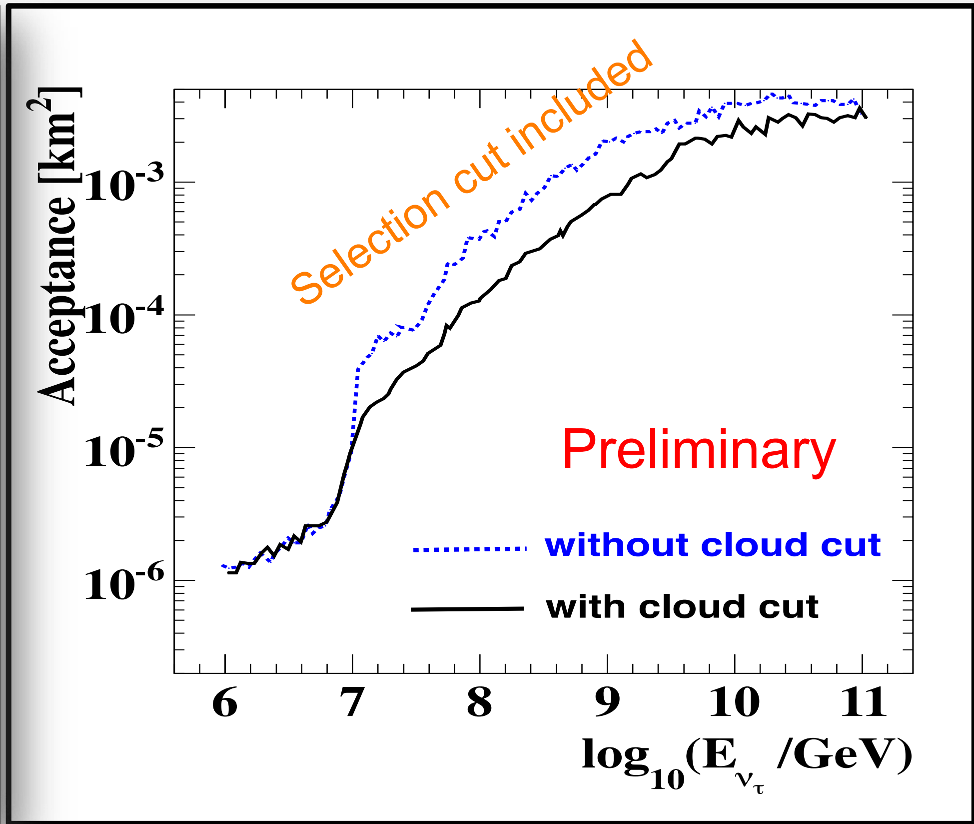


Trigger efficiency:
$T(E, r_{5km}, d, \theta) = N_{sim}/N_{trigger}$

Result: Aperture/acceptance

Tau neutrino point source acceptance for MAGIC





- the simple analytical calculations agree (besides the last point at 1000 PeV) with our MC estimate for case (2) i.e. d < 1.3 km
- the 3 km water layer leads to about a factor two smaller aperture than for the sperical Earth calc.
- the cloud cut leads also to a smaller (about factor two) acceptance

> Note the importance of specific effects (orography and cloud cut) in calculations of the IACT response to tau-induced showers

Event rate calculation AGNs

> **Event rate**

The neutrino flux

$$N = \Delta T \times \int_{E_{\rm th}}^{E_{\max}} A^{\rm PS}(E_{\nu_\tau}) \times \Phi(E_{\nu_\tau}) \times dE_{\nu_\tau}$$

The observation time

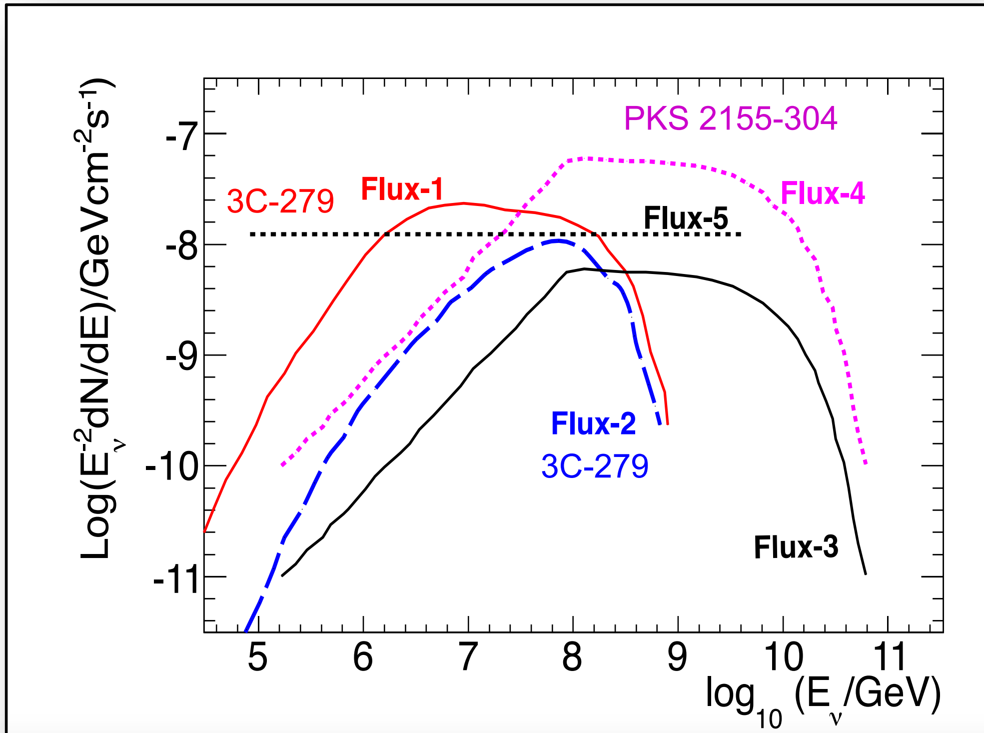


Table 4. Expected event rates for the MAGIC detector in case of AGN flares. Flux-1 and Flux-2 are predictions for neutrinos from γ-ray flares of 3C 279 (Reimer 2009). Flux-3 and Flux-4 are predictions for PKS 2155-304 in low-state and high-state, respectively (Becker et al 2011). Flux-5 corresponds to a prediction for 3C 279 calculated in (Atoyan et al. 2001) and is at a similar level in the PeV energy range like the flux reported by IceCube for astrophysical high-energies neutrinos Aartsen et al. (2014).

		Flux-1 ($\times 10^{-5}$/3 hrs)	Flux-2 ($\times 10^{-5}$/3 hrs)	Flux-3 ($\times 10^{-5}$/3 hrs)	Flux-4 ($\times 10^{-5}$/3 hrs)	Flux-5 ($\times 10^{-5}$/3 hrs)
$N_{\rm Events}$	without cloud cut	2.4	1.4	0.74	7.4	2.4
$N_{\rm Events}$	with cloud cut	1.1	0.6	0.30	2.9	1.2

The point source flux limit

Spectrum dependent limit: (integrated format)

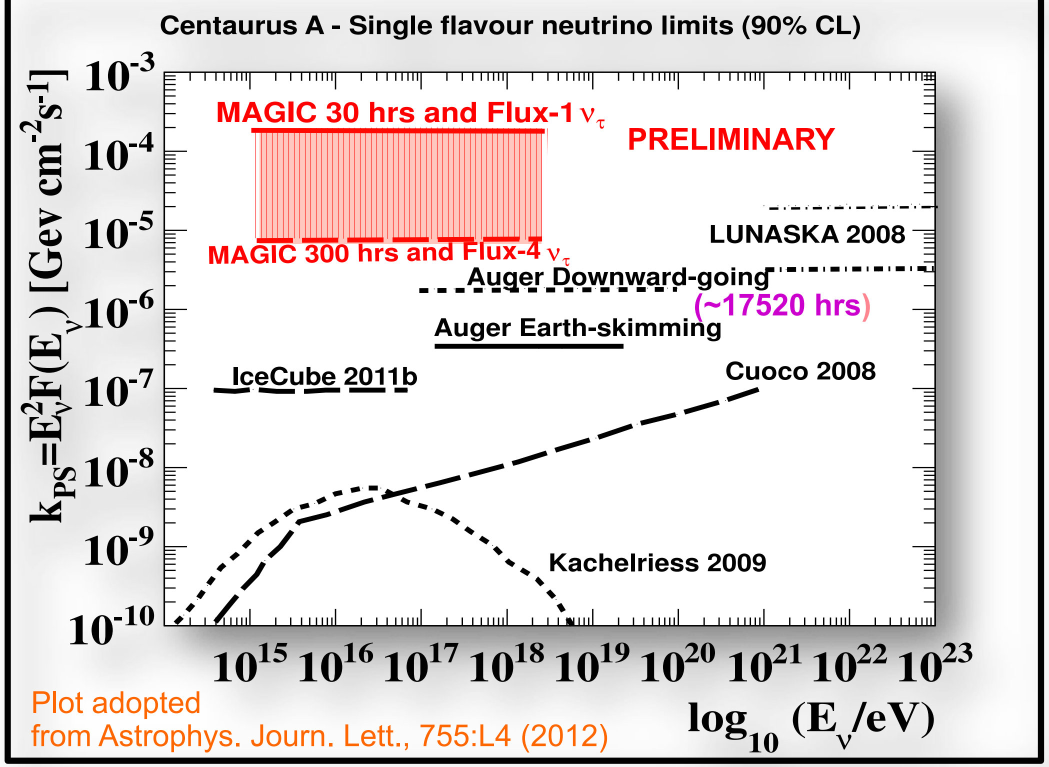
For the flux behaves with neutrino energy as:

$$\phi(E_\nu) = k \times \phi_0 \times E_\nu^{-2}$$
$$\phi_0 = 1 \times 10^{-8}\ [\mathrm{GeV\ cm^{-2}\ s^{-1}}]$$

$$k = \frac{2.44^*}{N_{event}}$$ 90 % C.L.

*2.44 for zero background events. Feldman and Cousins, Phys. Rev.D 57 (1998) 3873.

$$\mathrm{N_{event}} = 1.2 \times 10^{-4} \text{ for 30 hours}$$



Plot adopted from Astrophys. Journ. Lett., 755:L4 (2012)

$$E_{\nu_\tau}^2 \phi(E_{\nu_\tau}) < 2.0 \times 10^{-4} [\mathrm{GeV\ cm^{-2}\ s^{-1}}]$$

> **For 300 hrs and Flux-4:** $E_{\nu_\tau}^2 \phi(E_{\nu_\tau}) < 5.8 \times 10^{-6} [\mathrm{GeV\ cm^{-2}\ s^{-1}}]$
this is the twice of the level of down-going point source analysis in the Pierre Auger
Astrophysical Journal Letters, 755:L4 (2012)

> *Observation during high cloud periods can significantly improve the available observation time and limits (100 h or even 300 hr should be possible during 2/3 seasons)*

Summary and Outlook

> A considerable amount data at horizontal directions (~40 hours) is collected by MAGIC.

- we show that MAGIC can identify tau neutrino showers from the background of proton showers

> For 30 hours of observation the MAGIC limit for tau neutrinos is at level:

$$E_\tau^2 \phi(E_\tau) < 1.7 \times 10^{-4} [\mathrm{GeV\ cm^{-2}\ s^{-1}}]$$

- This is the first time that the limit is calculated with full simulations and with background measurements for IACTs

- Further observation during high cloud periods, when normal gamma-ray observation are not possible can significantly increase the limit estimate shown above, 100 hours or even more should be possible during 1-2 observation seasons

> This is ''cheap'', almost background free search, with potential high impact in science

> The next-generation Cherenkov telescopes. i.e. The Cherenkov Telescpe Array, could exploit its much larger FOV (in extended observation mode), and much larger effective areas

Thanks

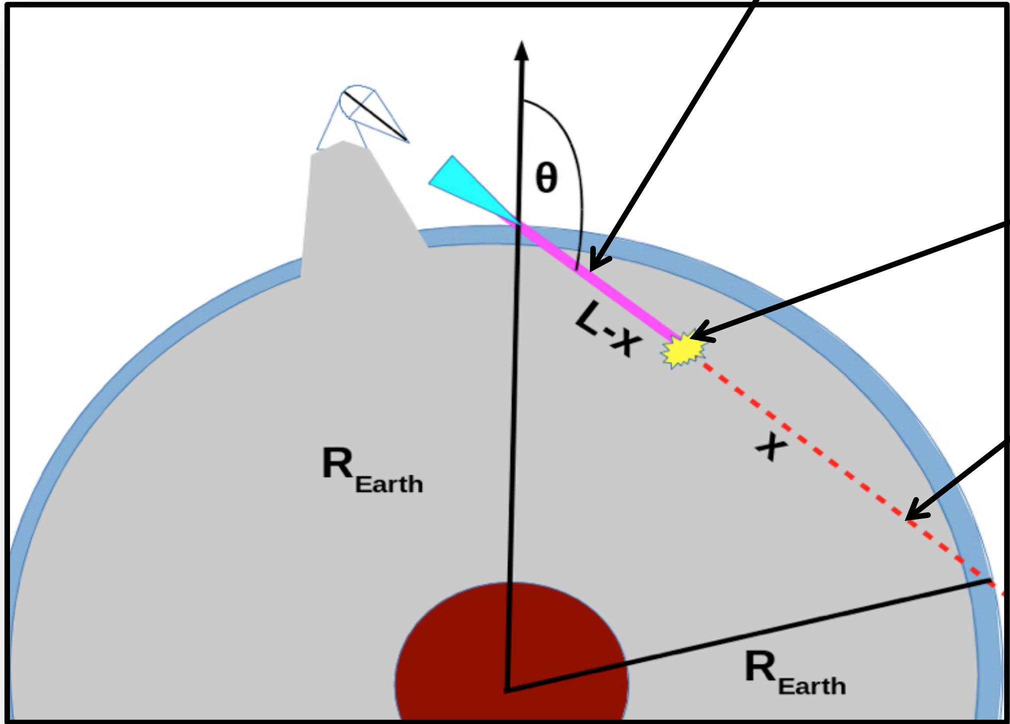
Analytical cross-check

Cross-check: analytical approach

(3) The probability for taus to survive the rest of the distance L−x

$$P_3(x) = \exp\left((L-x)/\lambda_\tau\right)$$

The decay length of tau: $\lambda_\tau = \left(\frac{E_\tau}{EeV}\right) \times 48.9\ \text{km}$



(2) The chance of neutrino interaction

$$P_2(x) = \frac{dx}{\lambda_\nu}$$

(1) The probability for neutrinos to survive distance x inside the Earth

$$P_1(x) = \exp\left(-x/\lambda_\nu\right)$$

The neutrino interaction length:

$$\lambda_\nu = \frac{1}{N_A \times \rho \times \sigma_{CC}}$$

Conversion probability:

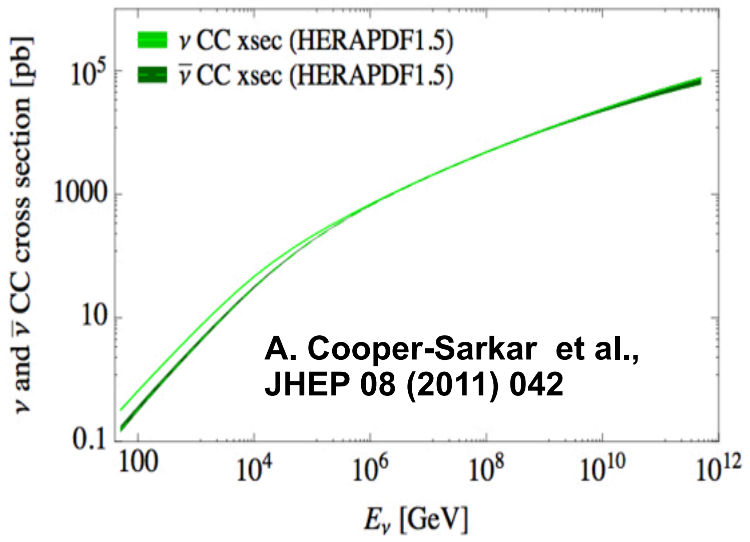
$$P(E_\nu, E_\tau, \theta) = \varepsilon = \int_0^L e^{-x/\lambda_\nu} e^{-(L-x)/\lambda_\tau} \frac{dx}{\lambda_\nu} = \frac{\lambda_\tau}{\lambda_\nu - \lambda_\tau}\left(e^{-L/\lambda_\nu} - e^{-L/\lambda_\tau}\right)$$

.

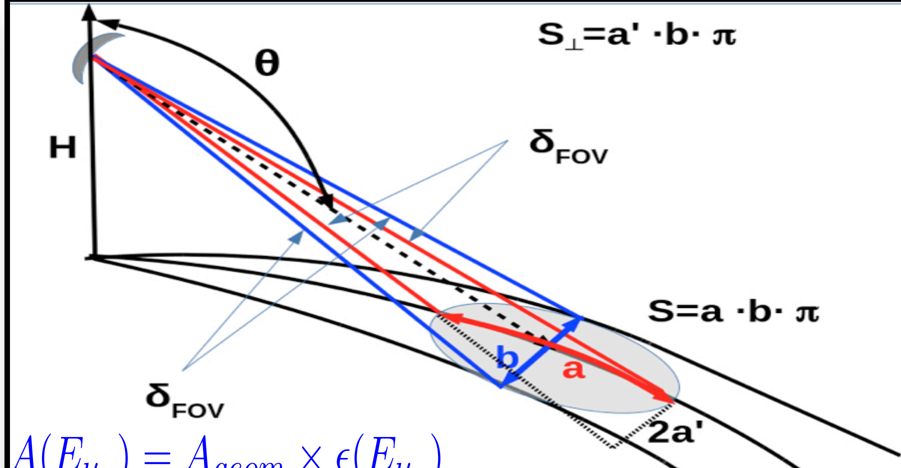
The energy of tau is approximated as $E_\tau = (1-y)E_\nu$, where y is the fraction of energy carried by the recoiling (shattered) nuclei or electron.

Cross-check: analytical approach

Neutrino cross-section



Geometric area of the MAGIC telescope



$$A(E_{\nu_\tau}) = A_{geom} \times \epsilon(E_{\nu_\tau})$$

$b = H \cdot \delta_{FOV} / (2 \cdot \cos(180-\theta))$

$a = H/2 \cdot (\tan(180-\theta+\delta_{FOV}/2) - \tan(180-\theta-\delta_{FOV}/2))$

Table 3. Comparison of MC aperture ($A^{PS}(E_{\nu_\tau})$) shown in Figure 10 (right panel) with the aperture obtained from simple analytic calculations ($A(E_{\nu_\tau})$). Results are obtained for a zenith angle of 92.5°, neutrino crossing distance $L = 546$ km, an average rock density $\rho = 2.65$ g/cm^3 and the charged current neutrino cross-section from Cooper-Sarkar et al. (2011). The energy of the tau particle is approximated as $E_\tau = 0.75 E_{\nu_\tau}$.

E_{ν_τ} (PeV)	$\sigma_{CC}(E_{\nu_\tau})$ (pb)	λ_{ν_τ} (km)	λ_τ (km)	$\epsilon(E_{\nu_\tau})$	A_{geom} (km^2)	$A(E_{\nu_\tau})$ (km^2)	$A^{PS}(E_{\nu_\tau})$ (km^2)
2	950	6596	0.073	1.0×10^{-5}	5.33	5.3×10^{-5}	1.5×10^{-4}
10	1900	3298	0.367	9.4×10^{-5}	5.33	5.0×10^{-4}	2.7×10^{-4}
100	4800	1305	3.670	1.9×10^{-3}	5.33	1.0×10^{-2}	8.0×10^{-3}
1000	11000	569	36.70	2.6×10^{-2}	5.33	1.4×10^{-1}	2.6×10^{-2}

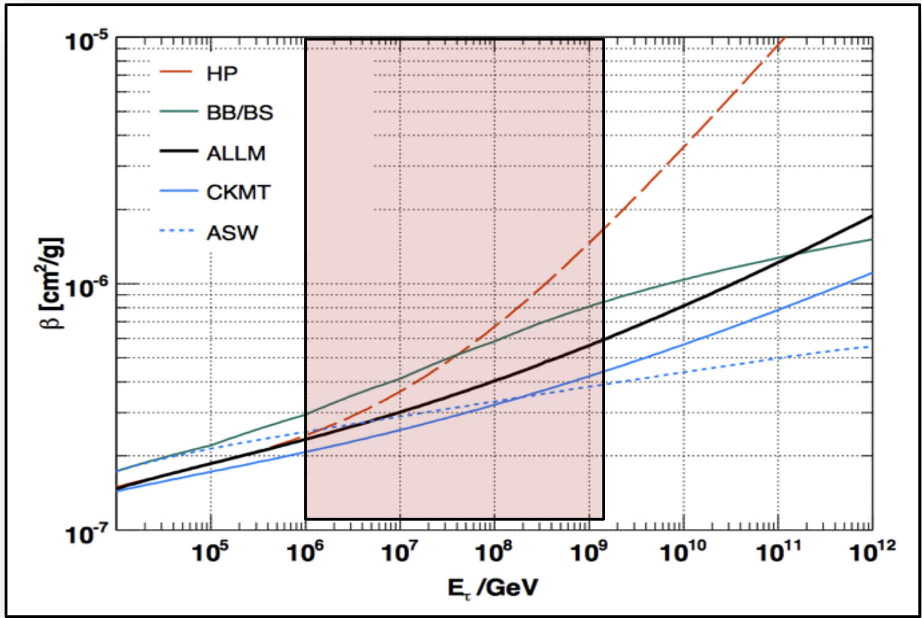
MC calculation

Systematics on event rate calculations

Continuous energy loss approach
(Bremss. pair production, photo-nuclear interaction)

$$\frac{\mathbf{dE}_\tau}{\mathbf{dX}} = -\alpha - \beta(\mathbf{E}_\tau) \times \mathbf{E}_\tau$$

Cross-section:
different parton distriburion function PDF



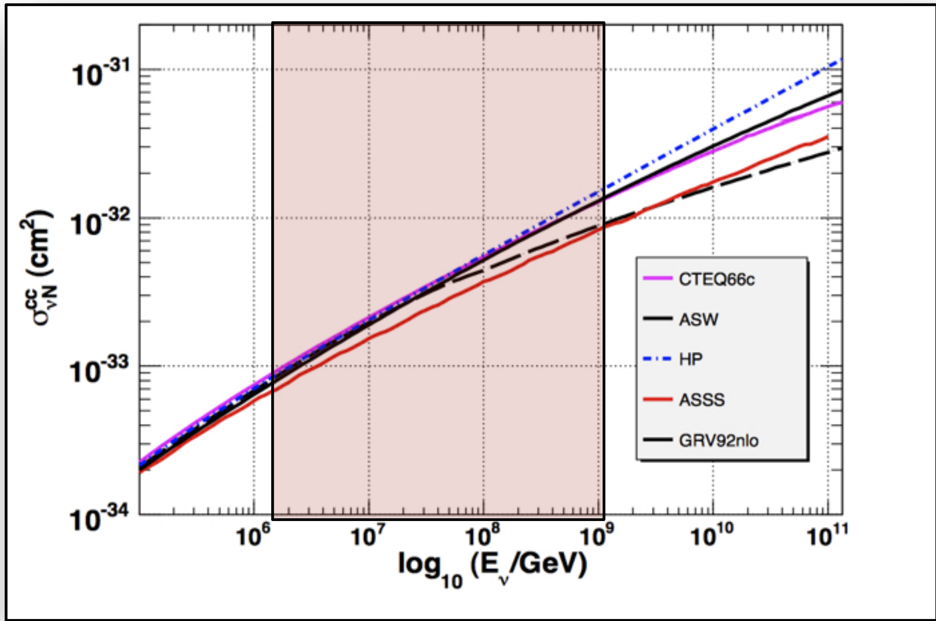


Table 6. Relative contributions to the systematic uncertainties on the up-going tau neutrino rate. As a reference GRV98lo and ALLM model for Flux-1 and Flux-3 was used.

model	PDF	β_τ	sum
Flux-1	$^{+14\%}_{-2\%}$	$^{+2\%}_{-7\%}$	$^{+14\%}_{-7\%}$
Flux-3	$^{+42\%}_{-7\%}$	$^{+7\%}_{-14\%}$	$^{+43\%}_{-16\%}$