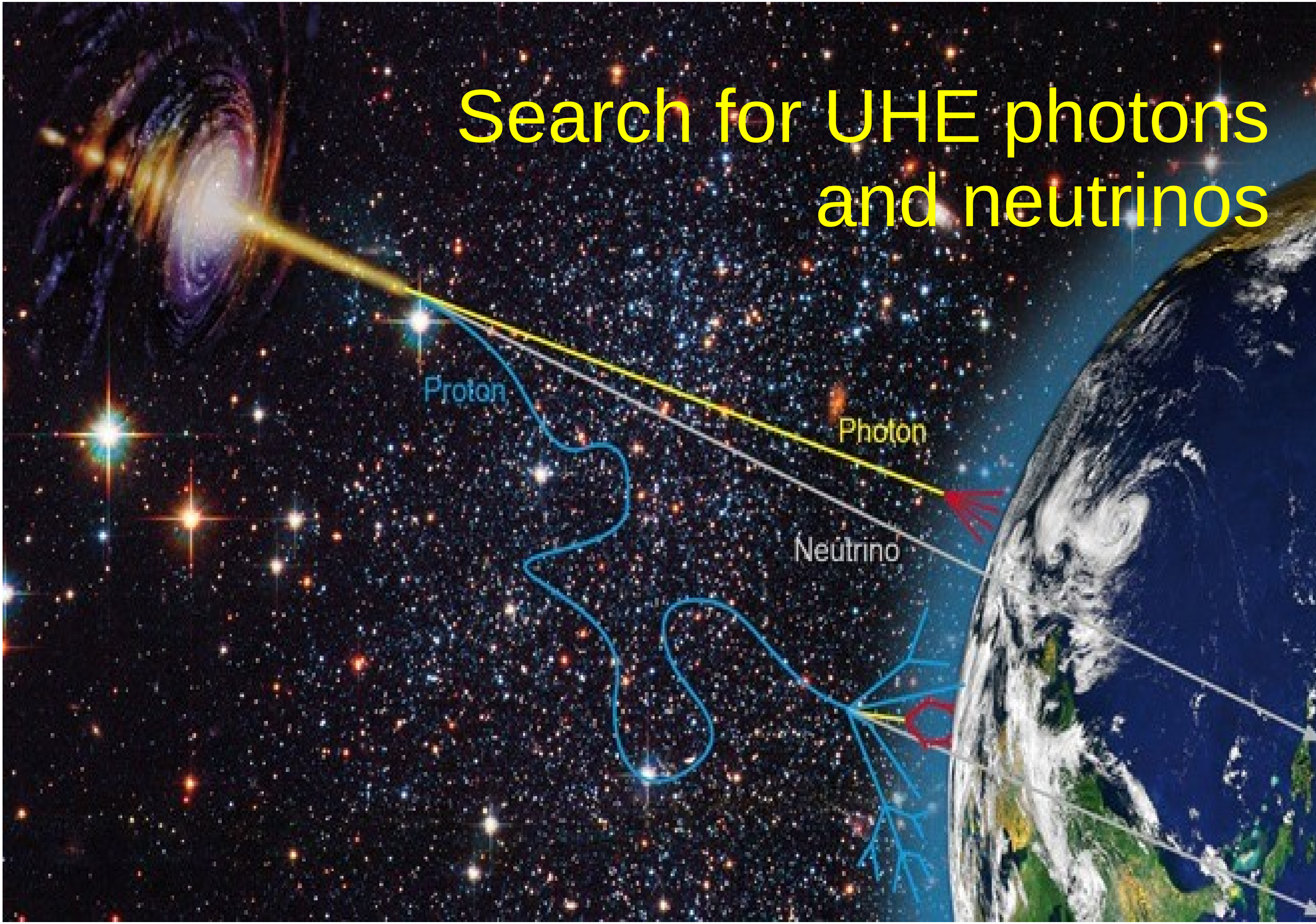
# Search for UHE photons and neutrinos




**Carla Bleve – INFN Lecce**

**20/6/2016 – MACROS 2016**

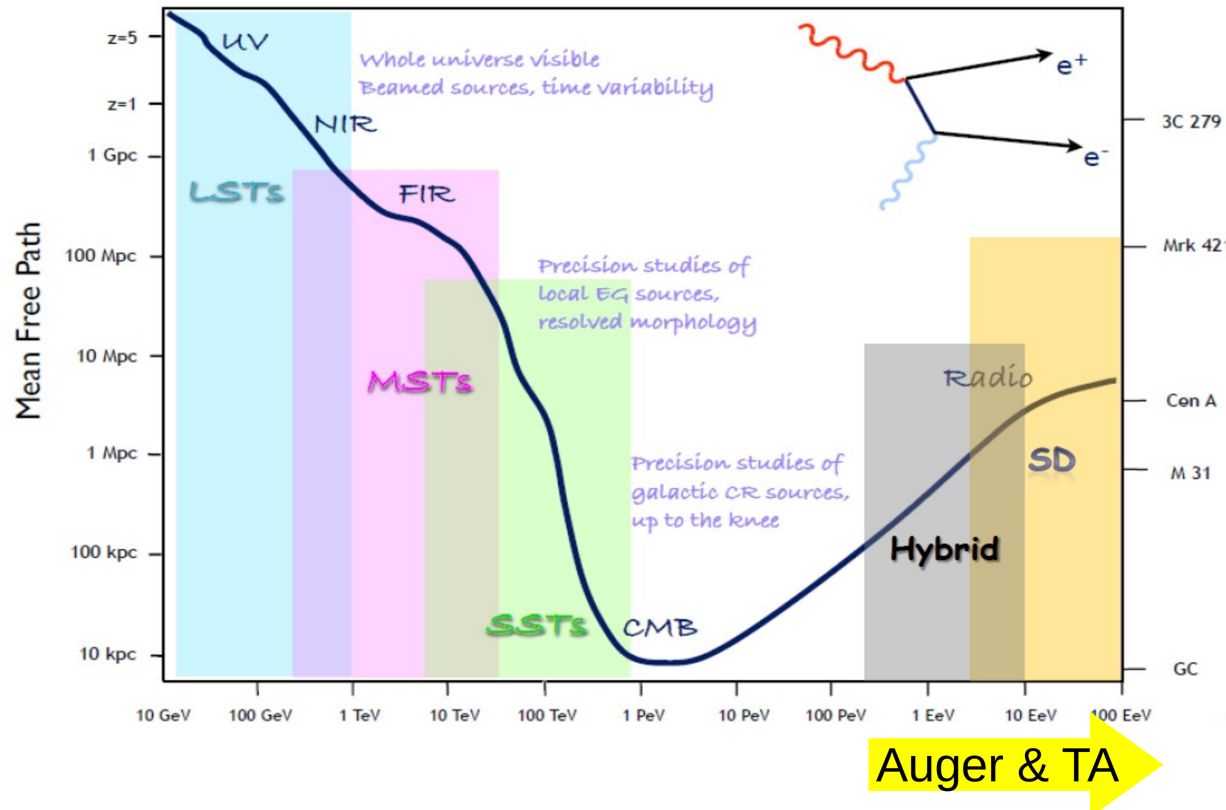
# Photons and Neutrinos above 0.1 EeV

→ Unlike charged UHECR, not affected by magnetic deflections and delays: messengers of UHECR sources

→ Extension of astronomy to the EeV range?

→ Photons have limited horizon (probe local universe)

→ Neutrinos: larger distances




→ Guaranteed **cosmogenic flux**

Produced in interactions of UHECRs with the CMB

$$p + \gamma_{2.7K} \rightarrow \Delta(1232) \rightarrow n + \pi^+ \nearrow \mu^+ + \nu_\mu \searrow e^+ + \bar{\nu}_\mu + \nu_e$$

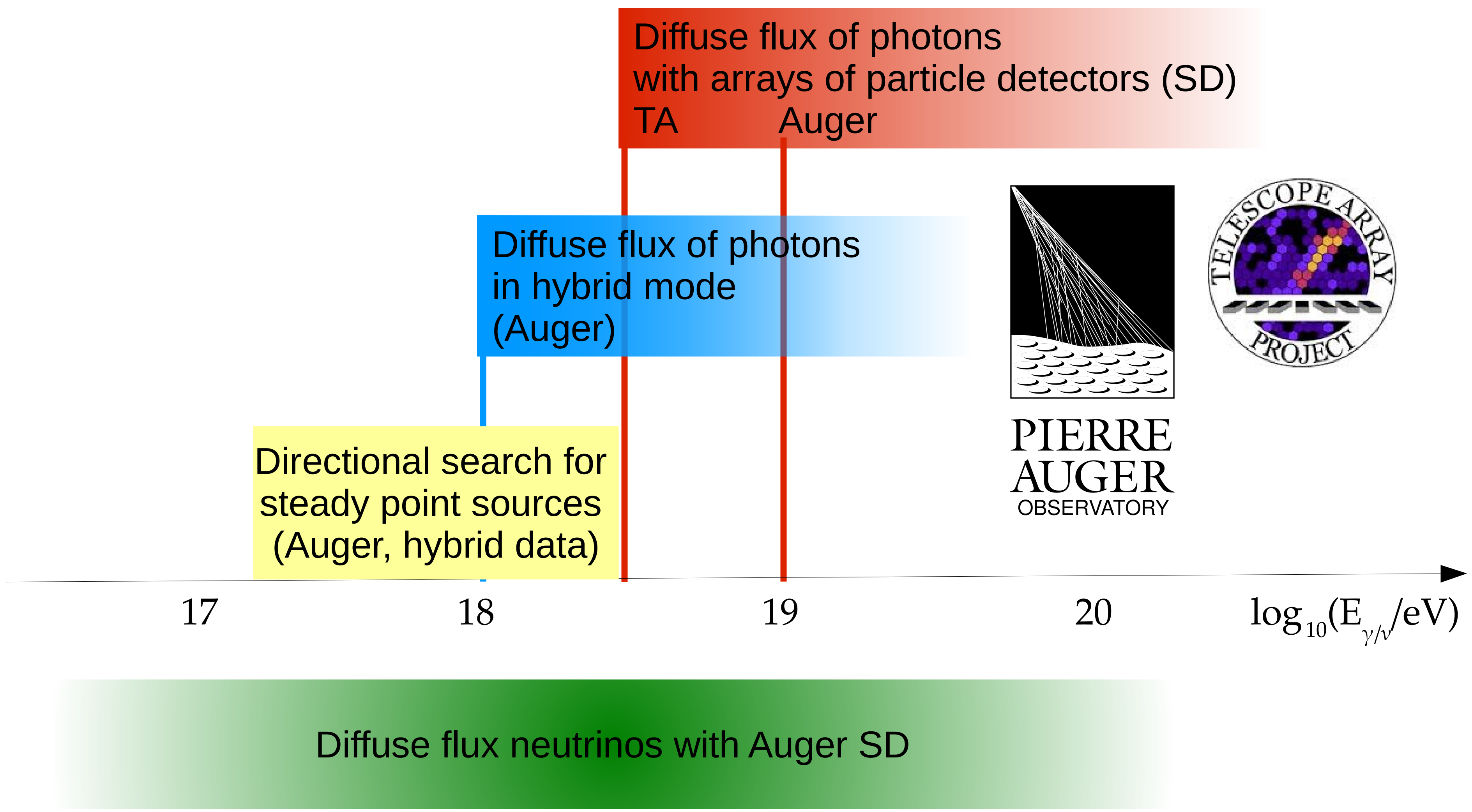
$$\Delta(1232) \searrow p + \pi^0 \searrow \gamma + \gamma$$

Gain information on:

**UHECR nature:**
- p or Fe-dominated ?
- mixed composition ?

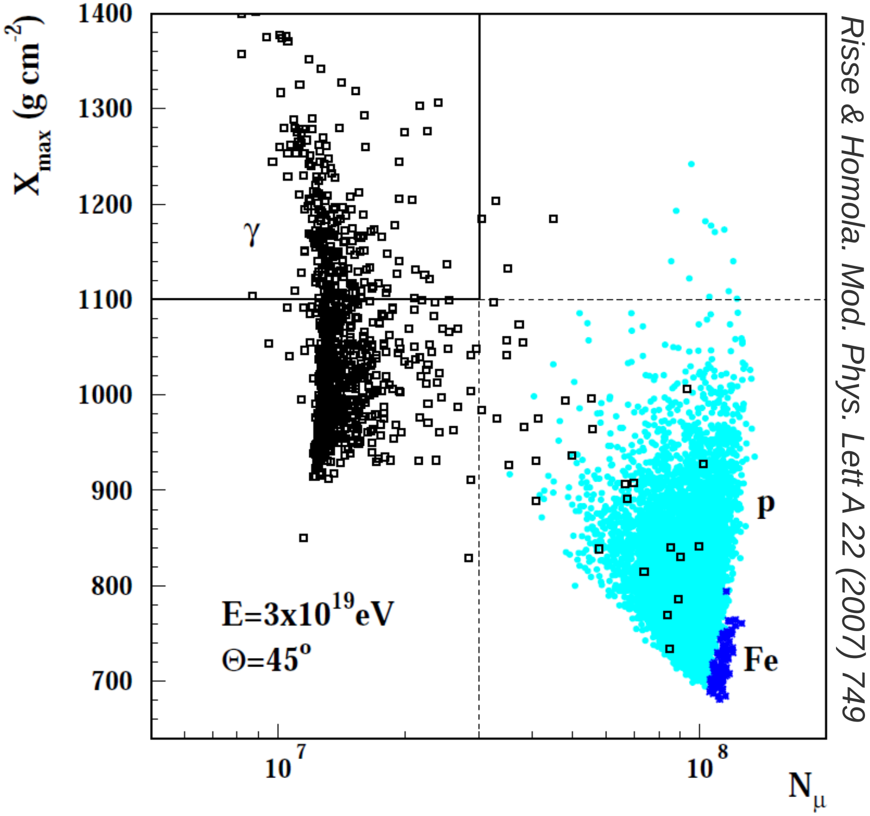
**UHECR origin:**
- evolution of sources with redshift
- max. energy attainable in sources

# Searches for photons and neutrinos with UHECR ground-based detectors: outline



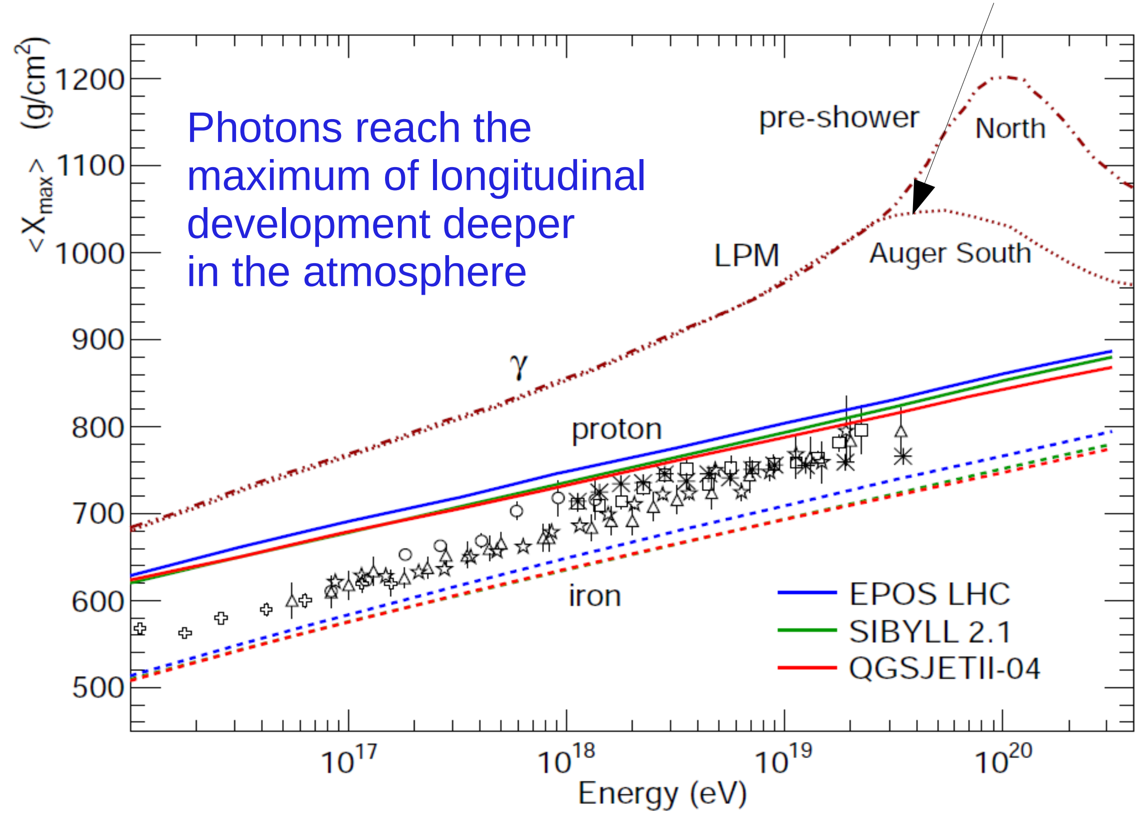
# Photons

# How to recognize a photon shower



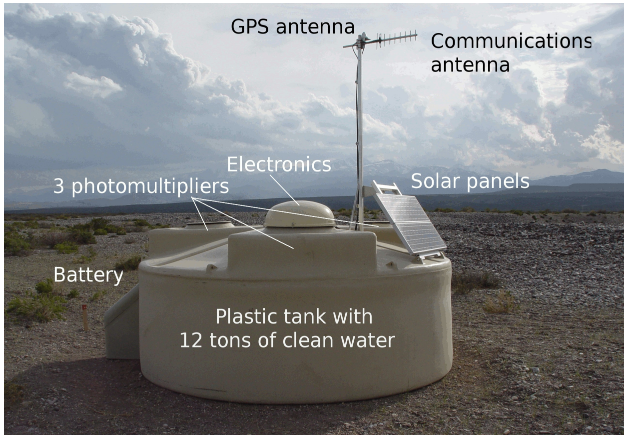

Air showers initiated by photons in the atmosphere:
→ Mostly **EM** showers
→ Minor photo-nuclear or muon pair production

Pre-shower in the geomagnetic field




Compared to hadron initiated showers (background), photon showers have:

→ **larger Xmax**
→ **smaller muon content**



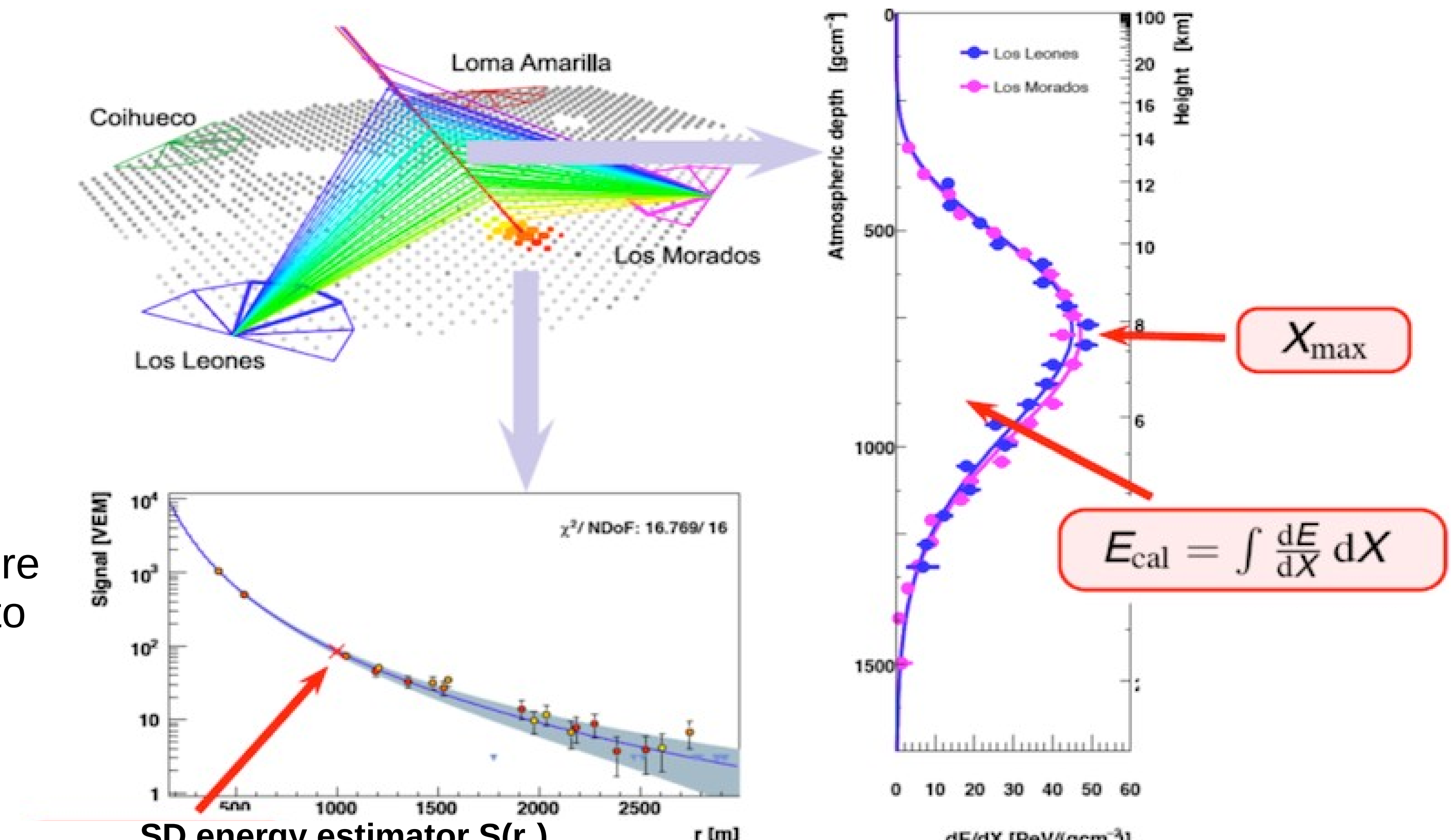

Auger:
WCDs
1.5 km spacing
~3,000 km$^2$

TA:
scintillators
1.2 km spacing
762 km$^2$

# Hybrid EAS detectors

**SD-only**:
100% duty cycle
– huge exposure
– analysis more difficult

**Hybrid:**
14% duty cycle
– limited exposure
– direct access to Xmax




**SD energy estimator S($r_0$)**
**($r_0$ = 1000 m for Auger, 800m for TA)**

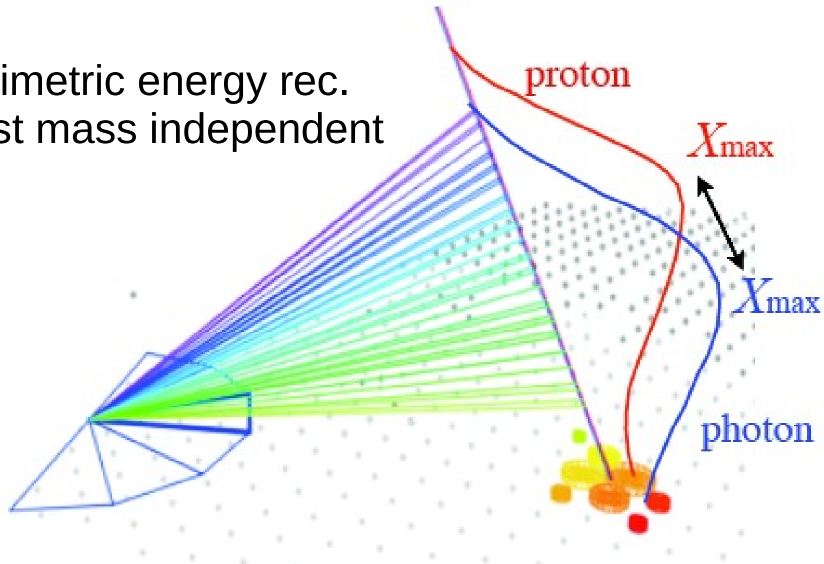
(R. Ulrich, APS meeting 2010)

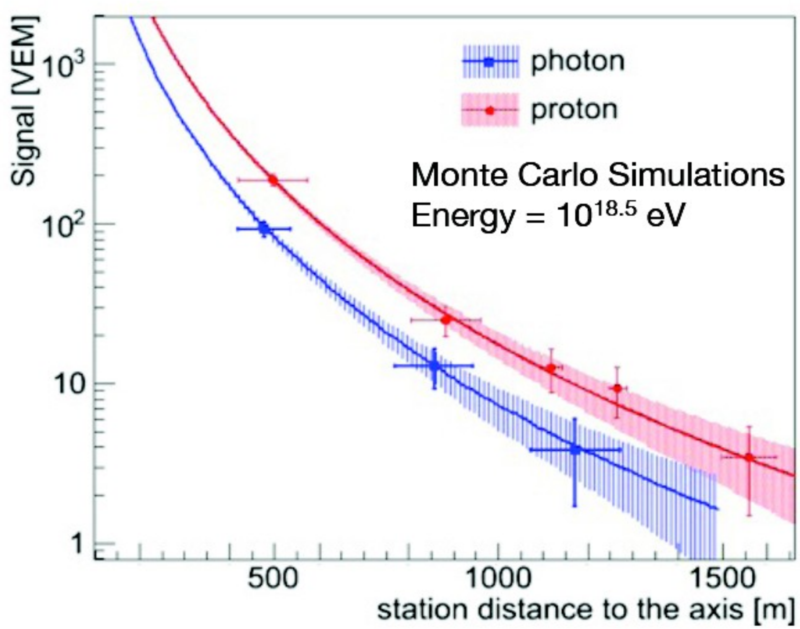
# Diffuse flux of photons 1:
# Search with Auger hybrid data ($E>10^{18}$ eV)

*The Pierre Auger Coll. @ icrc 2011*

# Observables for photon identification in hybrid data

Calorimetric energy rec.
almost mass independent




**FD**

Maximum of the longitudinal profile Xmax

photons → deeper Xmax

**SD**

Measure difference in normalisation and shape of LDF:

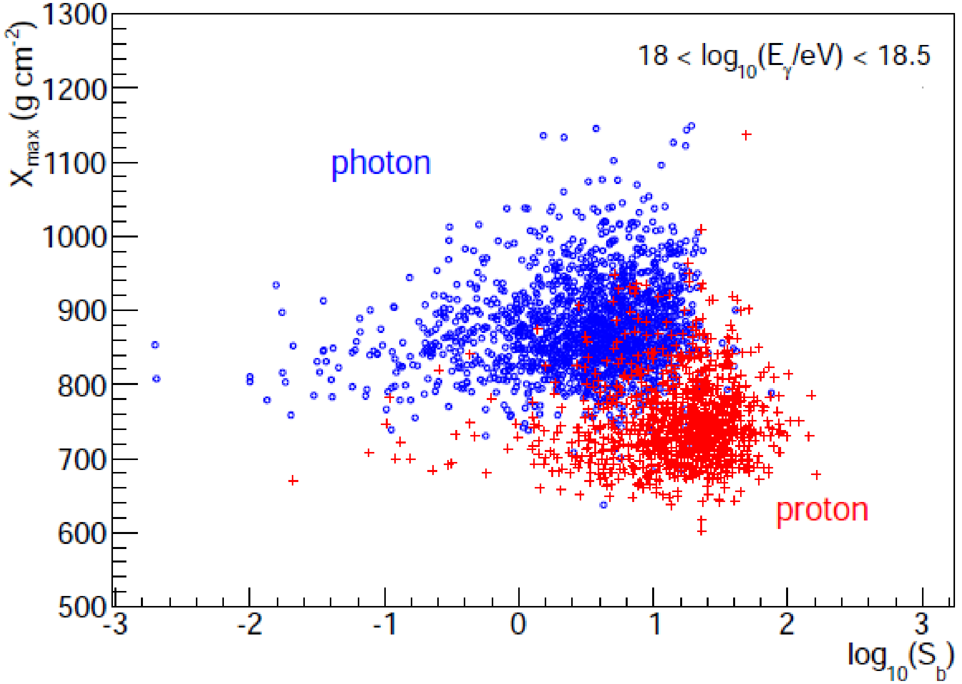
$$S_b = \sum_i S_i \left( \frac{R_i}{1000} \right)^4$$

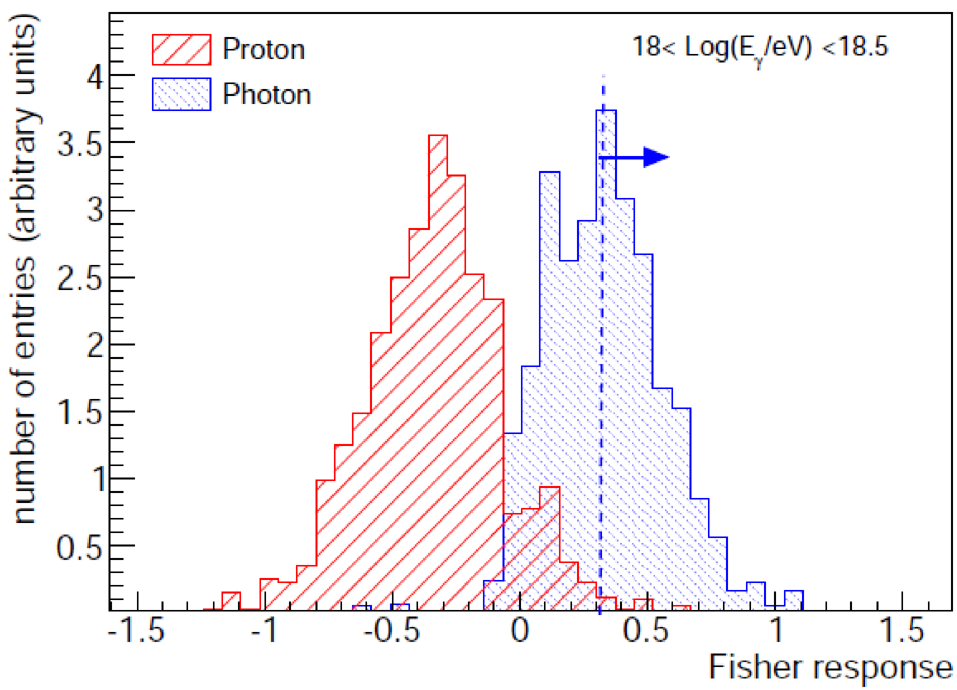
*Signal in the i-th station*

*Distance to the Shower axis*

photons → smaller signal, steeper LDF

# Define photon candidates




→ Fisher discriminant analysis to combine the observables

→ Trained on MC simulations of protons and photons

→ E dependent exposure for photons: from detailed simulations of observational conditions

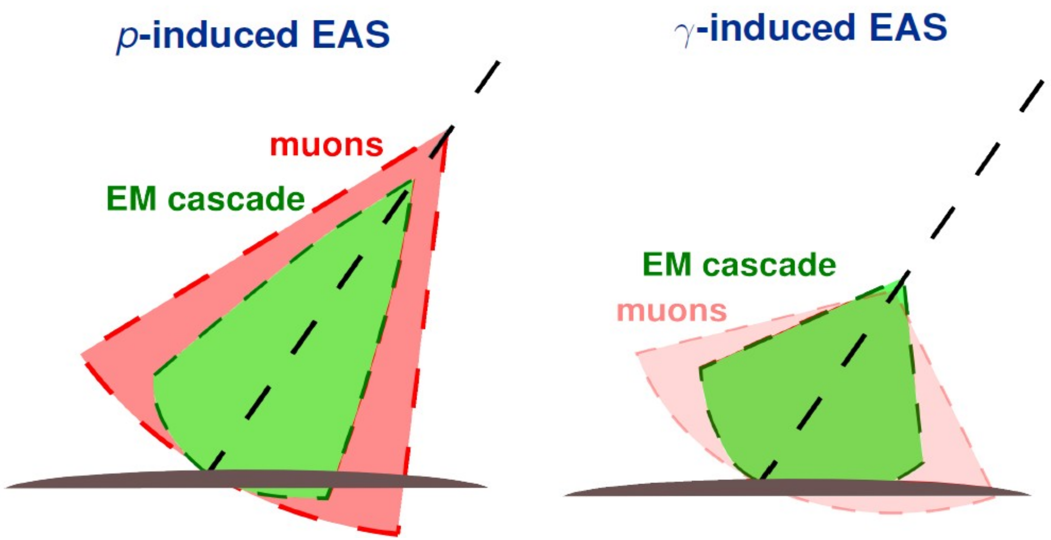
Candidate cut at the median of MC photon distribution

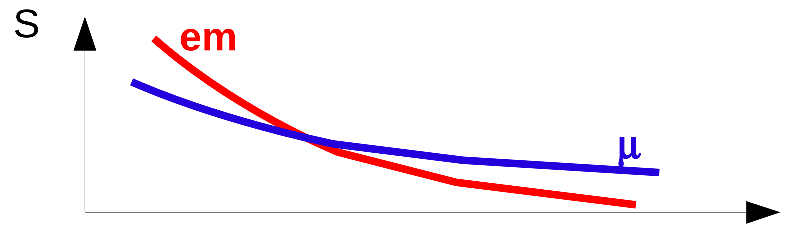
# Diffuse flux of photons 2: Search with SD arrays ($E>10^{18.5}$ eV)

*The Pierre Auger Coll. @ icrc 2015 (preliminary)*
*The Telescope Array Coll. @ icrc 2015 (preliminary)*

# SD observables for photon detection

No direct access to Xmax and number of muons,
but many measurable quantities - depending on one or both – help differentiate from hadron-induced showers.

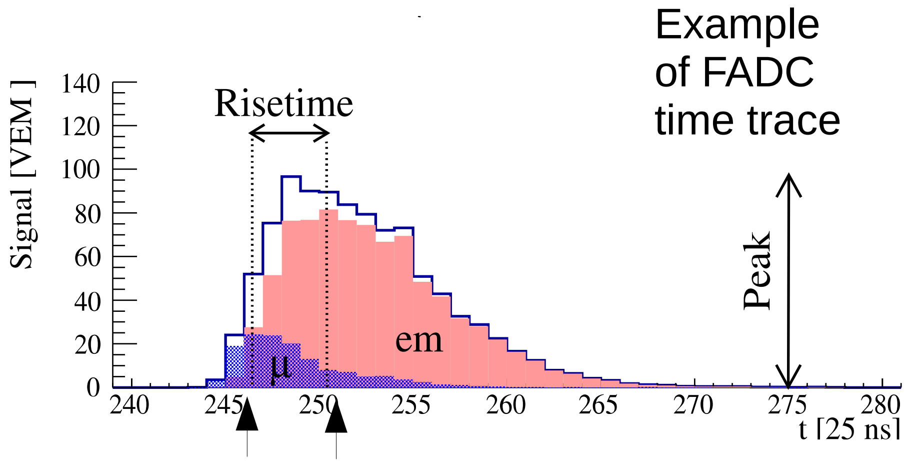


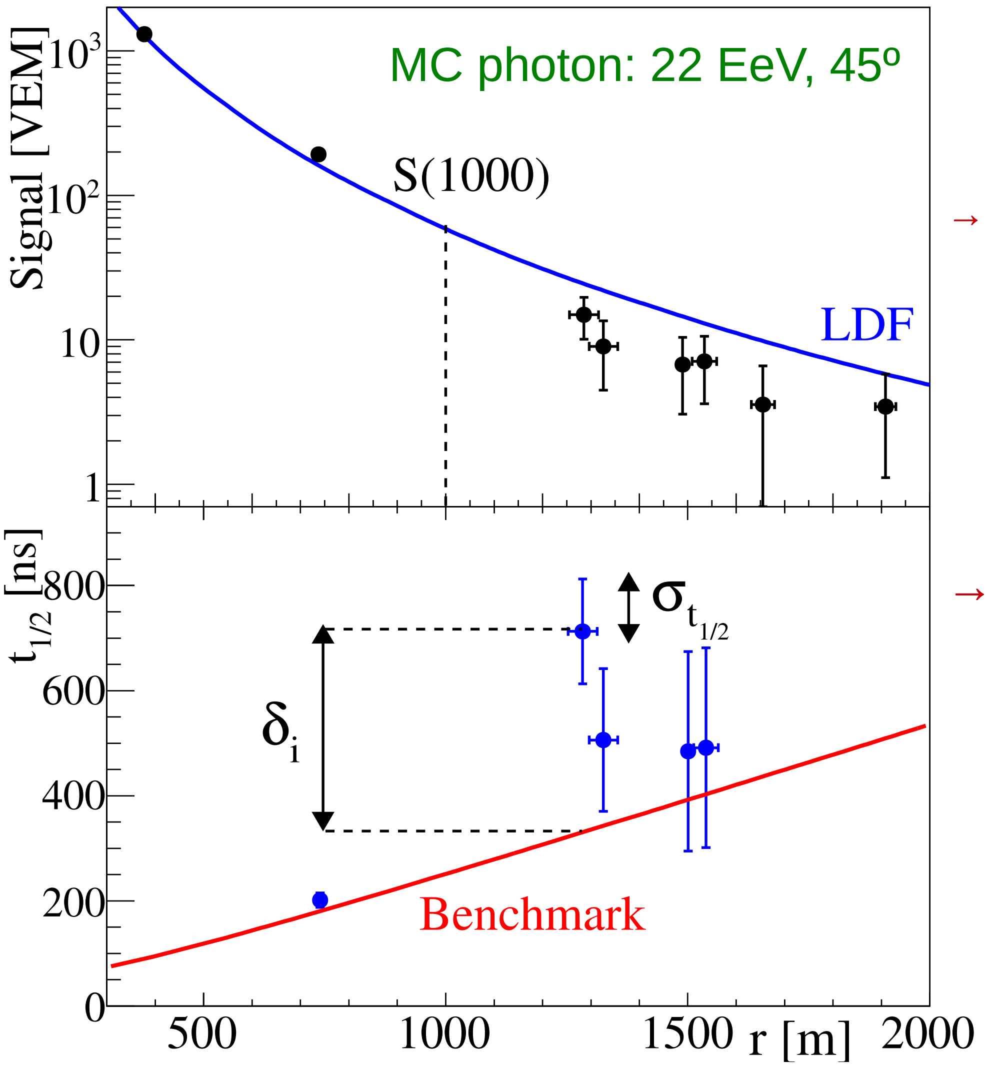

→ **Steeper LDF**: smaller footprint (and number of stations)

→ **Larger curvature of the front**
→ **Less muon peaks in traces**
→ **Broader time traces**
(larger RiseTime and AoP)

Example of FADC time trace



# Event variables for the photon search [Auger SD]




Photon-initiated EAS are characterised, with respect to the background, by:

→ **steeper LDF**

$$L_{LDF} = \log_{10}\left(\sum S_i / LDF(r_i)\right)$$

measurement of deviation from the data LDF

Expected ~0 for background

station selection: $r_i$ > 1000 m

→ **broader shower front (larger risetime)**

$$\Delta = \left(\sum \delta_i\right) / N$$

average deviation from the data benchmark

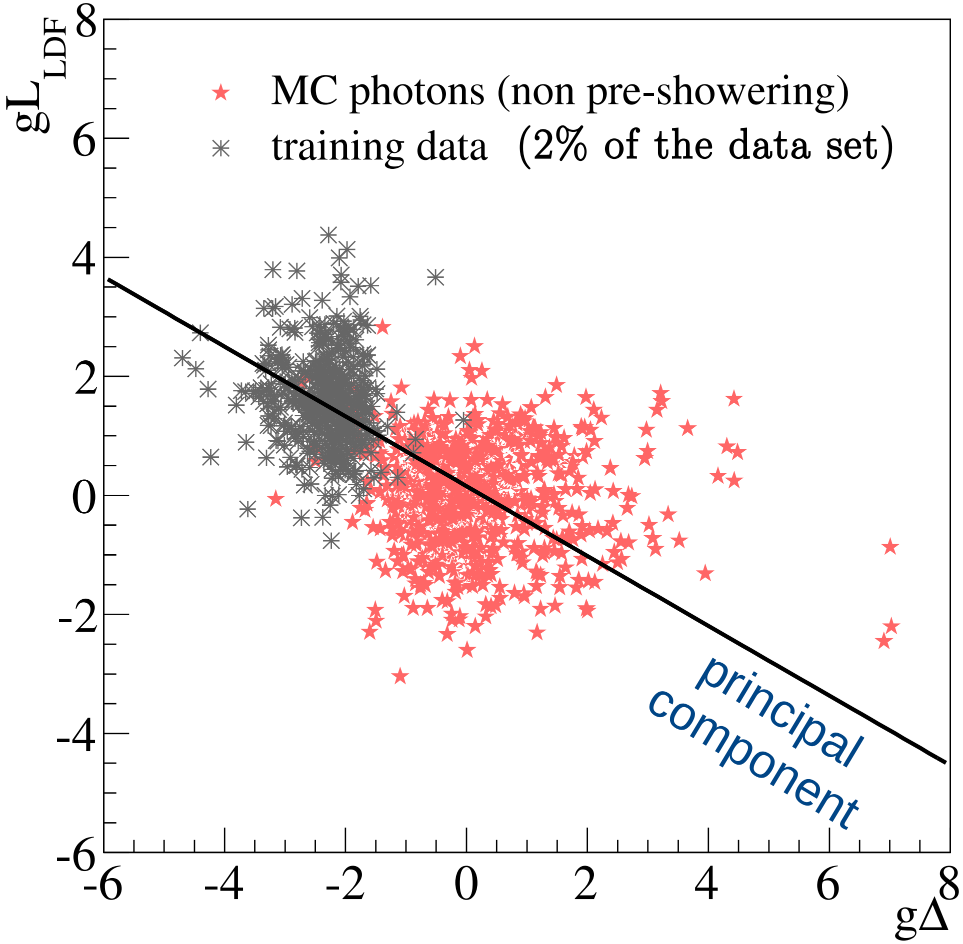
Expected ~0 for background

$$\delta_i = \frac{t_{1/2} - t^{Bench}}{\sigma_{t_{1/2}}}$$

station selection:

$S_i$ > 6 VEM, $r_i \in$ [600,2000] m

# PCA [Auger SD]




*Photon simulations: $E^{-1}$ spectrum*
*CORSIKA + QGSjetII.03*

Photon energy reconstruction:
(S1000, ϑ) → $E_\gamma$
calibrated with photon simulations

→ Redefine separation observables: taking $x = L_{LDF}$ or $x=\Delta$

$$gx = \left(x - \overline{x_\gamma}(E_\gamma, \theta)\right) / \sigma_\gamma(E_\gamma, \theta)$$

→ Find the linear combination that maximizes the signal/background separation

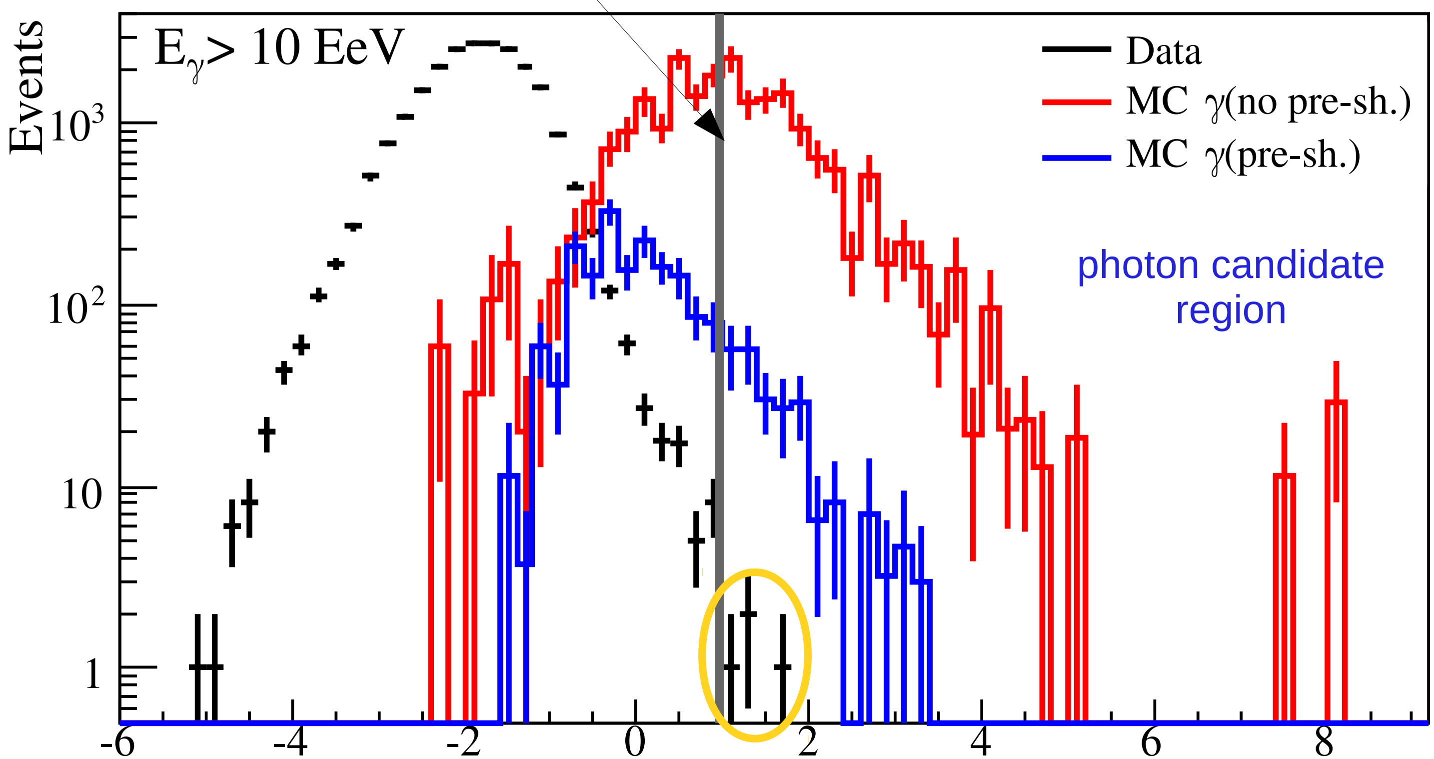
→ Use the principal component to identify photons

# Identification of photons [Auger SD]

data 01/01/04 – 15/06/13 zenith 30º-60º

"a priori choice",
NO cut optimization

Candidate cut: median of non pre-showering photon distribution (spectrum $E^{-2}$)




Search data sample (98% of the total): 22853 events

**4 photon candidates**

2 for E >20 EeV (8225 events)

0 for E>40 EeV (1941 events)

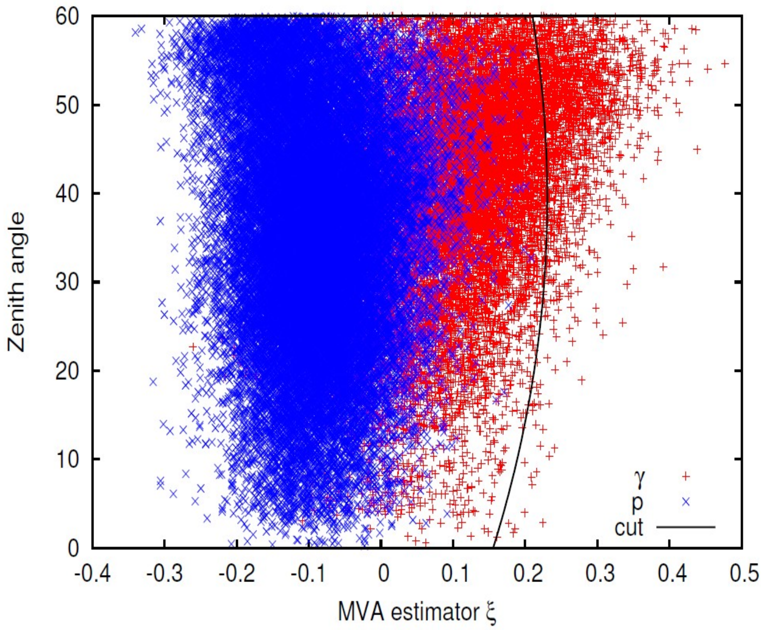
→ No bkg estimation yet

→ Conservative approach: set upper limits to the flux assuming the candidate are photons

# Telescope Array SD photon search

data 11/05/08 – 11/05/15  zenith 0º-60º

E > 10 $^{18.5}$ eV

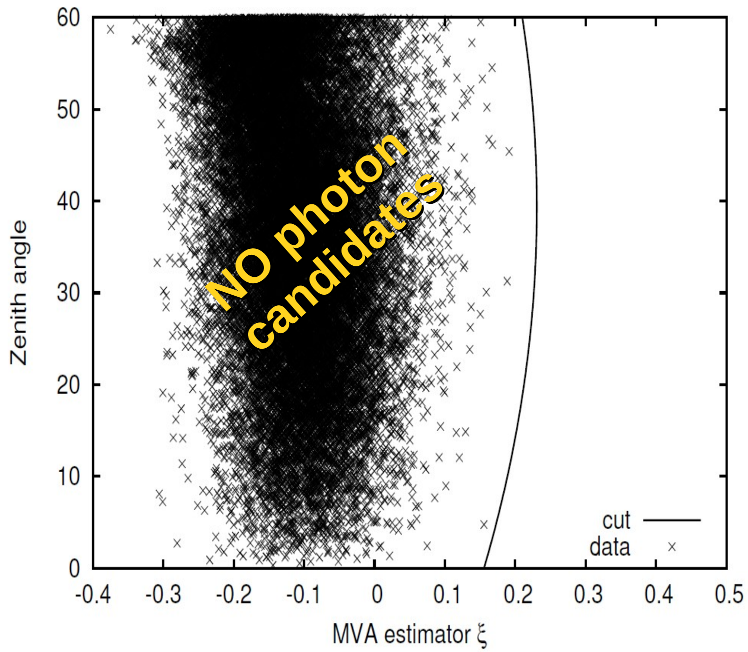



→ Dedicated photon energy reconstruction calibrated with photon simulations (as Auger)

→ Use **all available information**
13 variables (curvature, zenith, no. of peaks in the two layers, LDF shape, AoP for signal extension In time, ...)

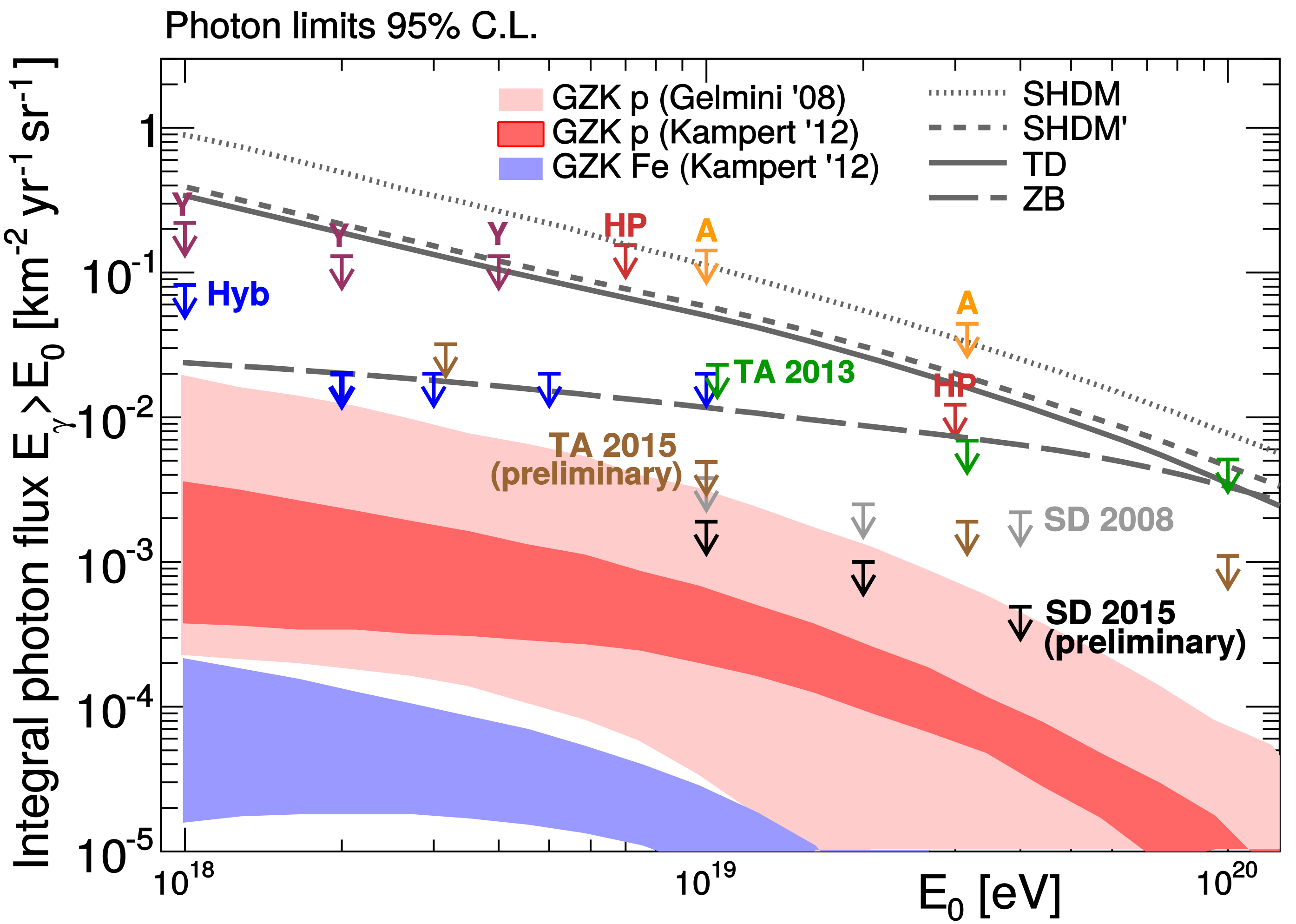
→ use BTD to combine in one variable ξ
(trained with proton and photon simulations)

→ **optimization of zenith dependent cut**:
select candidate photon cut that minimizes the upper limit in the case of null hypothesis (= no photons)




– Geometric exposure 3.5 times smaller than Auger SD :(
– Northern emisphere :)

# Searches for diffuse fluxes of photons: results




Feldman-Cousins limit to the number of photons

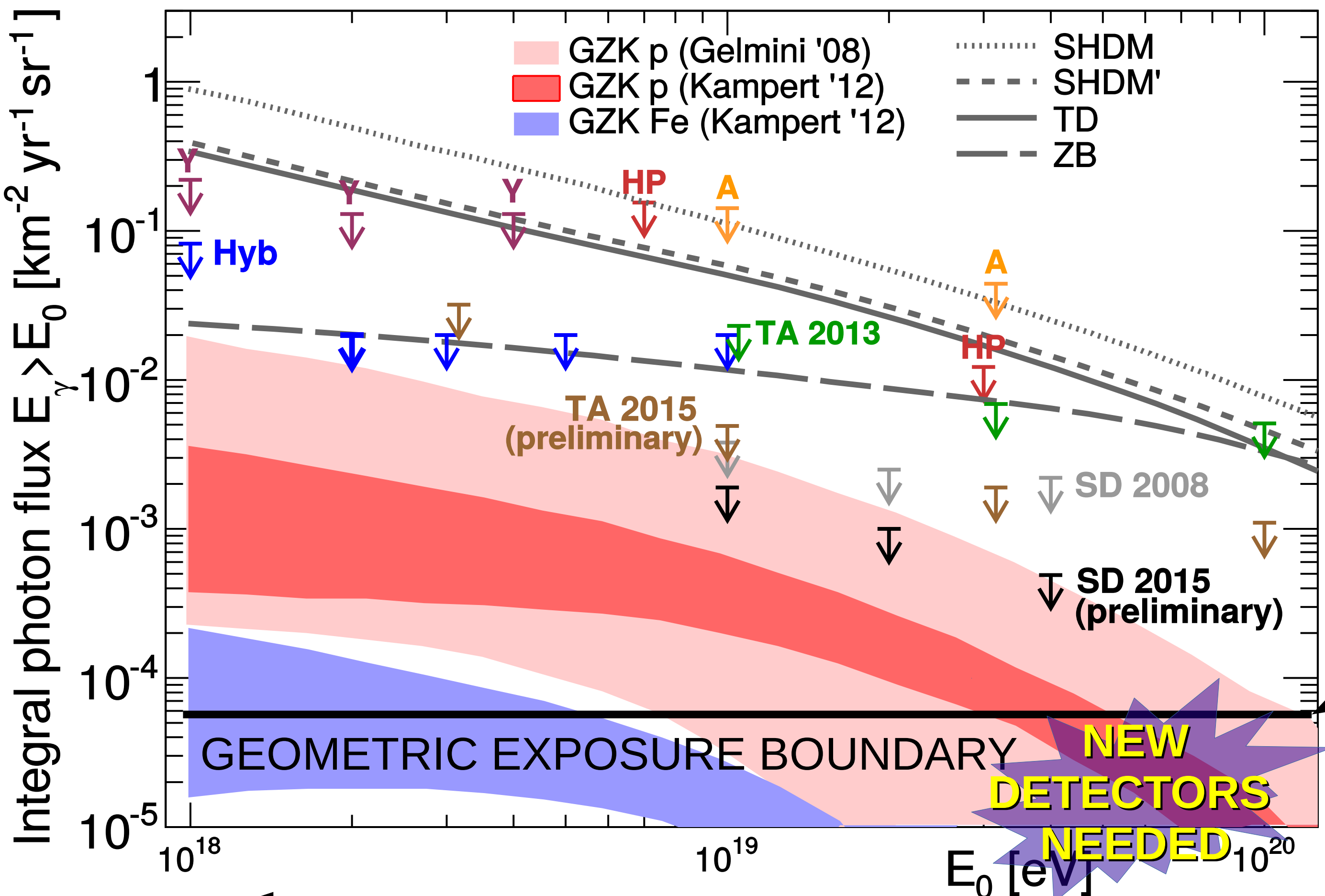
$$F_\gamma(E_\gamma > E_0) = \frac{N_\gamma}{\langle \varepsilon \rangle}$$

$E^{-2}$ spectrum-weighted average exposure for $E_\gamma > E_0$

→ Similar analyses can be applied to any flux yelding a sizeable number of photons in the FoV

→ Strictest limits from Auger Hybrid and Auger SD analysis
→ Top-down models highly disfavoured
→ First constraints to the most optimistic predictions for cosmogenic photon fluxes
→ Observation in both emispheres

# Searches for diffuse fluxes of photons: results (2)




$$F_\gamma(E_\gamma > E_0) = \frac{N_\gamma}{\langle \varepsilon \rangle}$$

TA to be extended to Auger size (**TA x4**) – but larger spacing => higher energy threshold

IDEAL DETECTOR:
100% efficiency for γs
No background
10 yr Auger SD size

→ Extension to low energy possible since 2013 with Auger new triggers

→ Signal/bkg separation expected to Improve with **AugerPrime**

→ Challenge: approach the ideal case at low energy to probe mixed comp./low Emax

**ASCII Scintillators on top Of WCDs**

# Point sources nearby searched with Auger hybrid data

*The Pierre Auger Coll., ApJ, 789, 160 (2014)*

# Search for point sources of photons

**Astronomy?**


→ Find of photons in a **blind directional search**

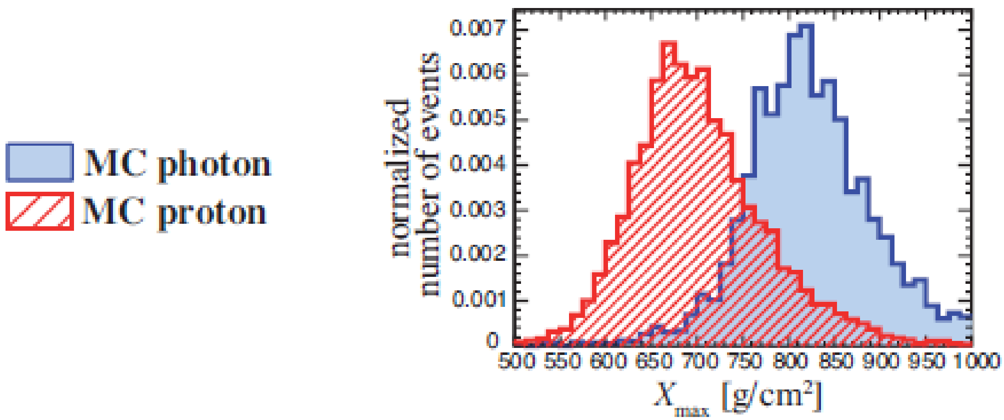
→ Needs large statistics: go to low energies
Hybrid data, **$10^{17.3}$-$10^{18.5}$ eV**
Horizon: **Milky Way and LG**

→ Aim: look for <u>steady</u> sources of photons (sources of galactic EeV CRs)

→ Method: build a sample of data with reduced background level
→ Search for excess flux in any direction

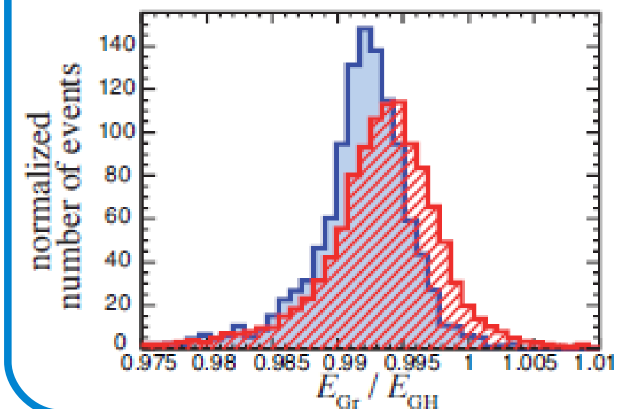
# Event observables

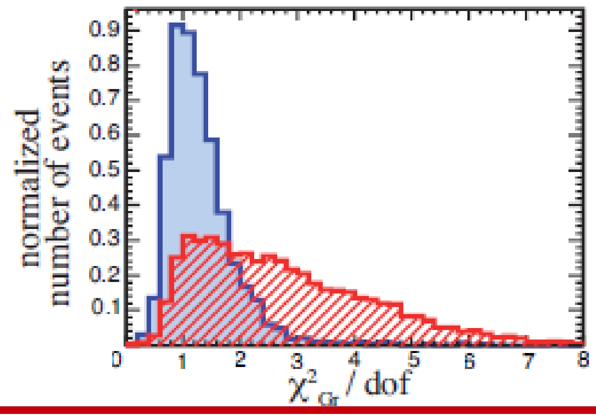
**FD**




Depth of the maximum
ongitudinal development

$X_{max}$



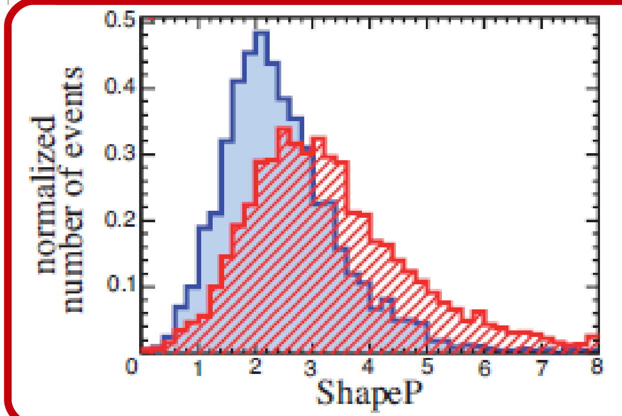



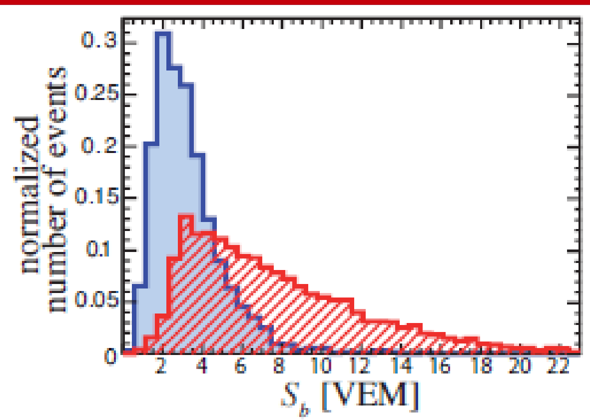

Comparison with Greisen
longitudinal profile (pure em)

$E_{Gr} / E_{GH}$

$\chi^2_{Gr} / dof$

**SD**



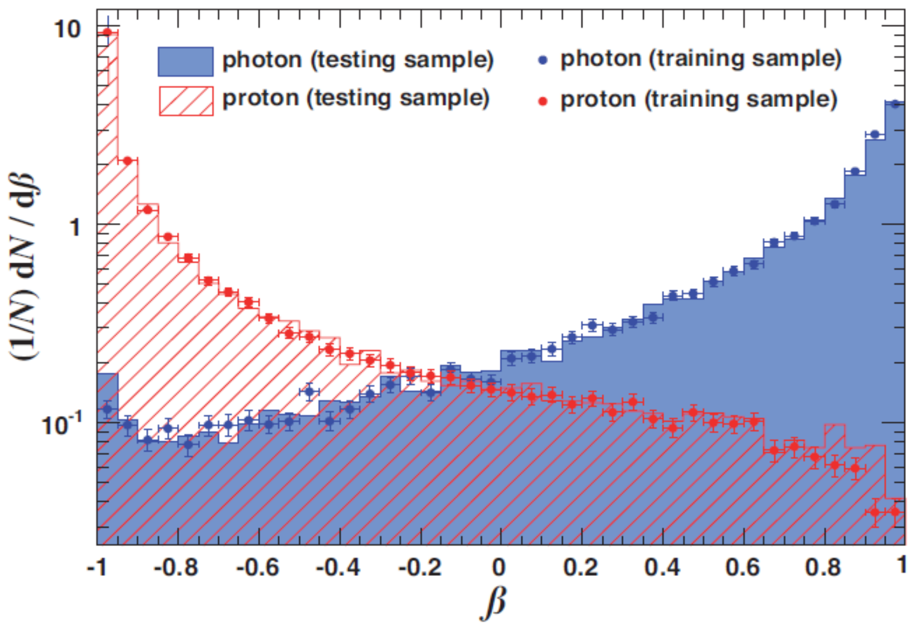

Ratio between “early” and “late”
signal in the highest S station

$ShapeP$

LDF related parameter (as in diffuse
searches)

$S_b$

# Multi Variate Analysis => Application to data




→ Trained with simulations

→ Highest ranking observables:
Xmax, $S_b$
(same as for diffuse hybrid search)

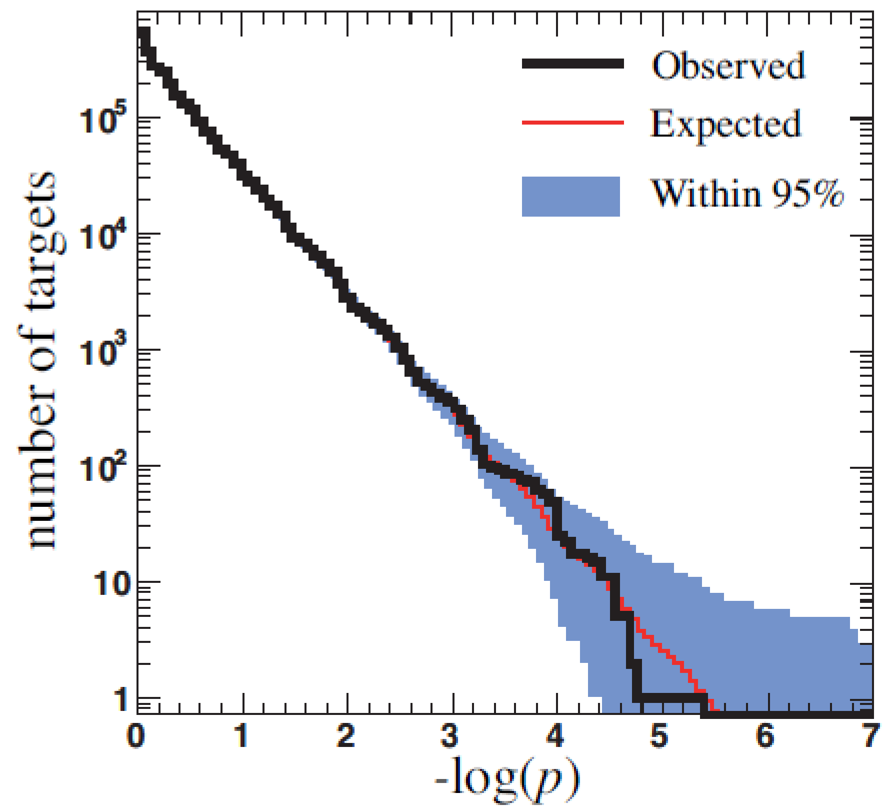
Directional optimisation of the photon cut to maximise the expected sensitivity (bkg from data scrambling).

Hybrid data: Jan 2005- Sept 2011
13,304 events selected, <E> = $10^{17.7}$ eV

p = Poisson probability of having a number of observed events ≥ expected bkg

Lowest p observed → $p_{chance}$ =36%

**No significant excess identifed**

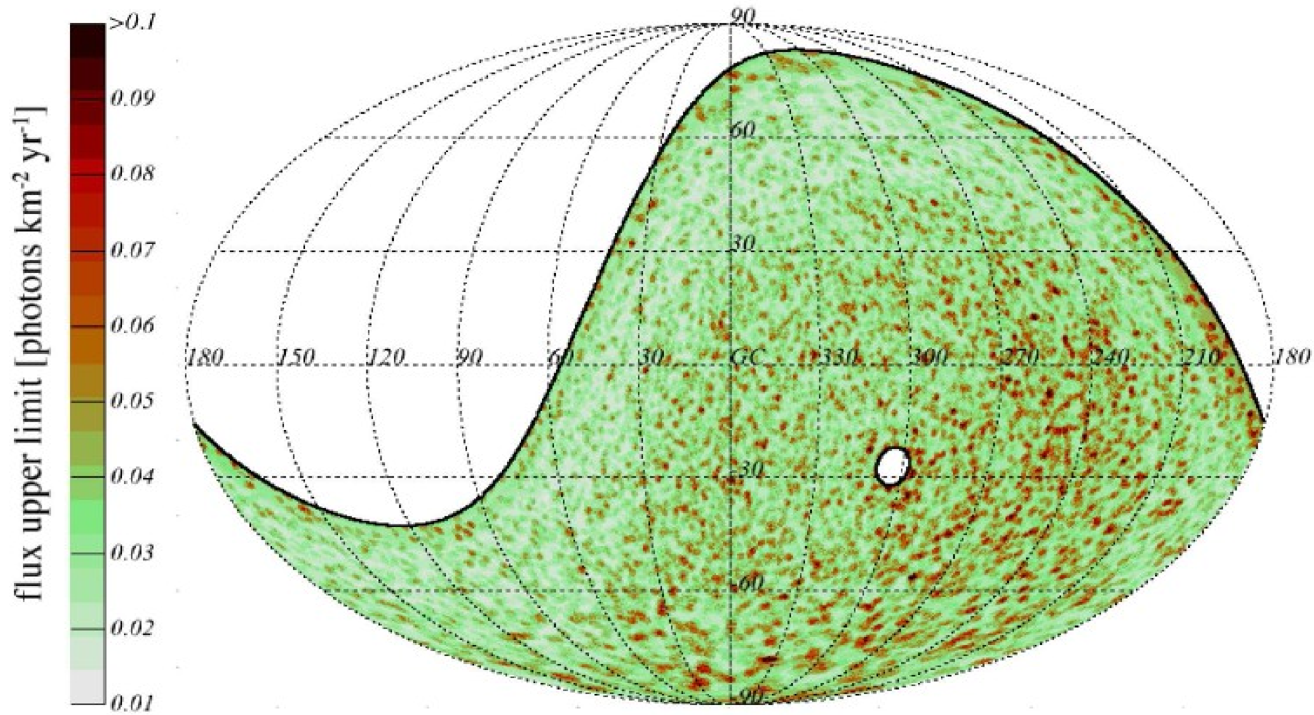


# 95% CL directional ULs on the photon flux

*ApJ, 789, 160 (2014)*

Bounds on non transient galactic sources

-85º < δ < 20º



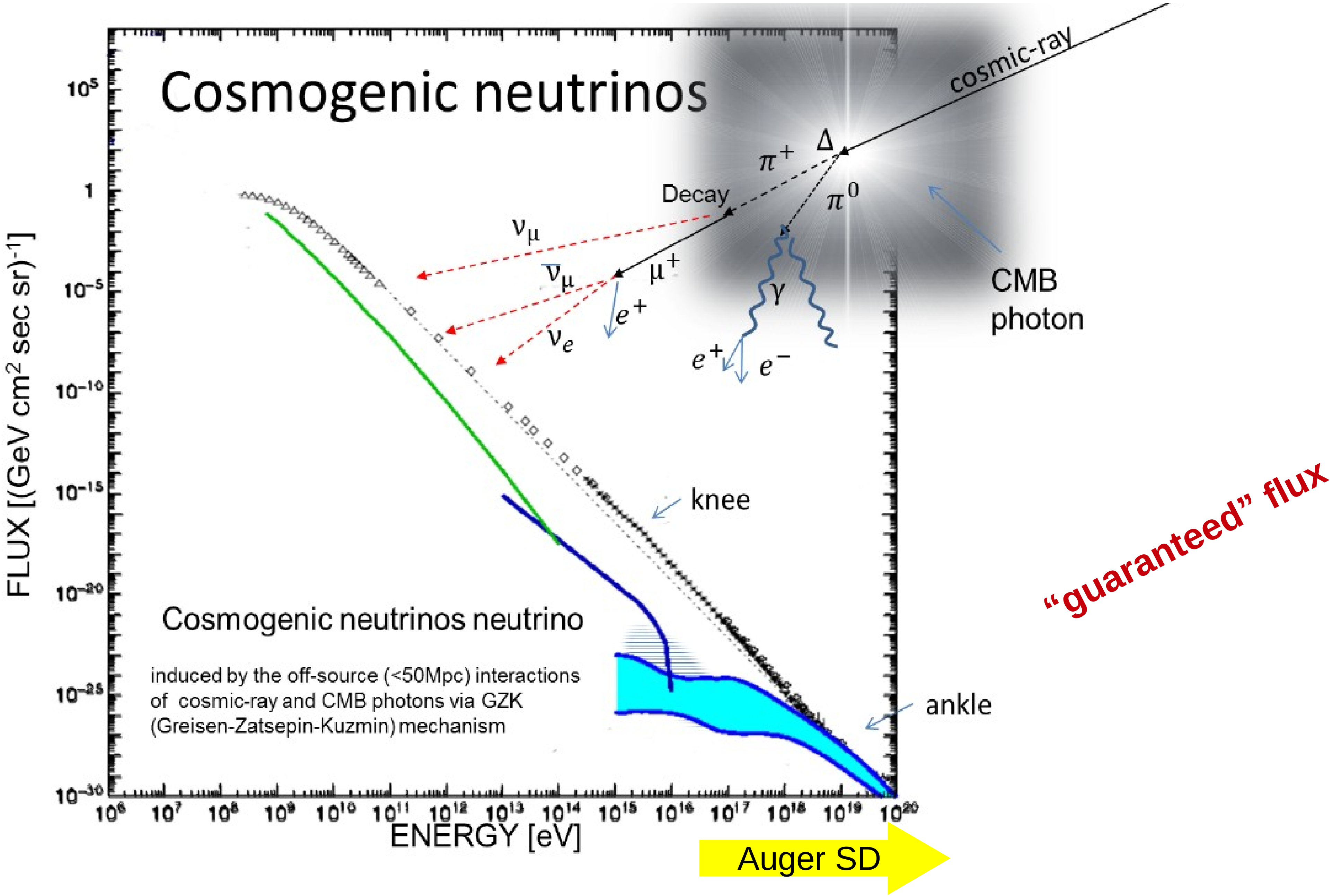

Mean value: **0.035 [max 0.14] photons km$^{-2}$ yr$^{-1}$**

Corresponding energy flux for E$^{-2}$ spectrum: **0.06 [max 0.25] eV cm$^{-1}$ s$^{-1}$**

→ Targeted searches in progress (soon to come!)

# Search for neutrinos
# with the Pierre Auger Observatory SD

*The Pierre Auger Coll.,Phys. Rev. D 91 (2015) 092008*




**EeV neutrinos:**

→ sensitive to the mass composition of UHECRs (flux decreases as mass gets heavier)

→ probe high-redshift source evolution

# Inclined showers
# and UHE neutrinos

→ Protons & nuclei initiate inclined showers high in the atmosphere.

Shower front at ground:

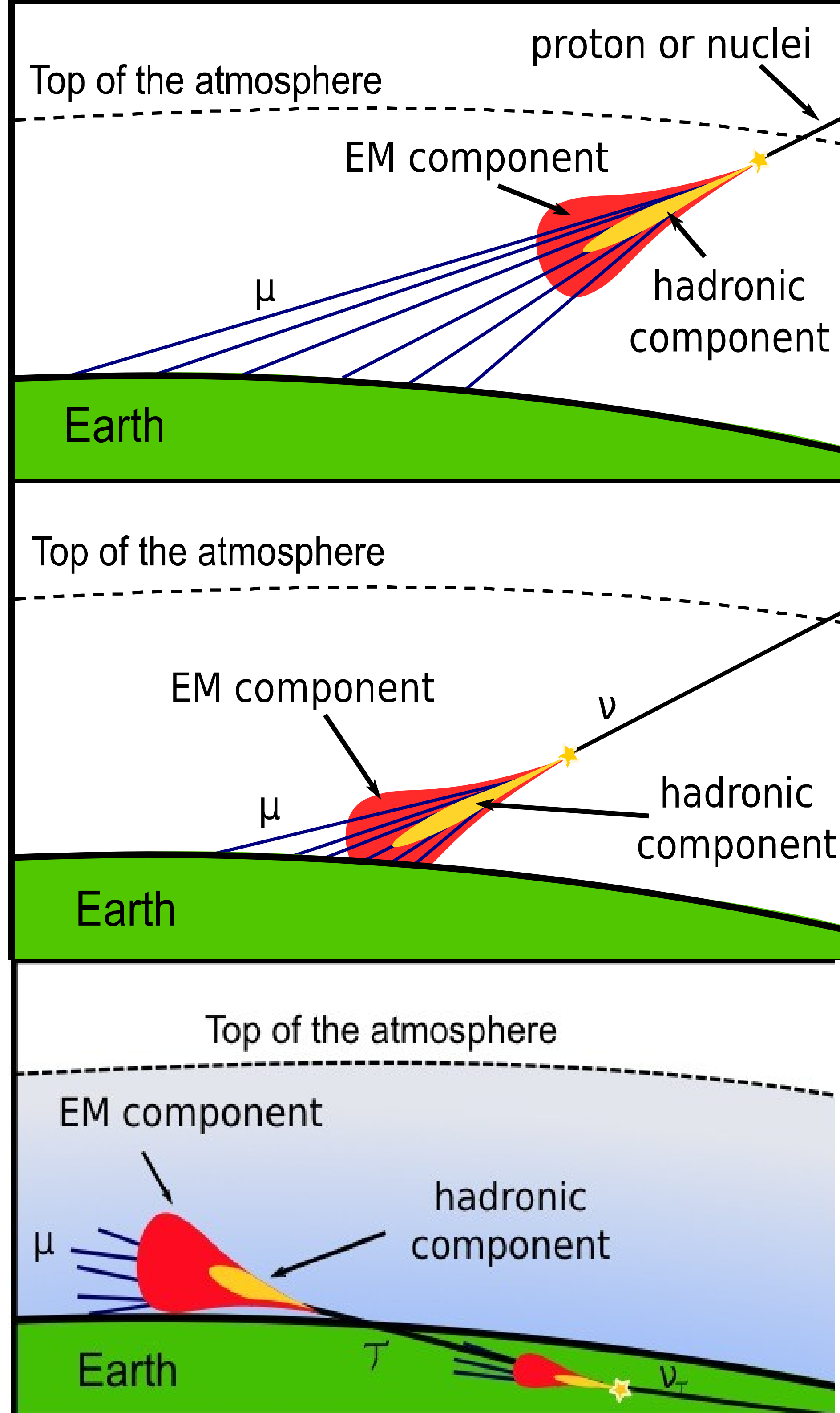
- electromagnetic component absorbed in atmosphere.
- mainly muons remaining

→ Neutrinos can initiate deep showers close to ground.

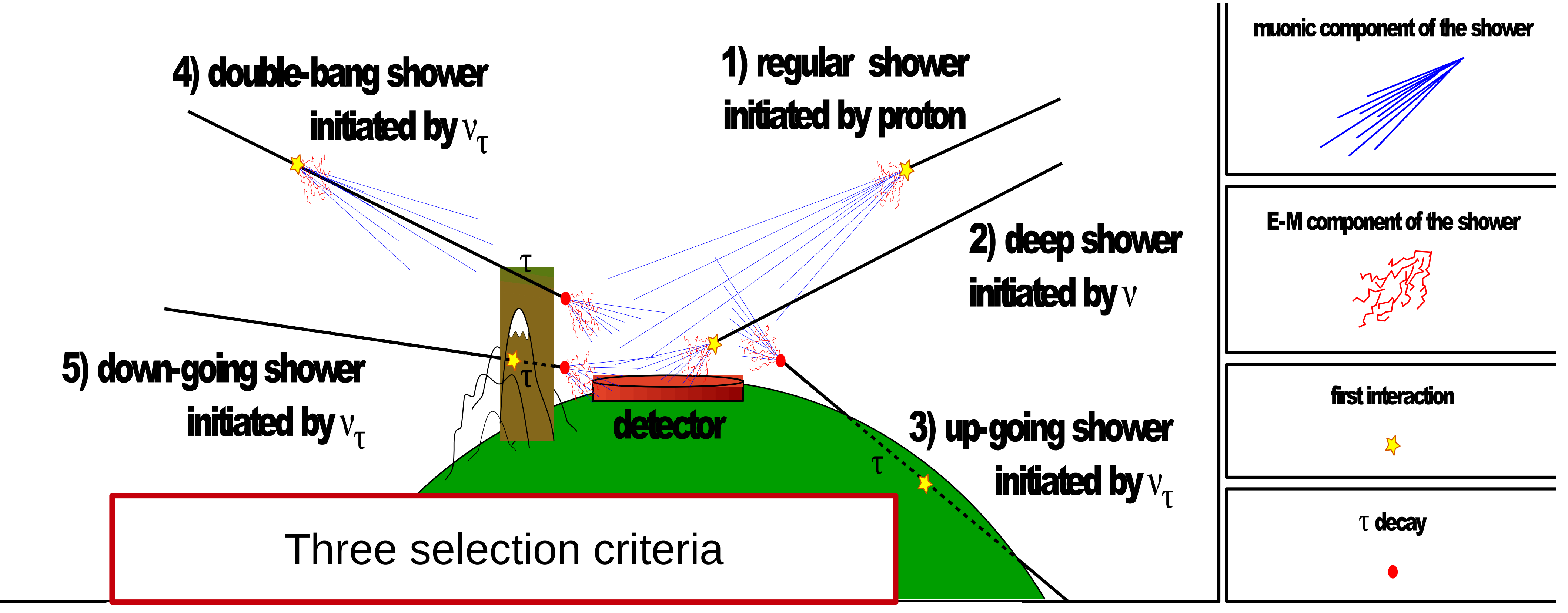
Shower front at ground:

<u>electromagnetic + muonic components</u>

**Searching for neutrinos**
**⇒ inclined showers**
**with electromagnetic component**



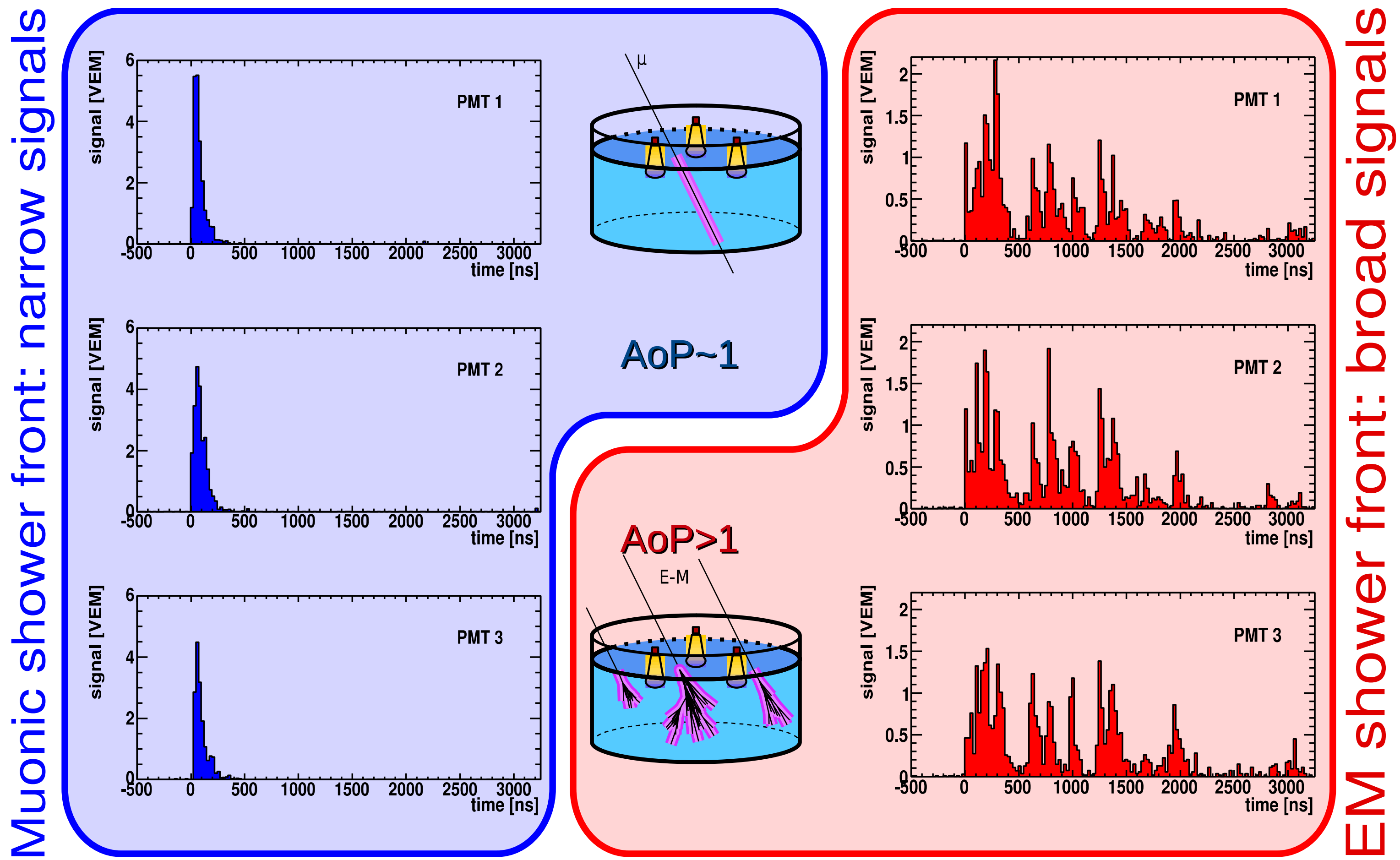
# Sensitivity to all flavours and channels




Down-going low angle (2 and 4) DGL 60º-75º
Down-going high angle (2, 4 and 5) DGH 75º-90º
} all flavours

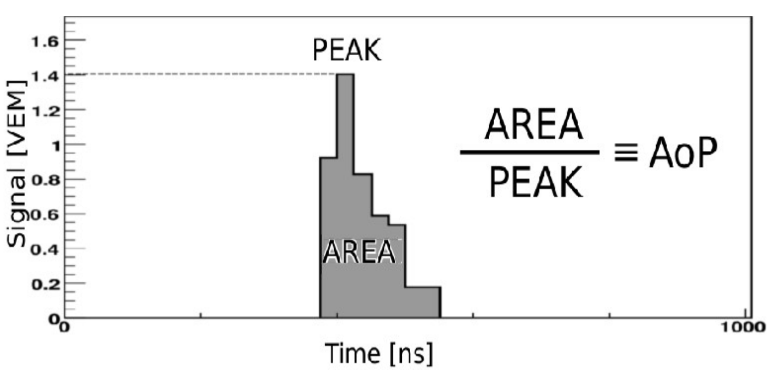
Earth-skimming (3) ES 90º-95º $\nu_\tau$

# Identifying electromagnetic shower fronts

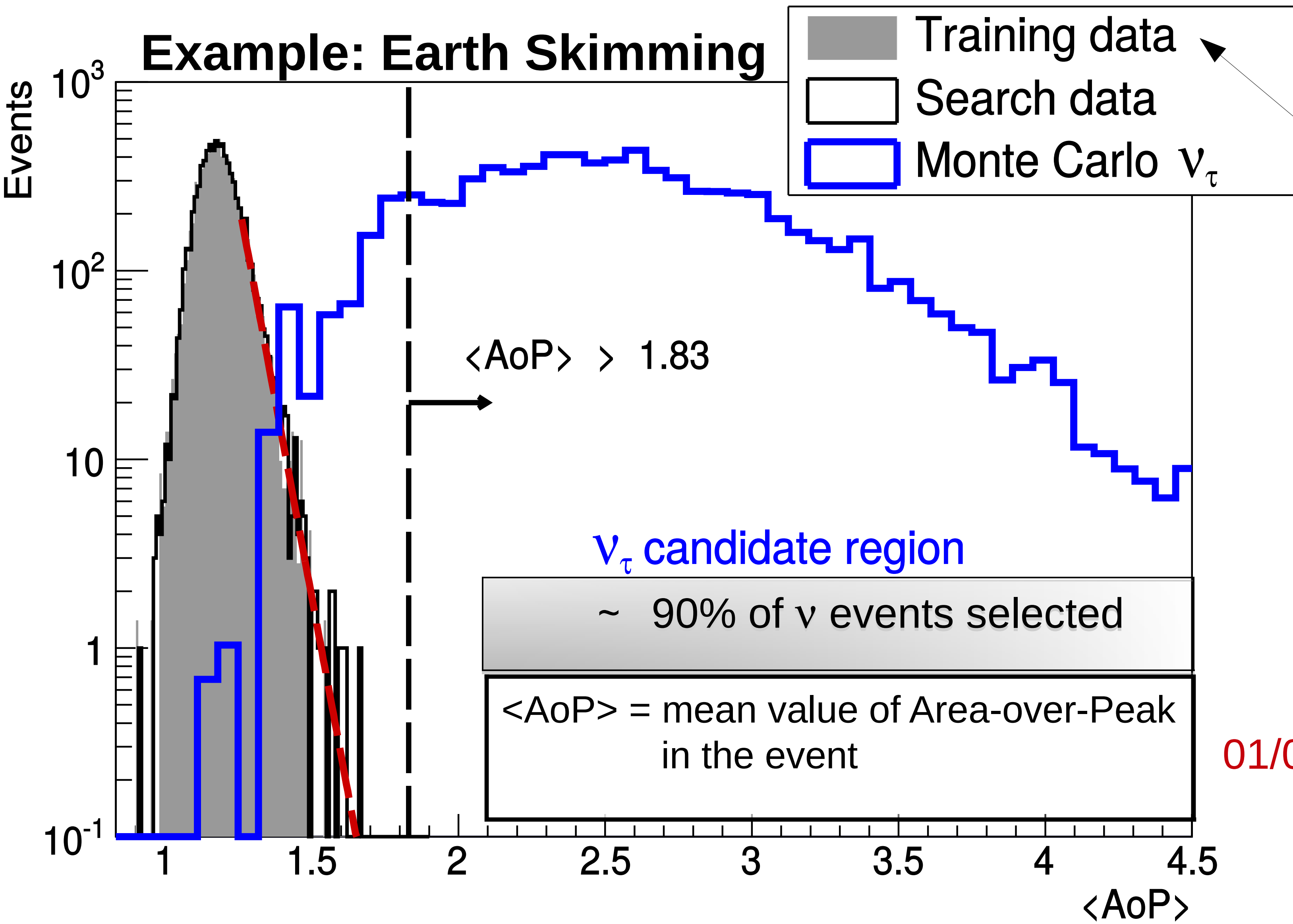



→ Select inclined events

→ Search for signals extended in time (large AoP)



# Identification of UHE neutrinos in Auger data

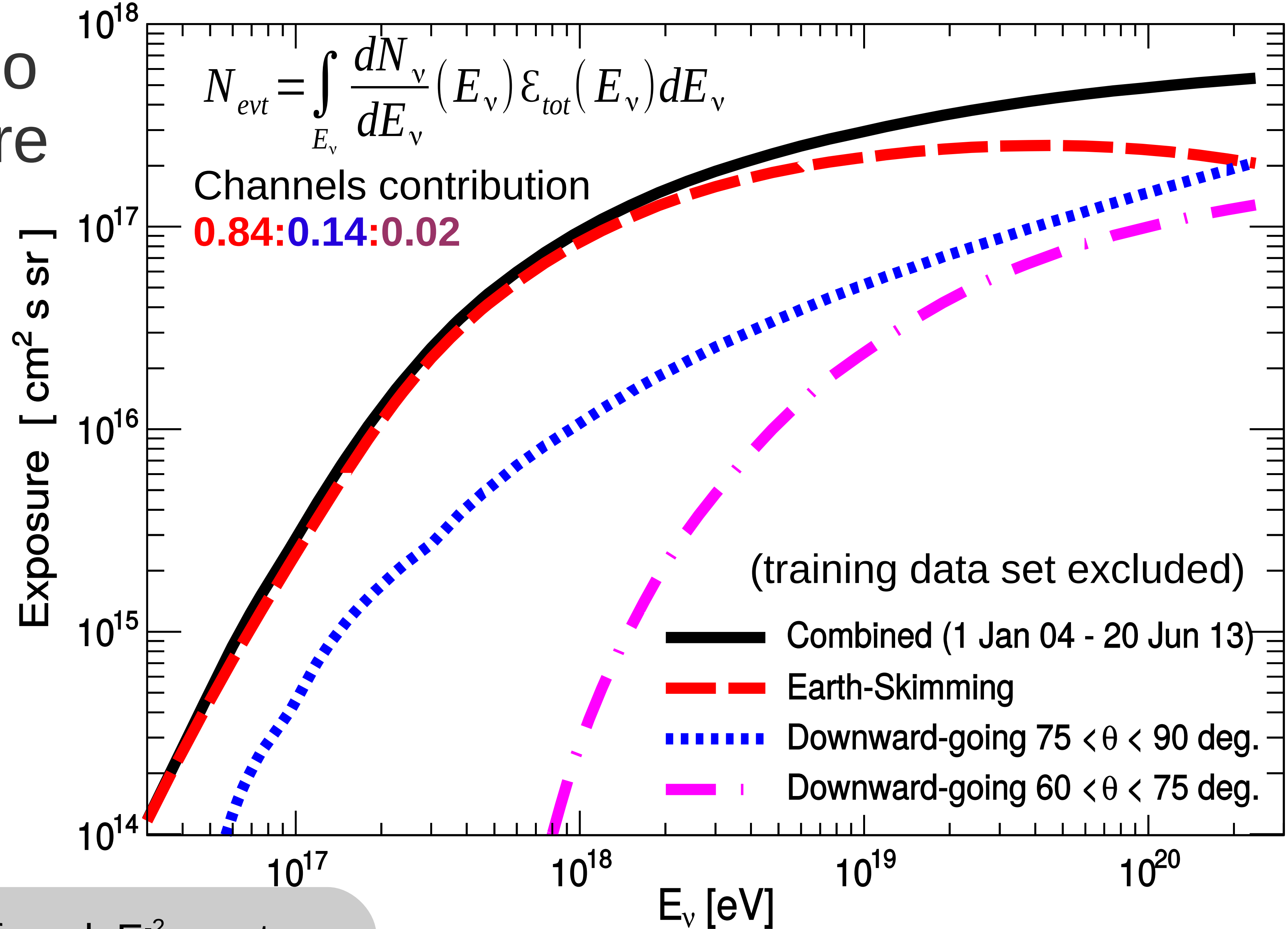



~20% of the data are used to estimate the expected background

Data taking:
01/01/04 – 20/06/13

Identification criteria applied “blindly” to the search data set
=> No candidates found in Earth Skimming or Downward-going

# Neutrino exposure

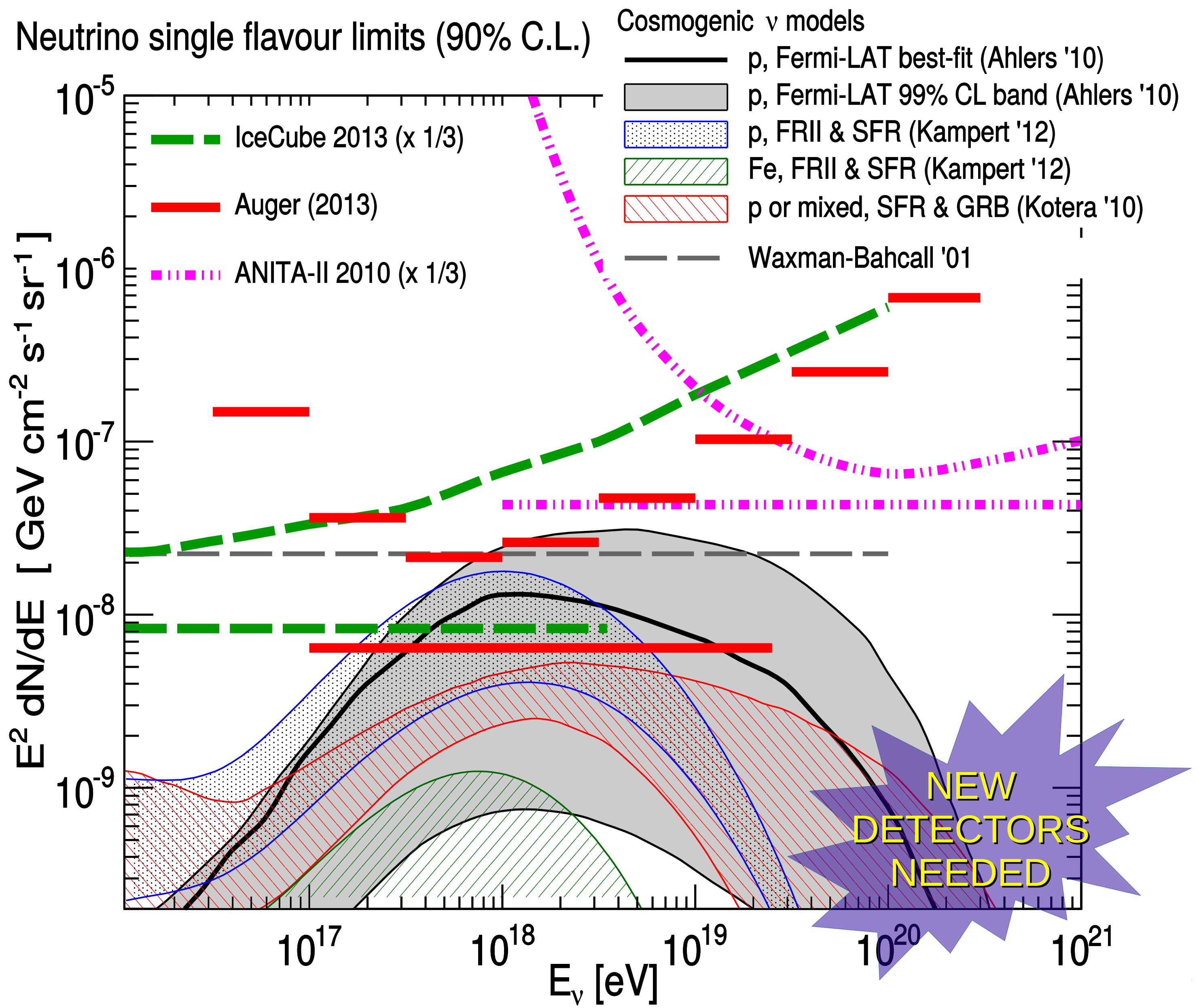



Upper limits for a k $E^{-2}$ spectrum:

$$k^{90\%} = \frac{N^{90\%}}{\int E_\nu^{-2}\,\mathcal{E}_{tot}(E_\nu)\,dE_\nu}$$

Upper limit to the number of neutrinos:
Feldman-Cousins + Conrad
(includes uncertainties in the
exposure calculation)

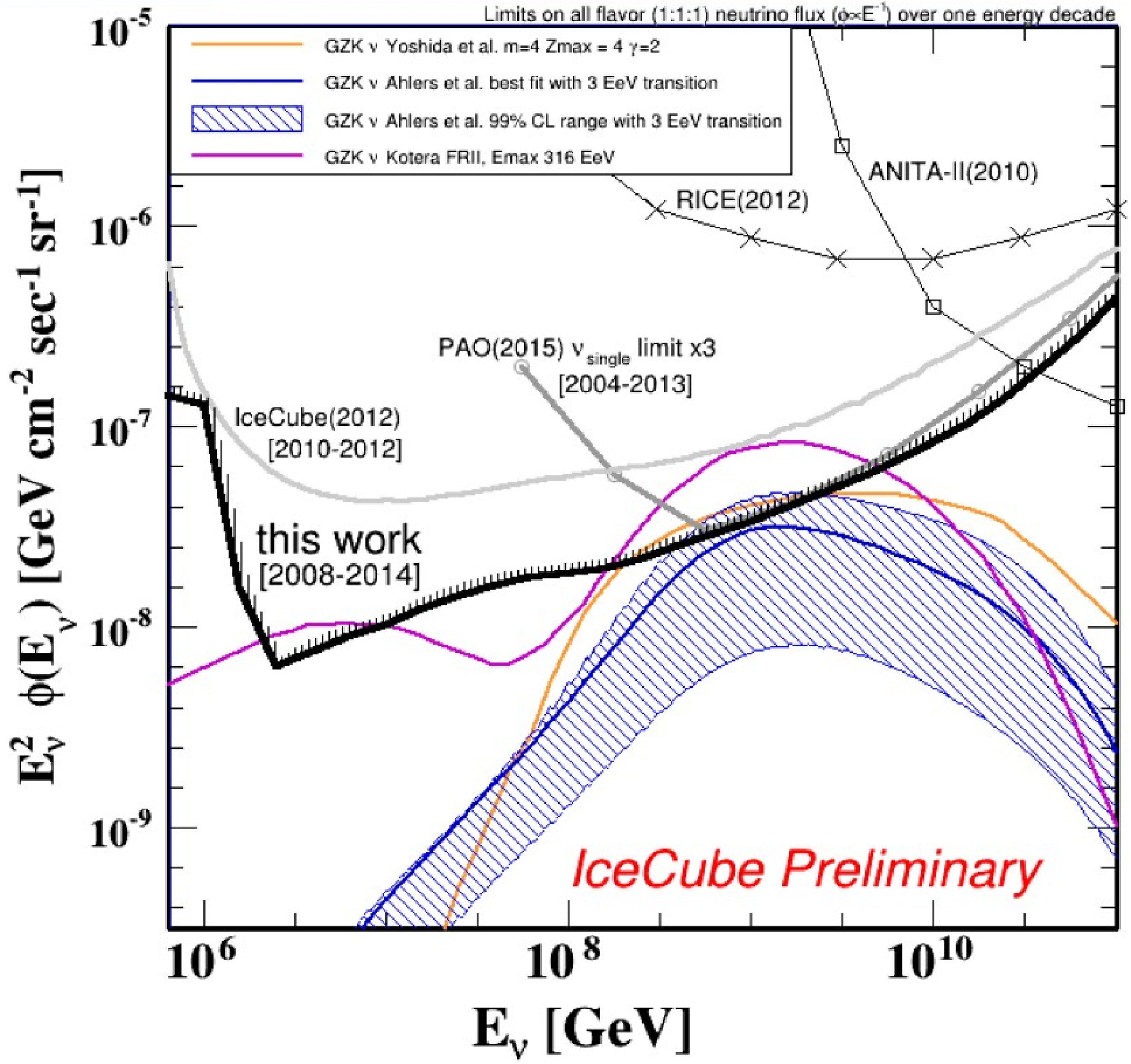
# Upper limits to the diffuse flux of neutrinos [Auger SD]




Corresponding exposure
~6.4 Auger full yrs
=> factor 10 lower
not feasible

→ Auger limit constrains models with proton primaries & strong evolution with redshift
→ First EAS detector to reach below WH level
→ **Search limited NOT by background but by exposure** (difficult to overcome)

A. Ishihara @ TeVPA 2015



# Thank you!

See next talk (T. Fujii)
for next generation UHECR observatories

# Target set for photon searches

- Galactic: As in targeted neutron search paper, BUT:
  - Included new (galactic) H.E.S.S. sources (ICRC 2015)
- Extragalactic: Short horizon
  - Cen A (d = 3.8 Mpc): Include core region
  - Large Magellanic Cloud (d = 50 kpc): (H.E.S.S. Science 347 (2015) 6220, 406)
    - N 157B J0537-691: Pulsar wind nebula
    - 30 Dor C J0535-691: Superbubble
    - N 132D J0525-696: Core-collaps SNR

| *Class* | *No. neutron search* | *No. photon search* | *galactic/extragalactic* |
|---|---|---|---|
| msec PSRs | 68 | 67 | galactic |
| $\gamma$-ray PSRs | 77 | 75 | galactic |
| LMXB | 87 | 87 | galactic |
| HMXB | 48 | 48 | galactic |
| H.E.S.S. PWN | 17 | 17 | galactic |
| H.E.S.S. other | 16 | 16 | galactic |
| H.E.S.S. UNID | 15 | 20 | galactic |
| Microquasars | 13 | 13 | galactic |
| Magnetars | 16 | 16 | galactic |
| Gal. Center | 1 | 1 | galactic |
| LMC | 0 | 3 | extragalactic |
| Cen A | 0 | 1 | extragalactic |