Pierre Auger Observatory

studying the universe's highest energy particles

PIERRE AUGER OBSERVATORY

UHE Neutrino searches with the Pierre Auger Observatory

and other UHECR experiments

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Universidad de Granada

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Primary objective of the Pierre Auger Observatory

"Measure the properties of Ultra High Energy Cosmic Rays ($E > 10^{18}$ eV)

with unprecedented statistics and accuracy"

Energy

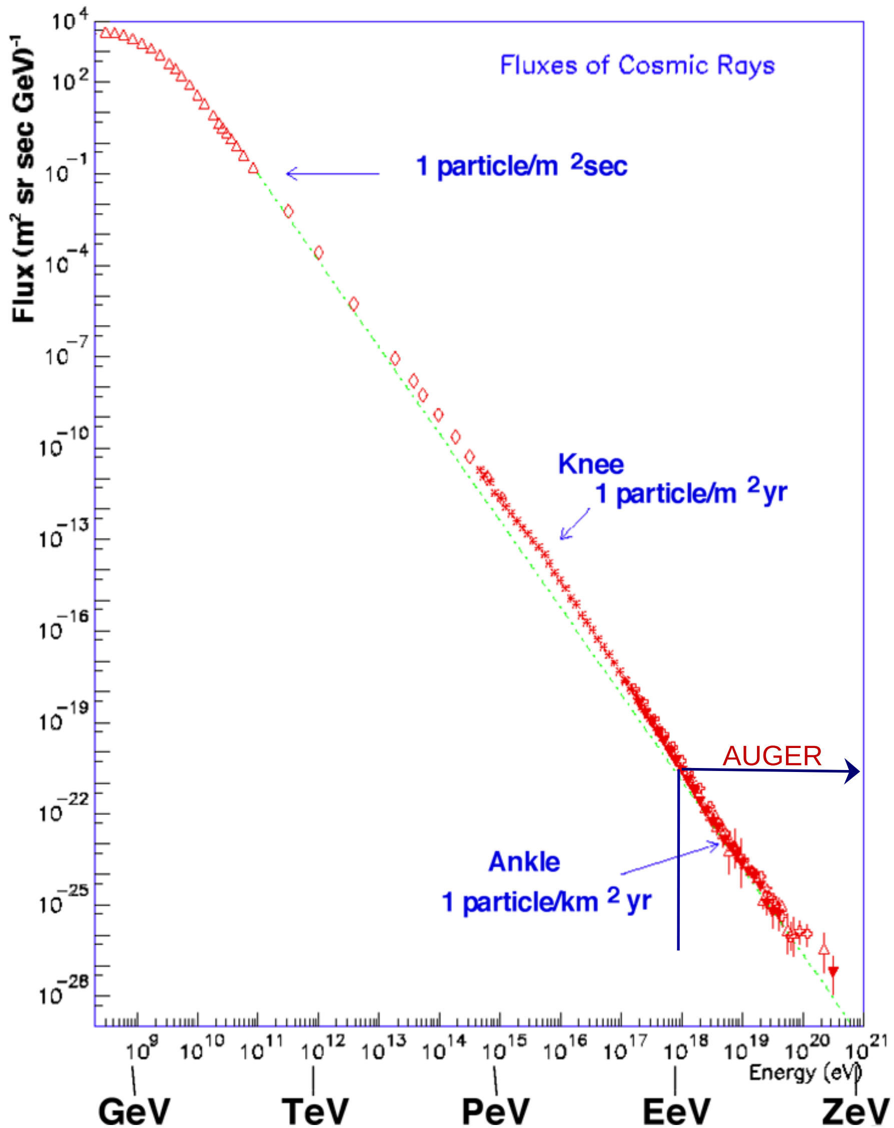
- Cutoff at the highest energies? Ankle?

Direction

- Is the UHECR flux isotropic ?
- Which are the UHECRs sources?

Mass composition

- Is the UHECR flux proton/iron-dominated?



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→ Phys. Lett. B 685 (2010) 239-246

Phys. Rev. Lett 101 (2008) 061101

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Neutrino and photon detection (!) ➡ **Astropart. Phys. 31 (2009) 399-406**

Phys. Rev. D 79 (2009) 102001

- As a bonus, the Observatory has the capability to detect UHE ν and γ

Expected sources of UHE neutrinos

Astrophysical Neutrinos

- Neutrinos are expected as a product of pion decays produced in hadronic interactions of cosmic rays with radiation or matter near the astrophysical sources (AGNs…)

"cosmogenic neutrinos"

$$p + \gamma_{CMB} \rightarrow \pi^{\pm} + X$$
$$\rightarrow \mu^{\pm} + \nu_{\mu} (\bar{\nu}_{\mu})$$
$$\rightarrow e^{\pm} + \bar{\nu}_{\mu} (\nu_{\mu}) + \nu_{e} (\bar{\nu}_{e})$$

- ≡ GZK neutrinos: produced by high-energy cosmic rays with the microwave background.

Predicted in "top-down" scenarios

- Decay of ultra massive objects (topological defaults, super heavy dark matter, Z burst…): harder spectrum & high γ and ν fluxes predicted.

- Neutral ⇒ propagation in straight line (point to the source)
- Weakly interacting ⇒ low probability to interact (cosmological distances)

} *ν astronomy*

The Pierre Auger Observatory

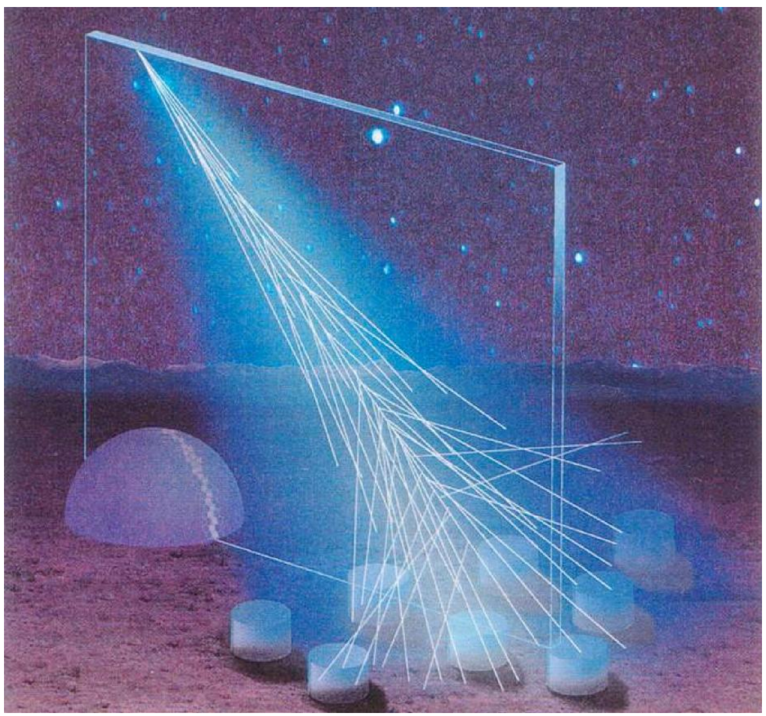
Malargüe – Argentina

(Pampa Amarilla)

- Detector completed in June 2008
- 70 institutions and 17 countries

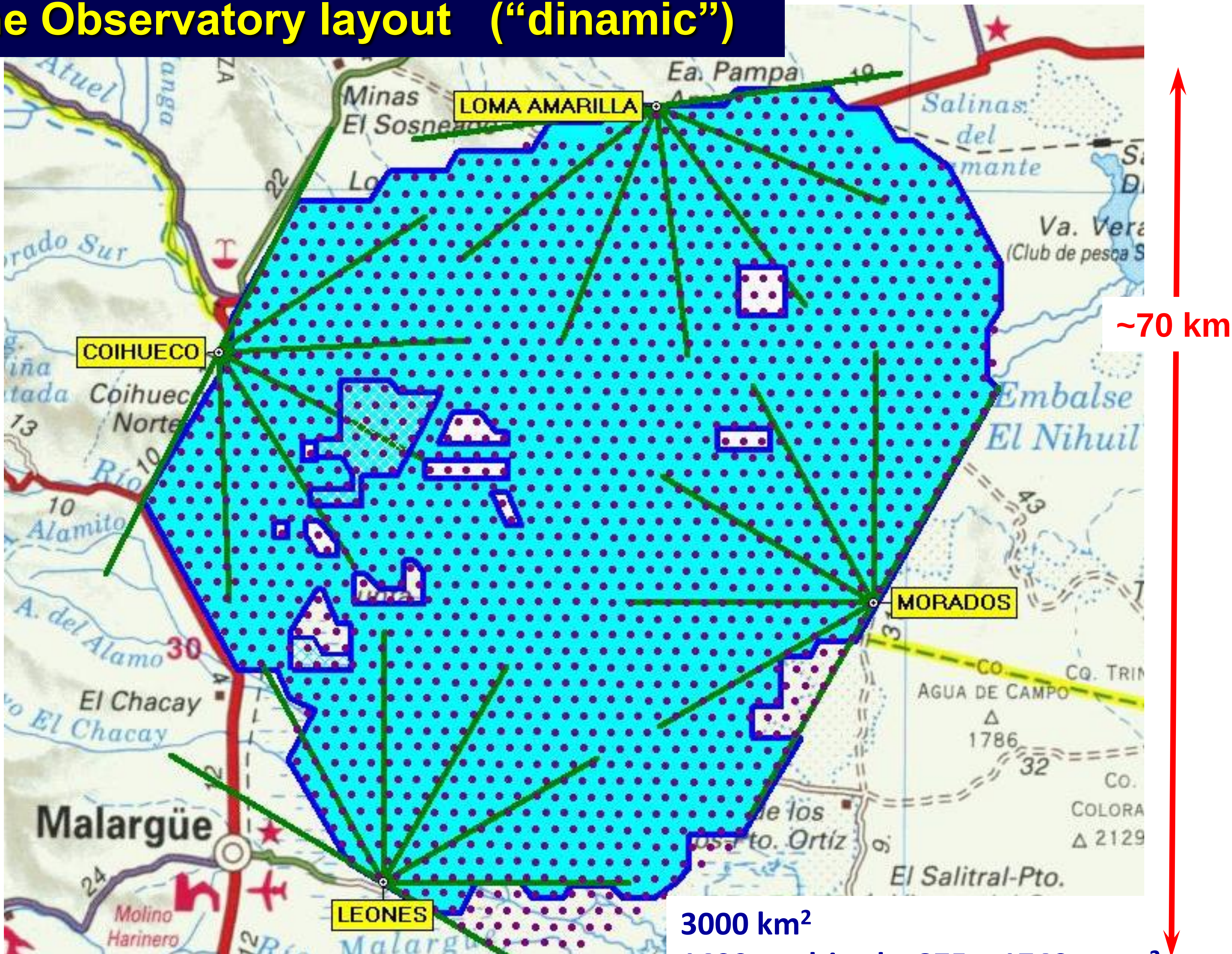
Argentina, Australia, Bolivia, Brazil, Czech Republic, France, Germany, Italy, Mexico, Netherlands, Poland, Portugal, Slovenia, Spain, U.K., U.S.A., Vietnam

- **HYBRID** detection technique



PIERRE AUGER OBSERVATORY

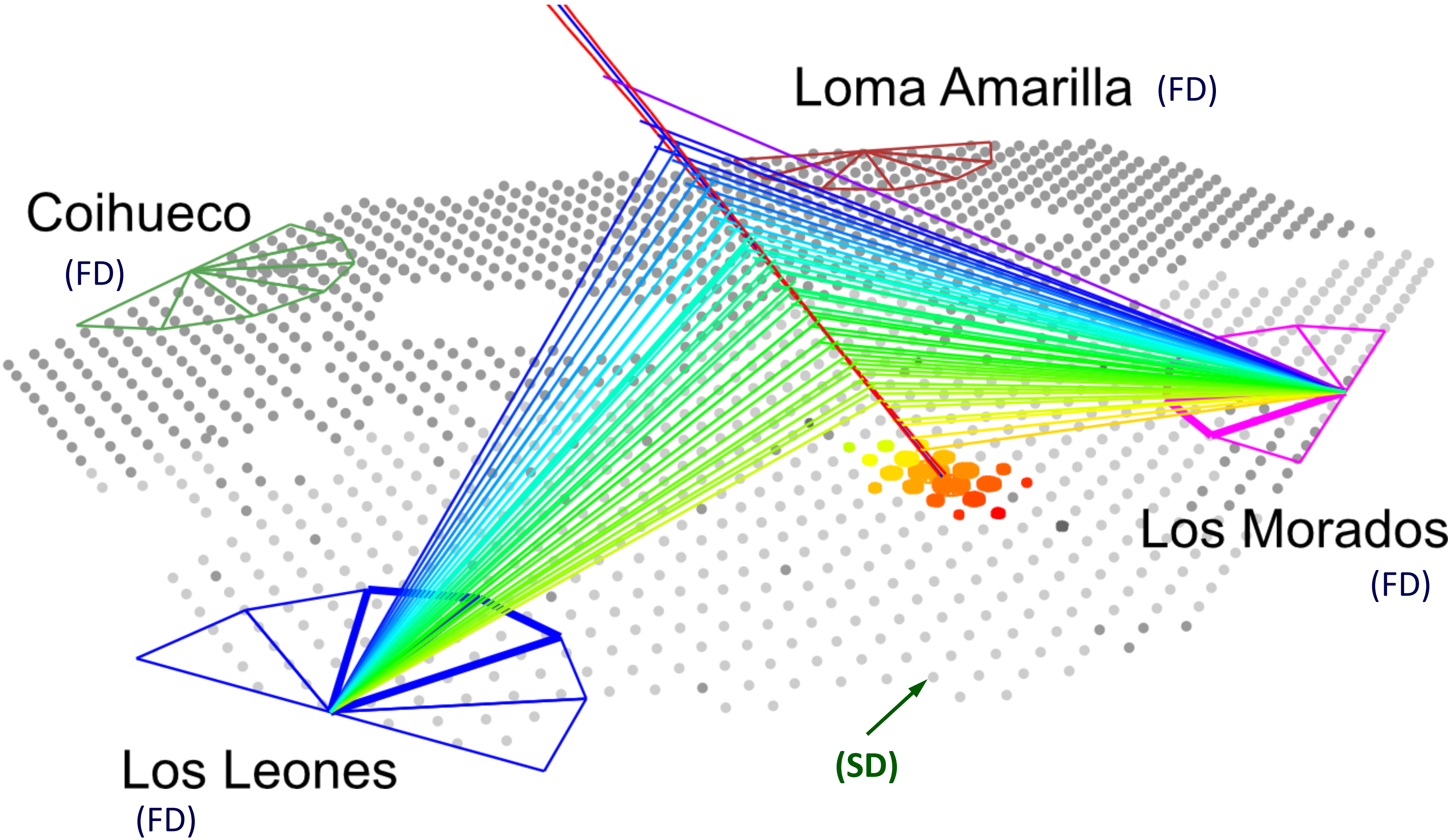
The Observatory layout ("dinamic")



3000 km²

1400 m altitud , 875 – 1740 g cm^{-2} (60º)

Example of "hybrid" event



Hybrid shower detection

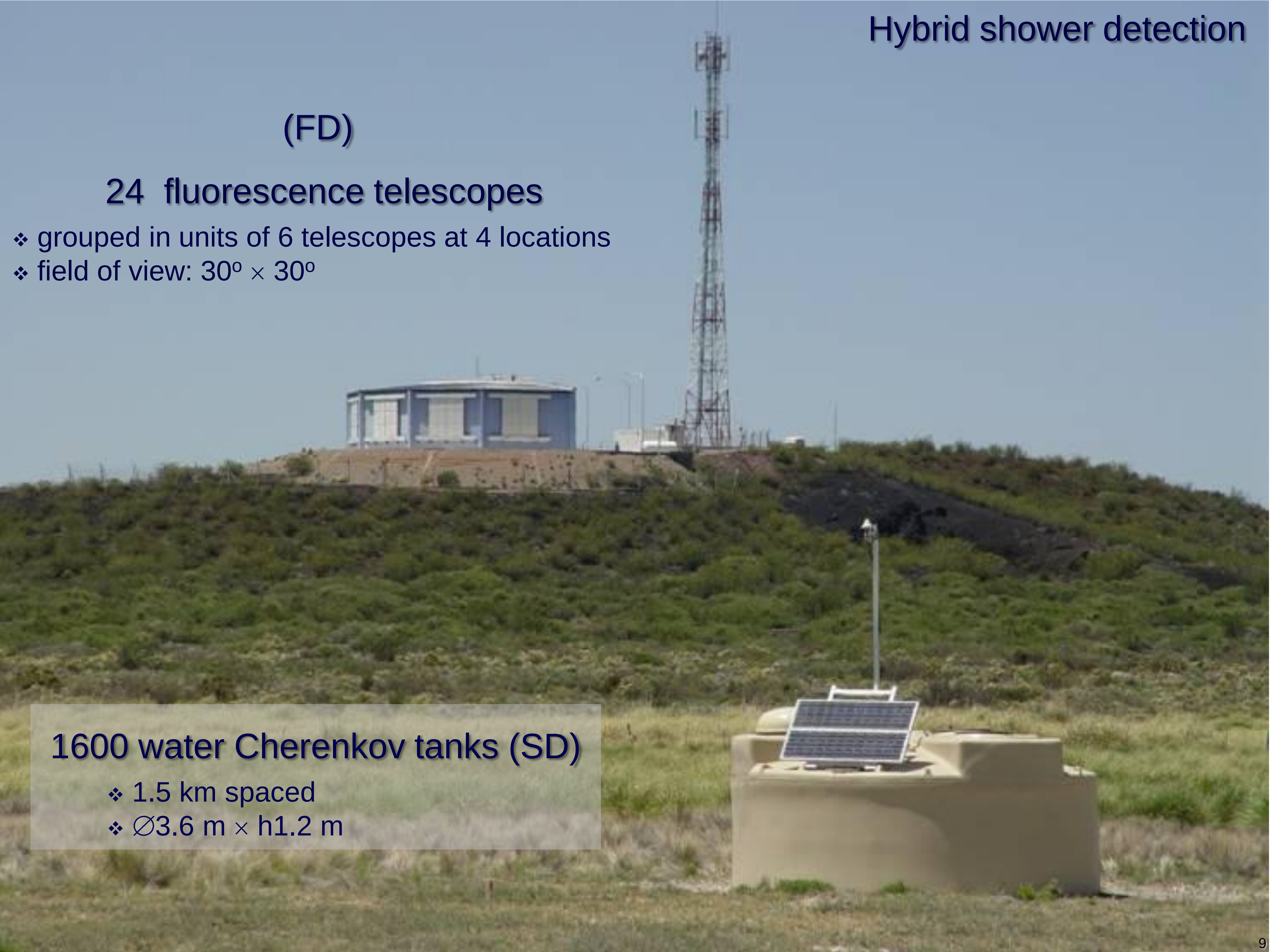
(FD)

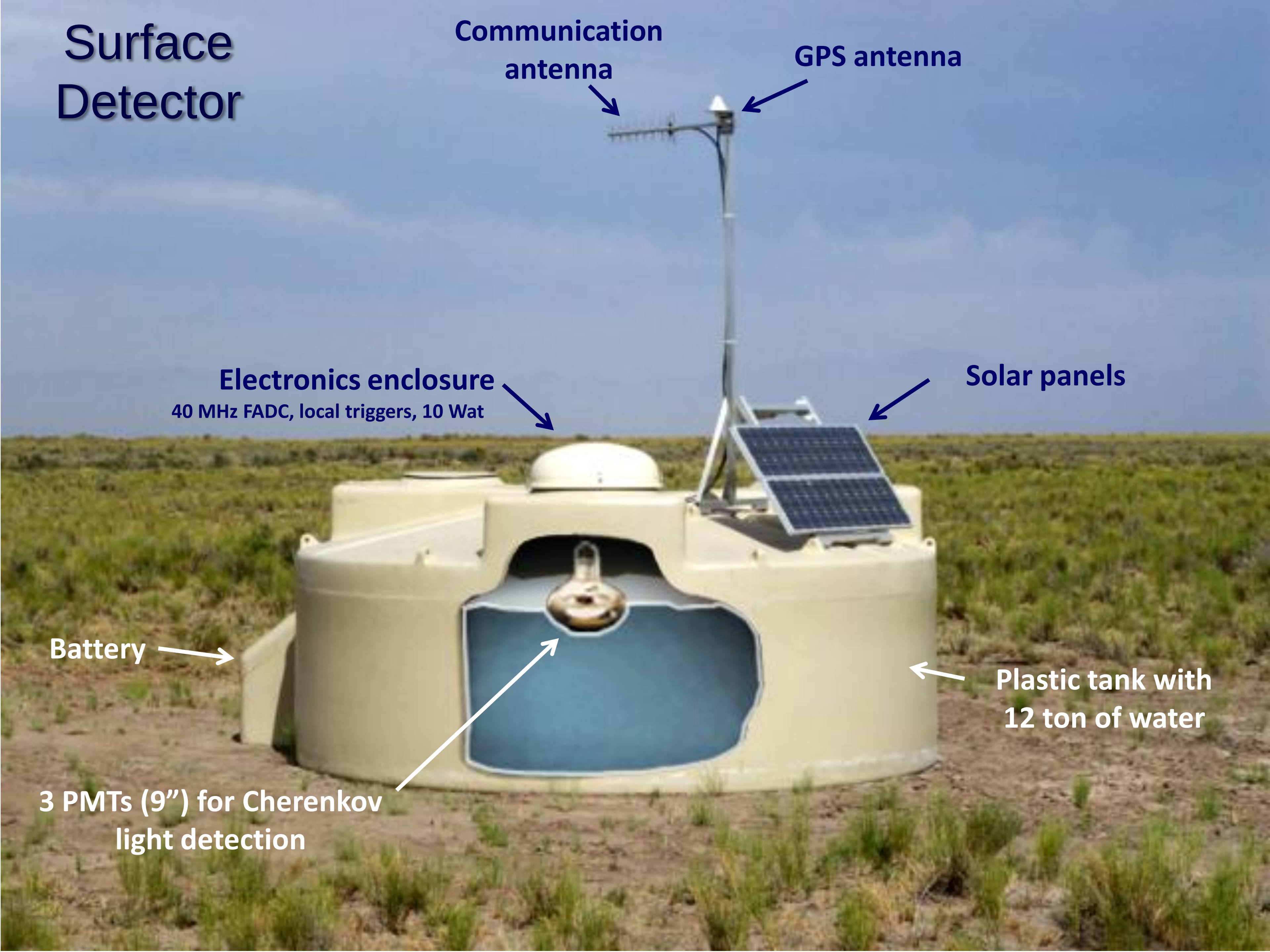
24 fluorescence telescopes

- grouped in units of 6 telescopes at 4 locations
- field of view: $30^{o} \times 30^{o}$

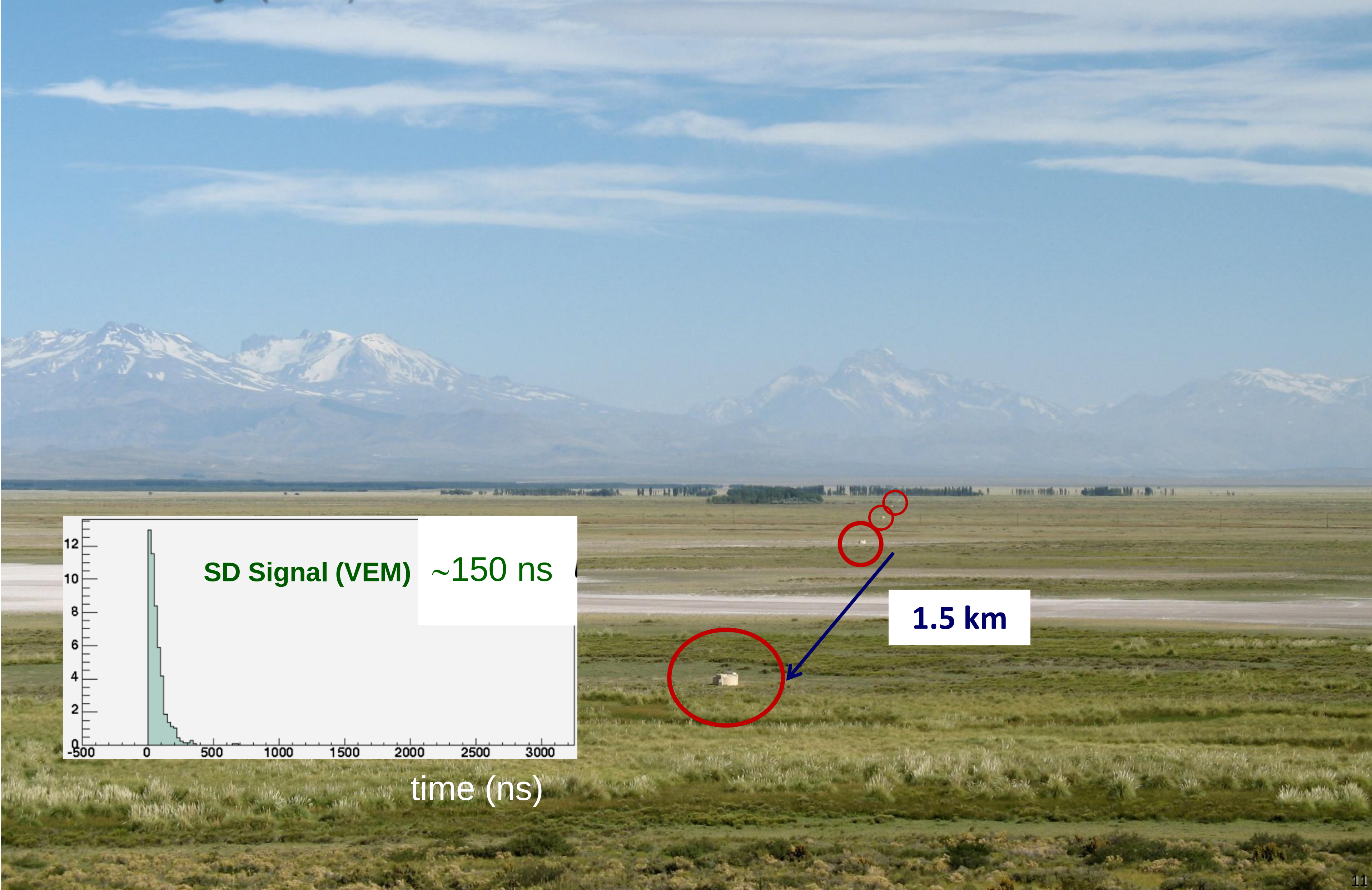
1600 water Cherenkov tanks (SD)

- 1.5 km spaced
- $\varnothing$3.6 m $\times$ h1.2 m




Surface Detector
Communication antenna
GPS antenna
Electronics enclosure
40 MHz FADC, local triggers, 10 Wat
Solar panels
Battery
Plastic tank with 12 ton of water
3 PMTs (9”) for Cherenkov light detection

Surface Detector array (SD)



What is a neutrino ?

What is a neutrino ?

ν = horizontal young (deep) shower

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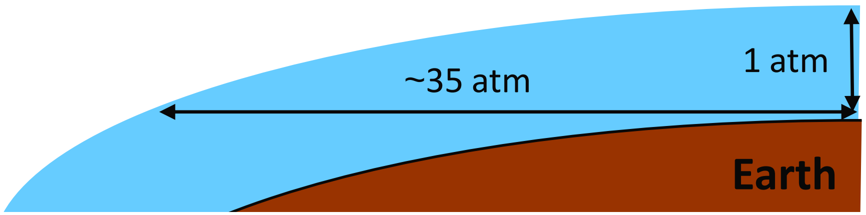
✓ Why horizontal ?

Due to the low neutrino cross-section → large amount of matter for interaction
→ **inclined** neutrinos are likely to induce EAS close to ground

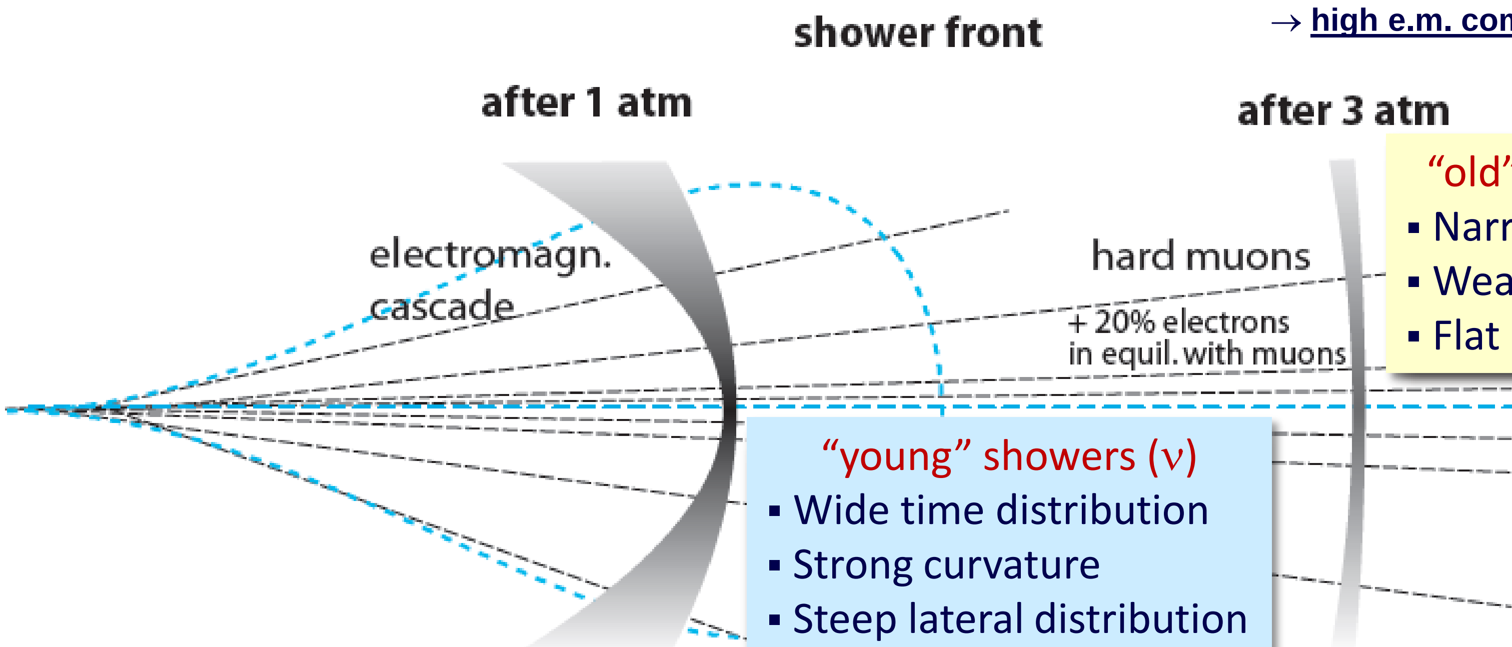


Atmosphere @ Auger site

Vertical ≈ 880 g cm^{-2}
Horizontal ≈ 32000 g cm^{-2}

✓ Why young ?

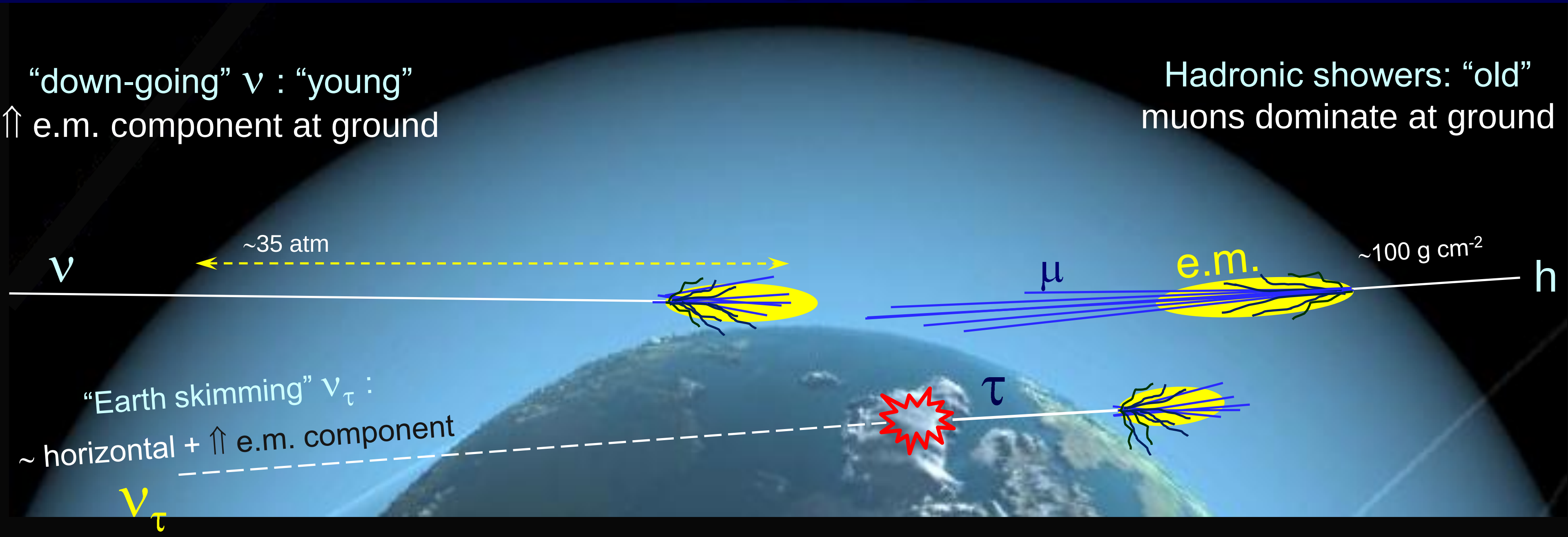
→ ν interact deep in the atmosphere
→ look for **young** showers
→ **high e.m. component in early stations**



"old" showers (hadrons)
- Narrow time distribution
- Weak curvature
- Flat lateral distribution

"young" showers (ν)
- Wide time distribution
- Strong curvature
- Steep lateral distribution

Two search channels:
"down" and "up" going neutrinos …



"down going" neutrinos

↑ Sensitivity to ALL ν flavours

↑ Sensitive to ALL interaction channels (CC & NC)

↑ Large solid angle (75º → 90º)

↓ Dilute mass target (air)

"Earth skimming" tau neutrinos

↑ τ travels long distances in the Earth without losing too much E before decay

↓ Sensitivity to ν_τ CC channel

↓ Small solid angle (few degrees)

↑ Dense mass target (Earth crust)

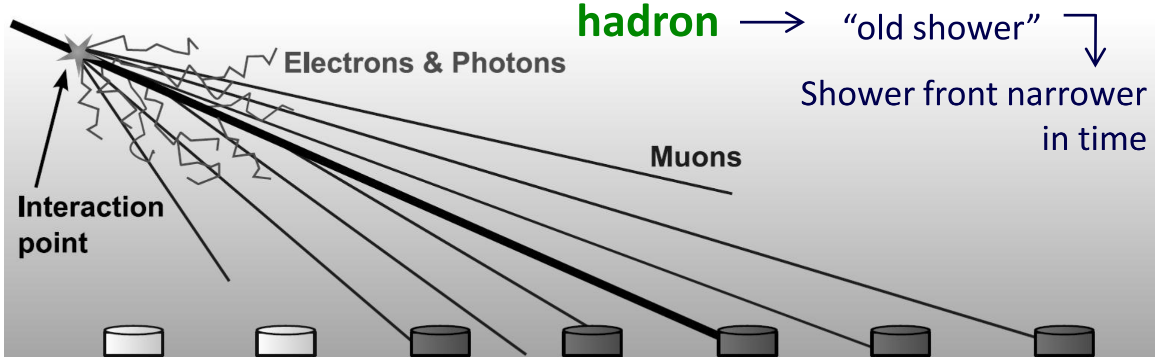
Which is the neutrino

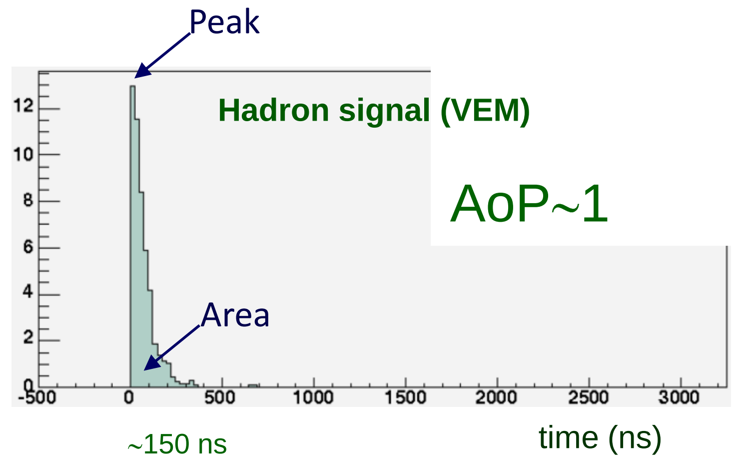
signature

in the SD array ?

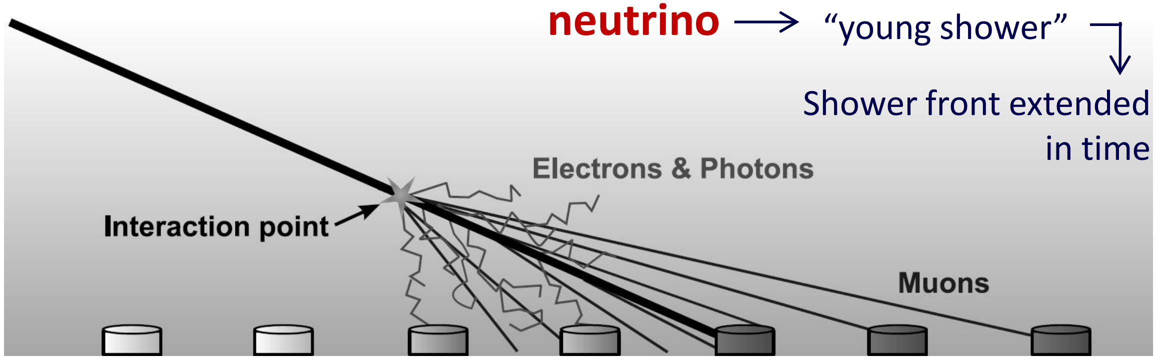
Main observable ⇒ AoP = Area / Peak

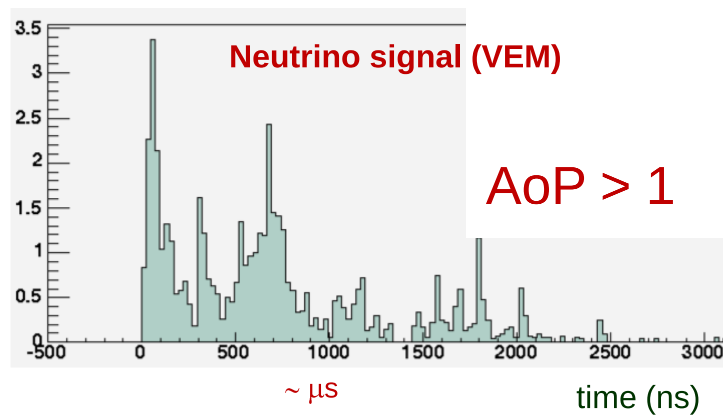
hadron → "old shower" → Shower front narrower in time





neutrino → "young shower" → Shower front extended in time





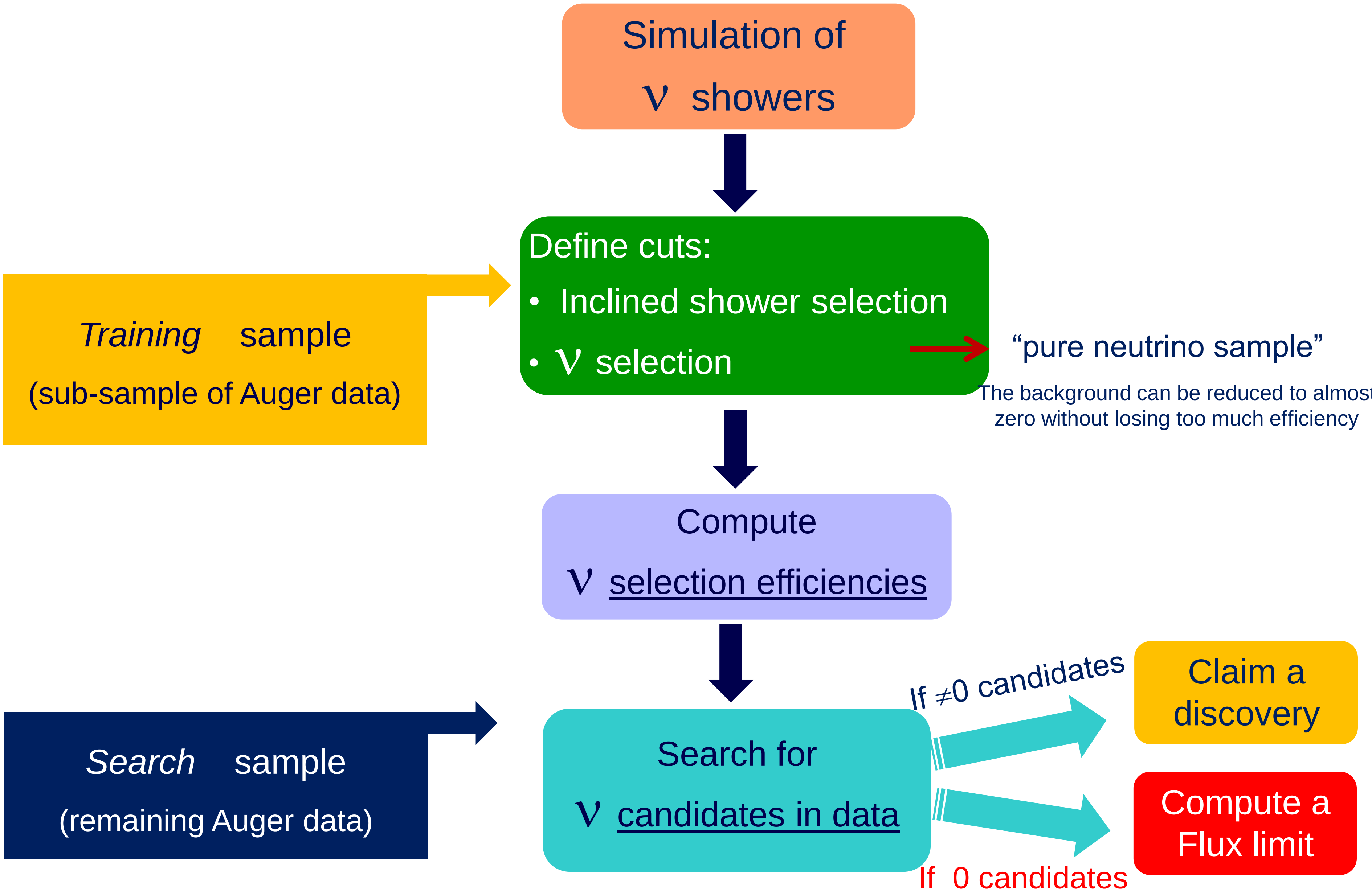
Broader signals in few first triggered tanks → early stations

late stations ← Larger grammage of atmosphere

SIGNATURE

⇒ inclined shower with significant electromagnetic content, mainly in the "early" part of the shower

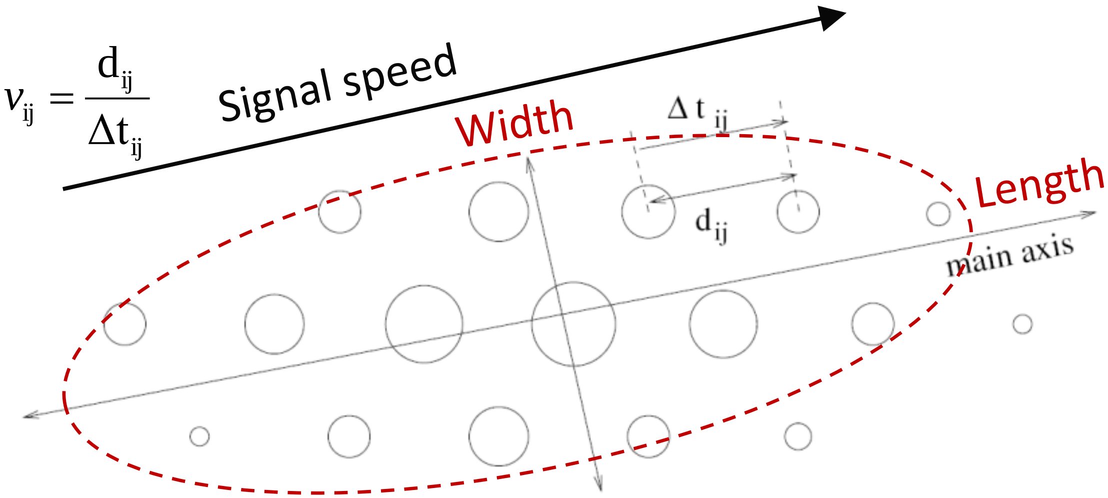
Search strategy : Blind analysis

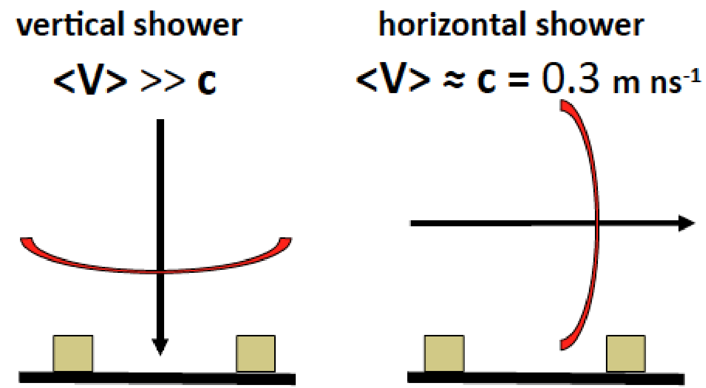


(remember!) ν = horizontal young shower

✓ Inclined shower selection:

$$v_{ij} = \frac{d_{ij}}{\Delta t_{ij}}$$





- **Down-going** ($\theta > 75^o$)
  - *<signal speed>* **<** 0.31 m ns^{-1}
  - L/W **>** 3
- **Earth-skimming** ($90 < \theta < 95^o$)
  - 0.29 m ns^{-1} **<** *<signal speed>* **<** 0.31 m ns^{-1}
  - L/W **>** 5

- *<signal speed>* relative error < 0.08 m ns^{-1}

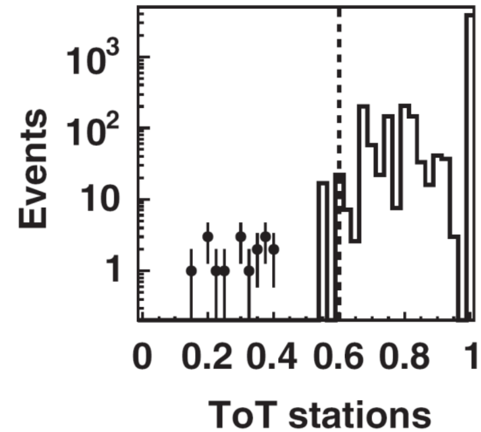
(remember!) ν = horizontal young shower

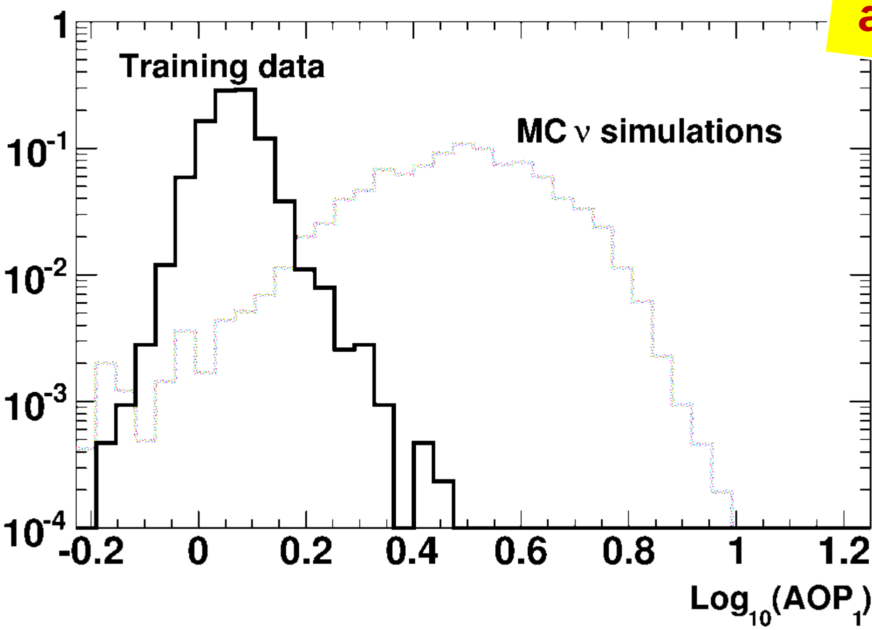
✓ Young shower selection:

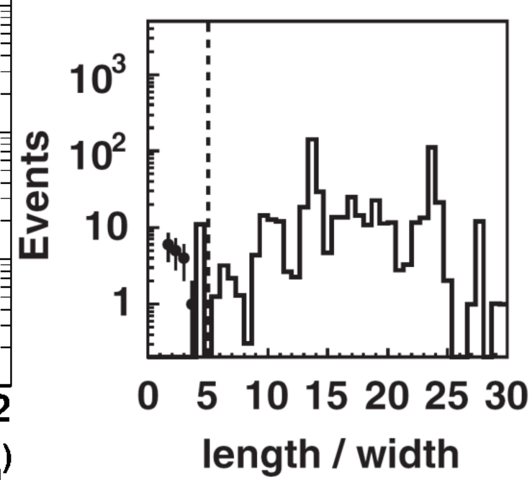
- **Down-going**
  - Area over Peak (AoP) of first four tanks
  - Combinations of them
  - Asymmetry: <Early AoP> – <Late AoP>

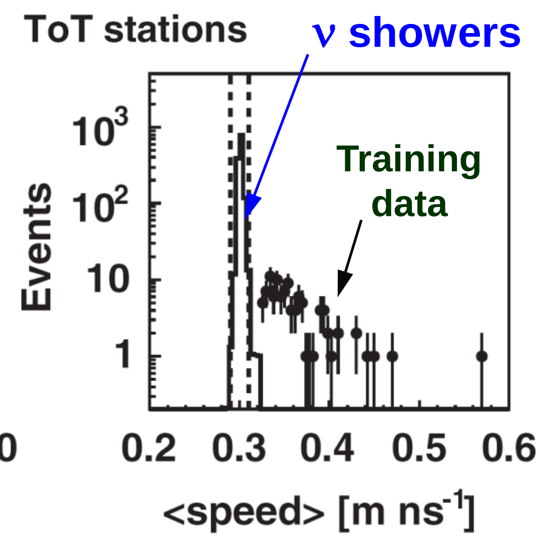
- **Earth-skimming**
  - Percentage of ToT triggered stations (selects broad signals) + high AoP

Fisher analysis





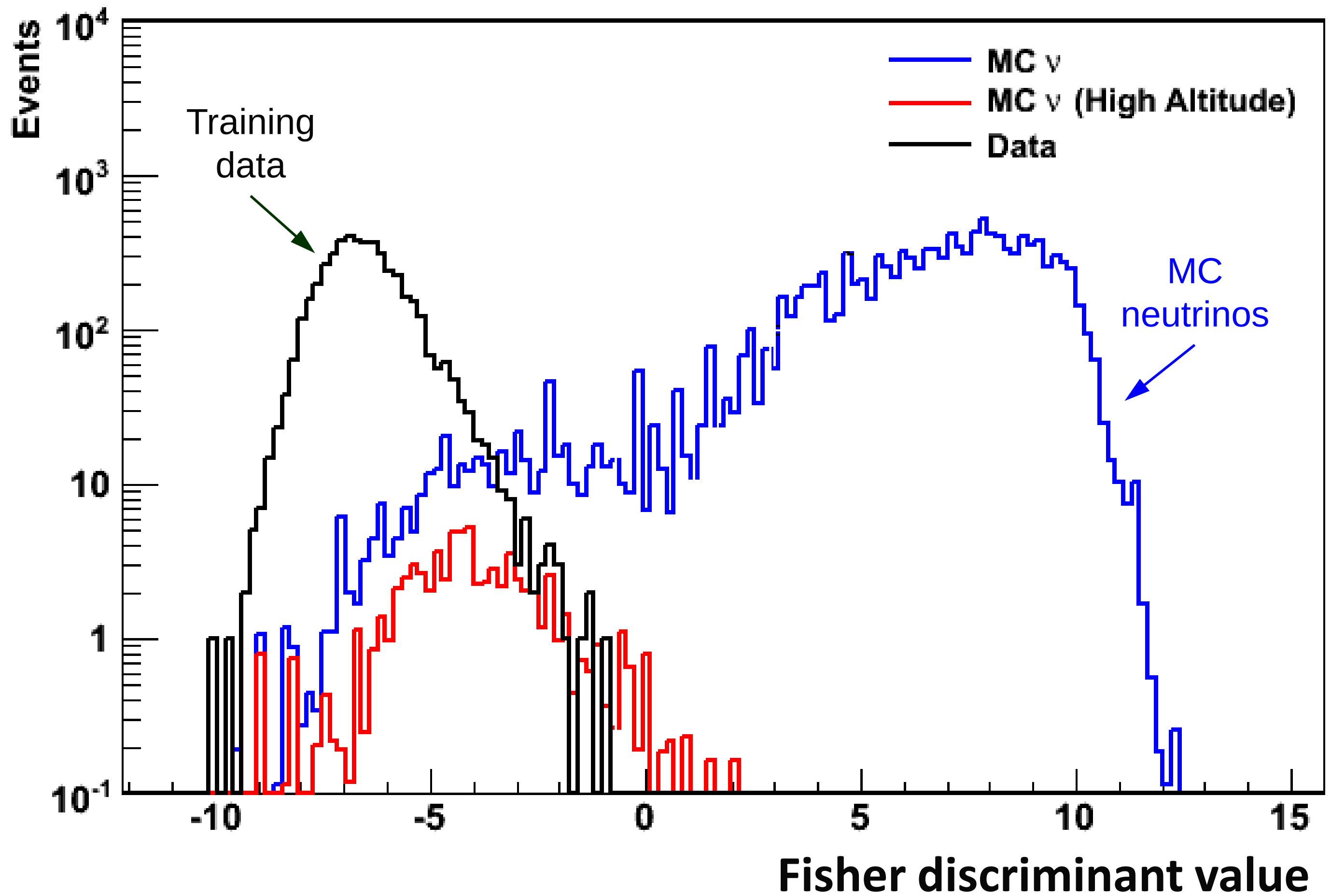




Signal / Background discrimination

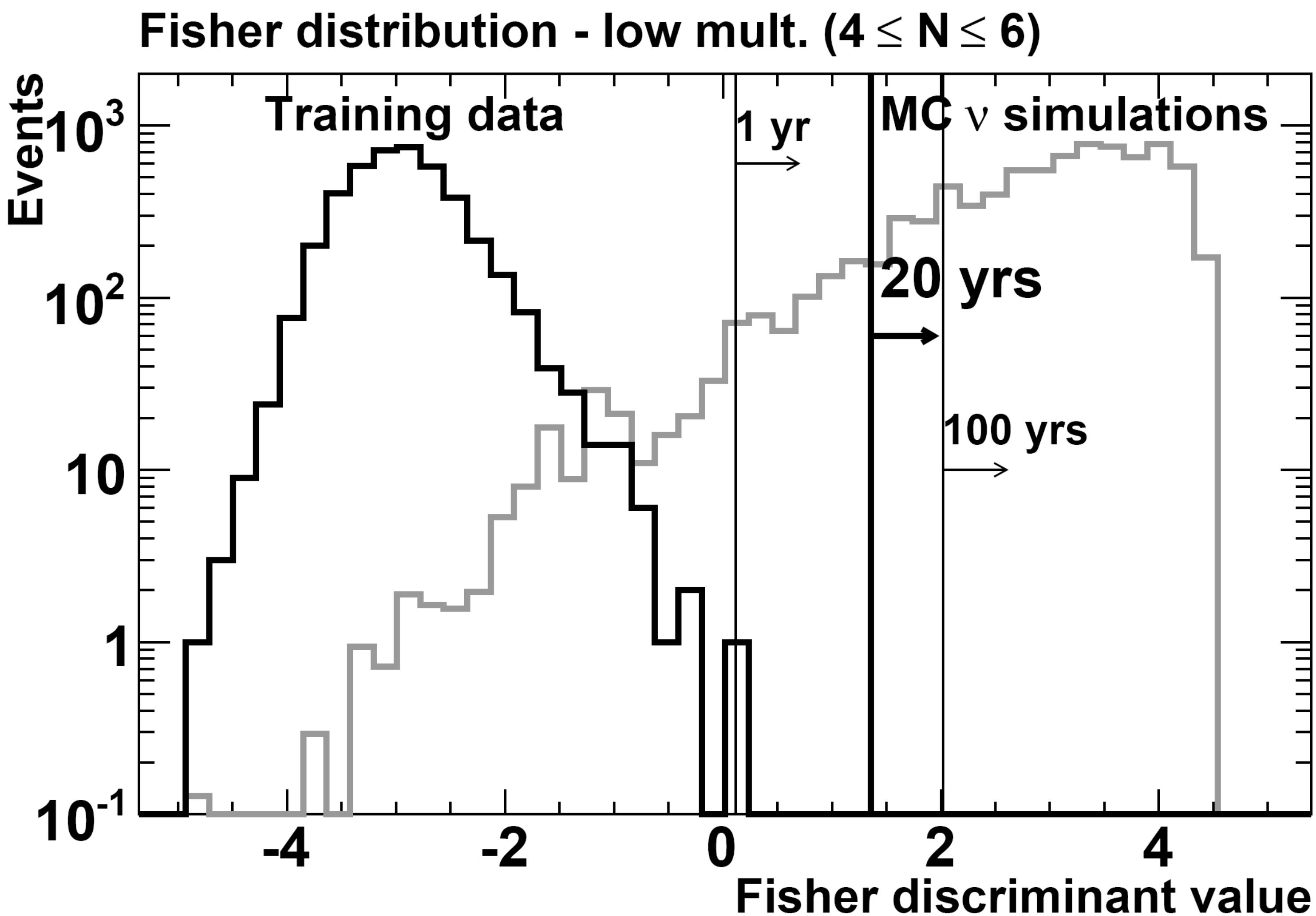
- ✓ Very good separation between the two event categories.
- ✓ The selection is now done on the basis of a **single cut** on the *Fisher* value.
- ✓ *Improved discrimination:* split sample in sub-samples according to the number of selected stations

Fisher distribution (6< #stations <12)



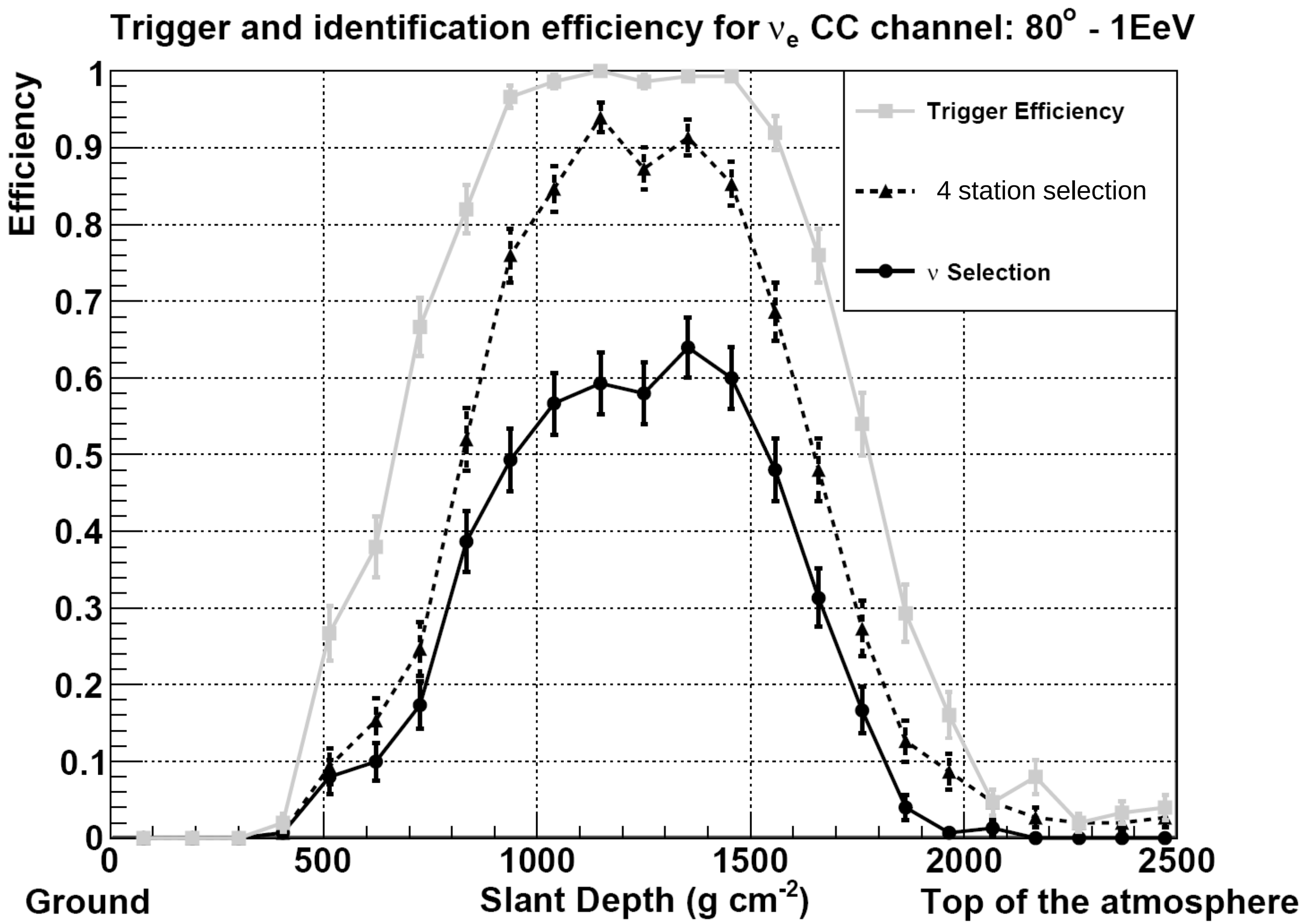
Fisher cut

- “safe” cut on *Fisher* value such that expected background **< 1 event / 20 years** of Auger data



Down-going selection efficiency

- Fraction of neutrino-induced showers triggering the SD and passing the identification criteria (quality, *Fisher*…)



After unblinding..

0

candidates for the search period

Down-going ν : Nov 07 to May 10

Up-going ν : Jan 04 to March 09

Exposure calculation

- The **Exposure** is computed through the **time integral of the Mass Aperture × the interaction cross section** (sum over the three neutrino flavors and interaction channels)

$$\text{Exposure} \Rightarrow \quad \mathcal{E}(E_\nu) = \frac{1}{m}\sum_i \left(\sigma^i(E_\nu)\int \mathrm{M}^{\mathrm{i}}_{\mathrm{ap}}(E_\nu, t)\,\mathrm{dt}\right)$$

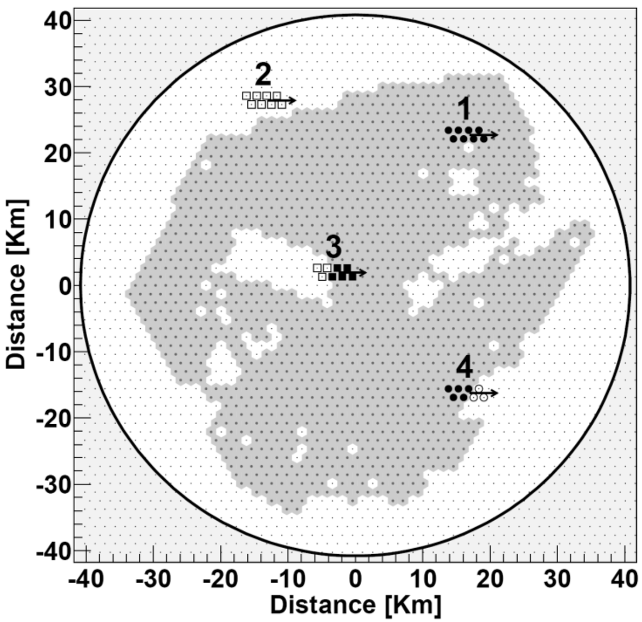
Sum over three ν channels and CC&NC

$$\mathrm{M}^{\mathrm{i}}_{\mathrm{ap}}(E_\nu, \mathrm{t}) = 2\pi \iiiint \sin\theta\cos\theta\,\varepsilon^i_{ff}(\vec{r}, \theta, D, E_\nu, t)\;\mathrm{d}\theta\,\mathrm{dD}\,\mathrm{dx}\,\mathrm{dy}$$

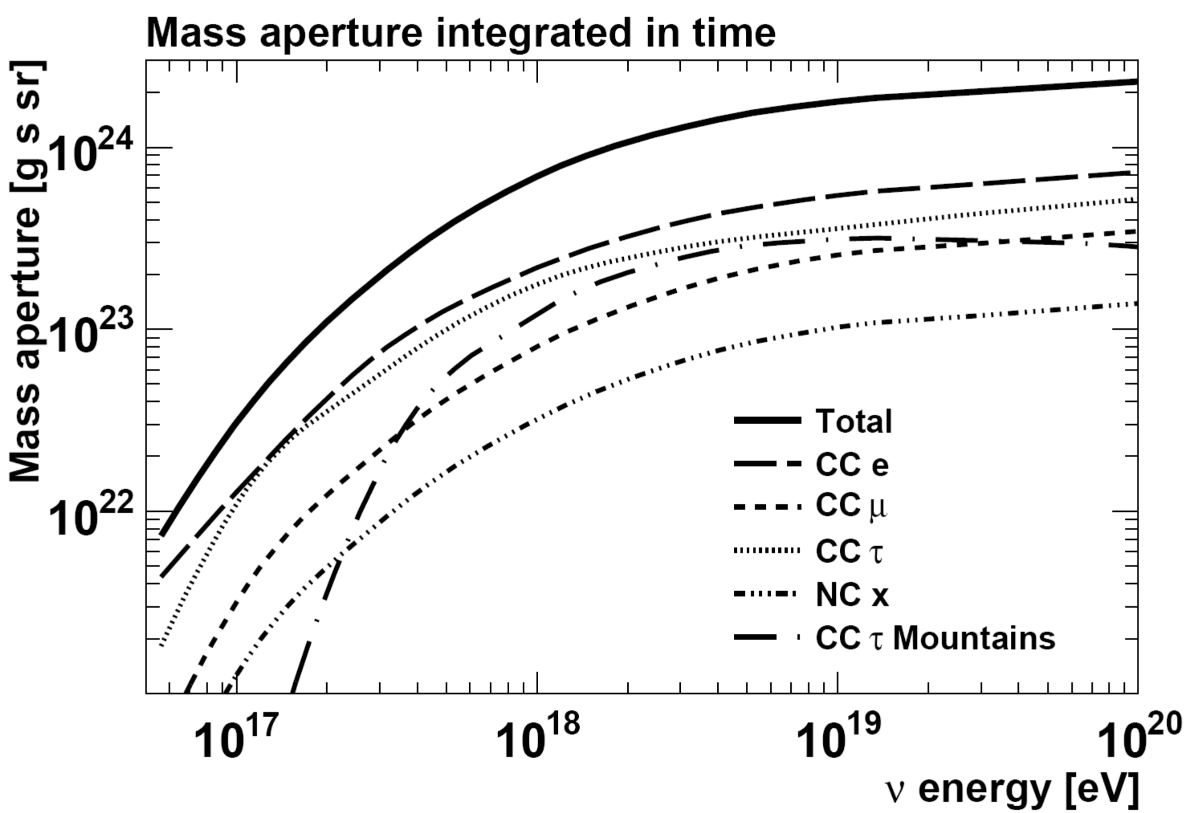
Mass aperture for each channel

ν detection efficiency

The array configuration varies with time !

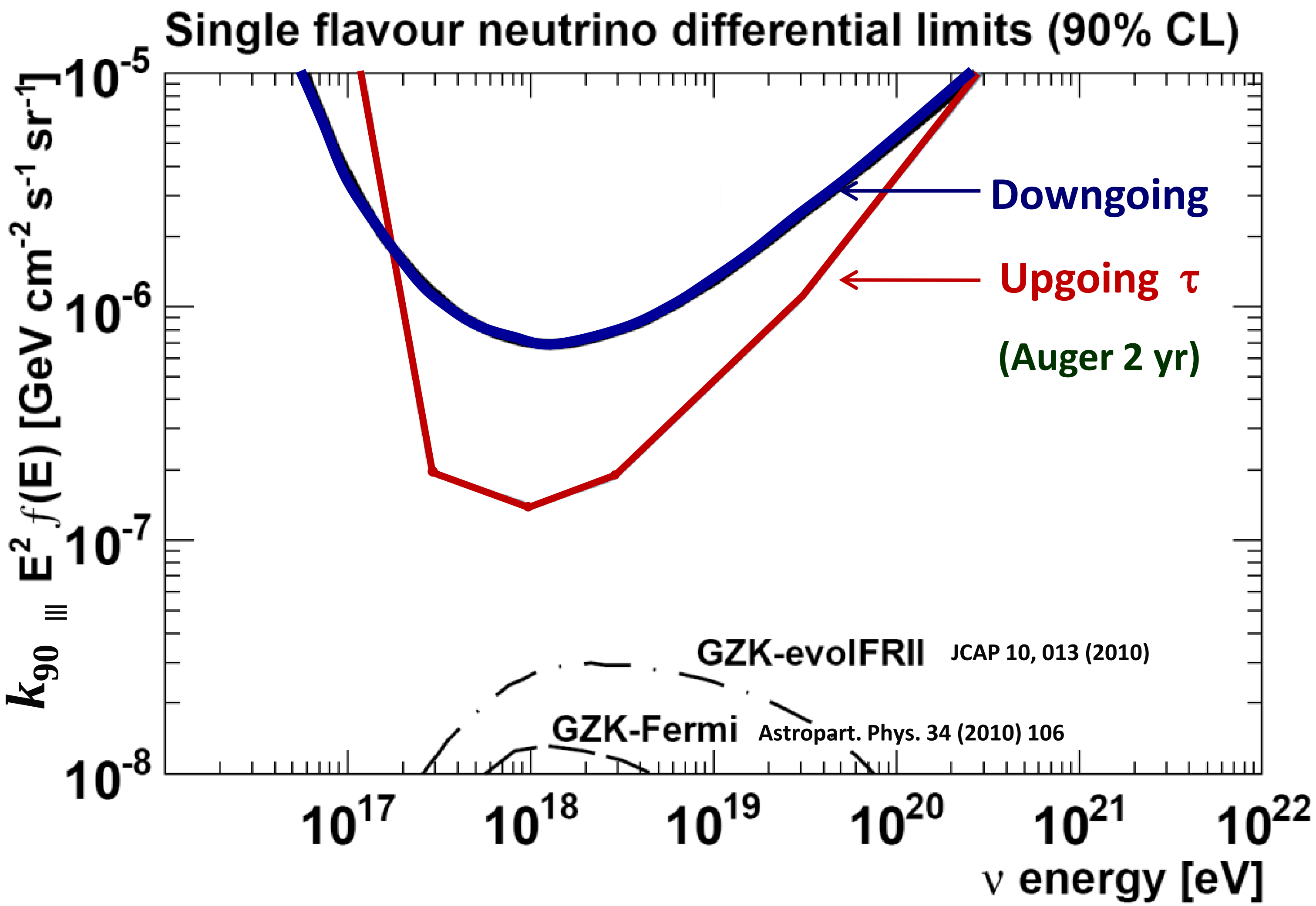


Snapshot of the array configuration in October 27th , 2007



Differential flux limit

Assuming $$\frac{dN}{dE} \equiv f(E_\nu) = k \cdot E_\nu^{-2} \quad \Rightarrow \quad f(E_\nu)_{lim} = \frac{N_{exp}}{E_\nu \cdot \mathcal{E}(E_\nu) \cdot \Delta \ln E_\nu}$$



HiRes experiment

Astrophysical Journal, 684 (2008) 790

- HiRes is a **fluorescence** experiment :
  - Charged particles in cosmic ray air shower excite N_2 molecules.
  - Emit ~ 5 UV photons/mip/meter, 300-400 nm wavelength.
- Mono: wider energy range ($10^{17.2} < E < 10^{20.5}$ eV), best statistics.
- Stereo: best resolution, $10^{18.5} < E < 10^{20.5}$ eV, fewer events.
- Looks for **UHE electron-neutrino-induced showers** thanks to the large interaction cross section and the **LPM effect** which causes a significant decrease in the cross sections from bremsstrahlung and pair production, allowing CC ν_e showers occurring deep in the Earth's crust to be detectable as they exit the Earth into the atmosphere.

HiRes I

- 21 mirrors, 1 ring, 5.1 m^2, 16×16 PMTs
- Complete azimuth, zenith 3^o – 17^o
- Data: July 1997 – April 2006

HiRes II

- 42 mirrors, 2 rings
- Complete azimuth, zenith 3^o – 31^o
- Data: December 1999 – April 2006

ANITA – II experiment

Phys. Rev. D 82 (2010) 022004
Astropart. Phys. 32 (2009) 10

Searches for **impulsive coherent radio Cherenkov emission** from **200 to 1200 MHz** arising from the **Askaryan** charge excess in ultrahigh energy neutrino-induced cascades within Antarctic ice.

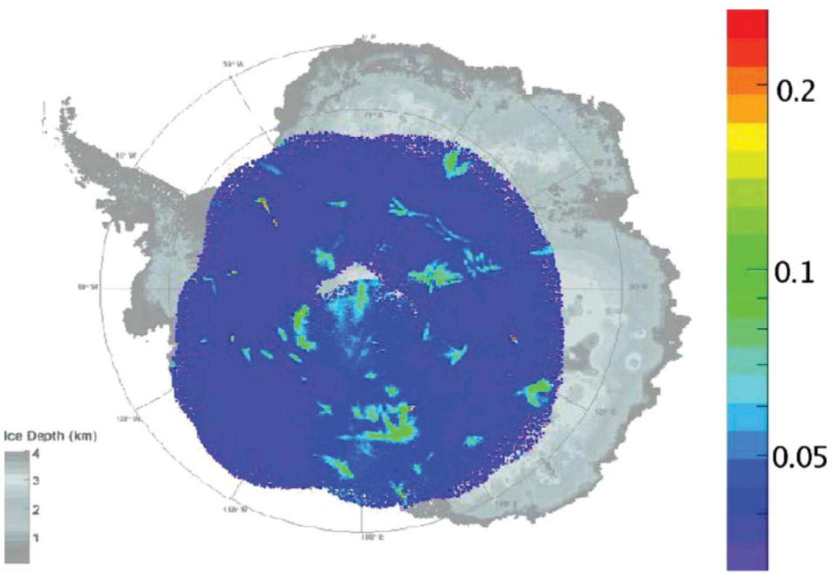
Launched on Dec. 21, 2008 ⇒ **30 days** time aloft

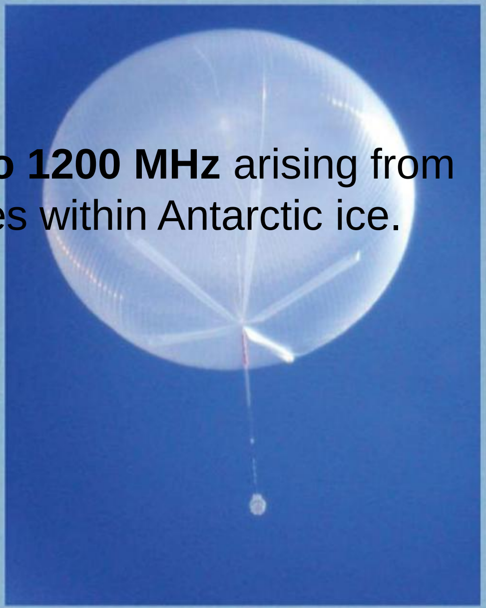
Altitude: 33 – 35 km above ice surface

Volume: ~1.6 M km^3 of ice

~21 M quality events

No expected particle physics background
Ambient random thermal noise
Anthropogenic background (HV discharges, Iridium phones, spark plugs, spark gaps…)
Resolution: 0.3° in elevation and 0.5° – 1.1° in azimuth

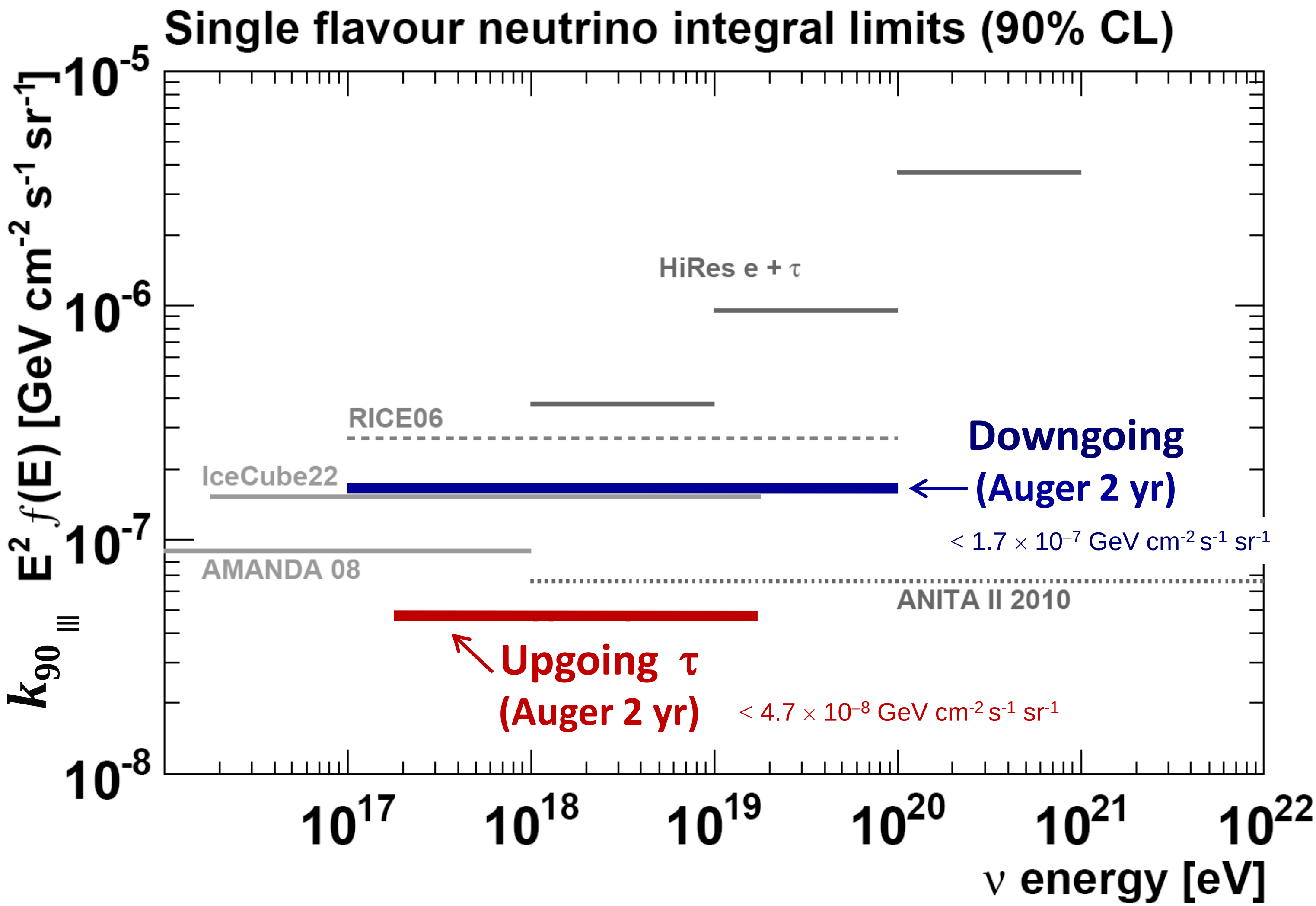




V_{pol}	2	0.97±0.42
H_{pol}	3	0.67±0.24

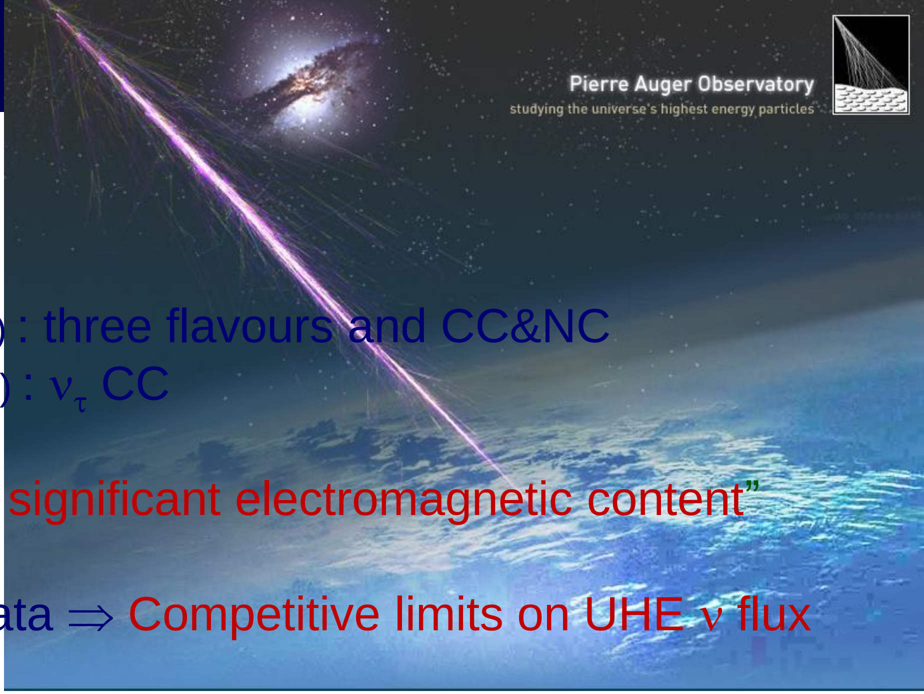
Integrated flux limit

$$N_{exp} = \int f(E_\nu) \cdot \mathcal{E}(E_\nu) \cdot dE_\nu$$ and assuming $$f(E_\nu) = k \cdot E_\nu^{-2}$$



HiRes:
Astrophys. J. 684 (2008)
RICE06:
Phys. Rev. D73 (2006)
IceCube22:
arXiv:1009.1442 (2010)
AMANDA 08:
Astrophys. J. 675 (2008)
ANITA II:
Phys. Rev. D 82 (2010)
AUGER:
Phys. Rev. D 79 (2009) 102001
ICRC'09 conf. proceedings

Summary

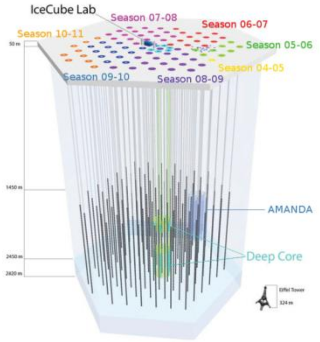


- The Pierre Auger Observatory is sensitive to UHE neutrinos:
  - ✓ "down-going" neutrinos $(\theta \in [75^o - 90^o])$: three flavours and CC&NC
  - ✓ "Earth-skimming" neutrinos $(\theta \in [90^o - 95^o])$: ν_τ CC

- Main signature: "very inclined showers with significant electromagnetic content"

- **ZERO** neutrino candidate events found in data $\Rightarrow$ Competitive limits on UHE ν flux

- Maximum sensitivity at the most relevant range for GZK neutrinos (~1 EeV)



- A number of different experiments (IceCube, ANITA, Auger …) showing very good performances to UHE neutrino detection … let's wait for the first UHE neutrinos in the next years !

Backup

transparencies

Systematic uncertainties

Transport equation	Interactions in Earth	±5%	MC Simulations
Modeling UHE had. interac.	Extensive Air Shower	+20% , –5%	MC Simulations
Triggering/selection efficiency, Aperture…	Acceptance	±2%	Pierre Auger Observatory
Andes, Pacific Ocean…	Topography	±6%(↓) ±18%(↑)	Pierre Auger Observatory
Depends on PDFs…	Cross section	±10%	Theory
	Energy Losses (Breemstralhung, pair prod., DIS)	+25% , –10%	Theory

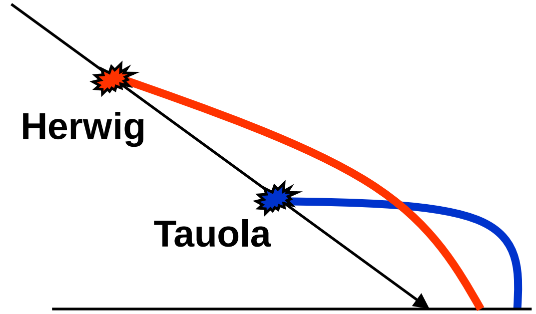
Relative contribution of different channels (down-going analysis)

(%)	ν_e	ν_μ	ν_τ	Total
CC	33	13	39	85
NC	5	5	5	15
CC + NC	38	18	44	100

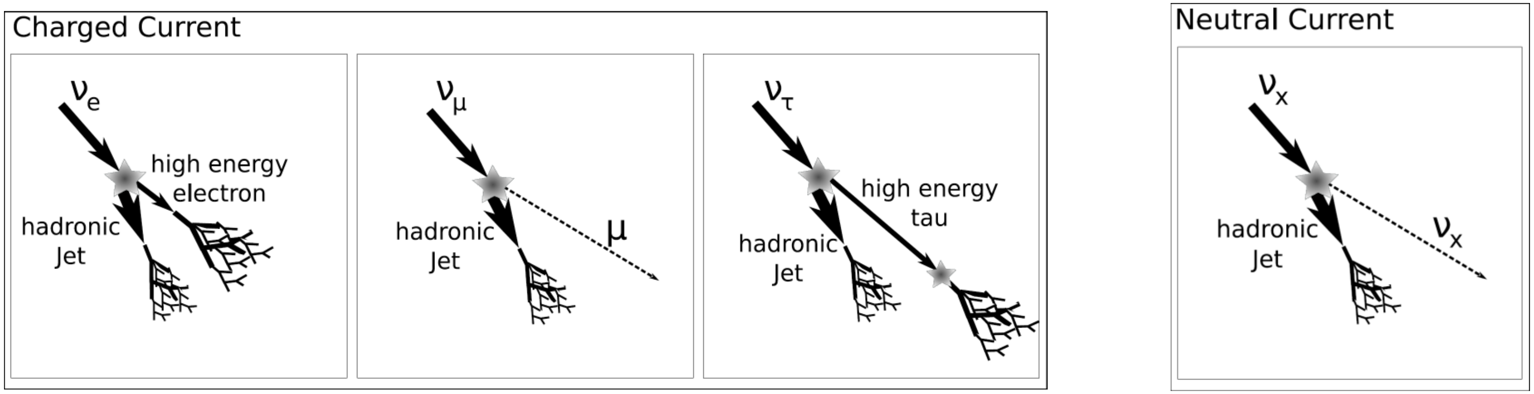
Expected number of events using current exposure of down going ν measured by Auger for several models

	Reference		N expected
"cosmogenic"	**GZK - Fermi**	JCAP 10, 013 (2010)	0.12
	GZK – evolFRII	Astropart. Phys. 34 (2010) 106	0.30
"astrophysical"	**MPR – max**	Phys. Rev. D 63 (2001) 23003	2.08
	BBR	Astropart. Phys. 23 (2005) 355	0.89
"exotics"	**TD – Necklaces**	Phys. Rev. D 66 (2002) 063004	0.84
	Z – Bursts		8.16

Neutrino simulation technical details



- First interaction: HERWIG
- Tau decay: TAUOLA
- Shower development: AIRES 2.8.0 + QGSjetII.03
- Detector simulation: Auger Offline
- All flavours (ν_e , ν_μ , ν_τ) and channels (NC & CC):



~ 150.000 showers ~ 200.000 showers ~ 150.000 showers

Parameters of simulations:

- Energy: E = 10^{16} eV – 10^{20} eV
- Zenith: $\theta_{down\text{-}going}$ = 75º – 89º (6 bins in sec(θ))
- Depth of 1st interaction: X_{inj} = 0 – 8000 g cm^{-2} (slanted from ground)