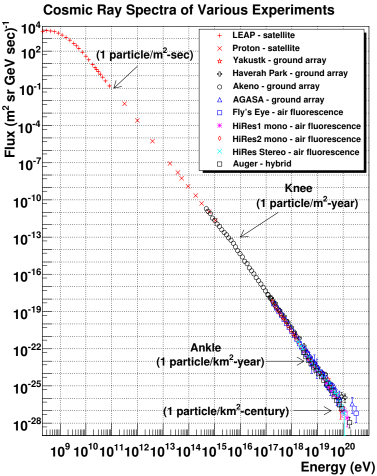
# UHE Neutrino searches with the Pierre Auger Observatory

Javier Tiffenberg

February 21, 2012

Universidad de Buenos Aires, Argentina

# Cosmic rays

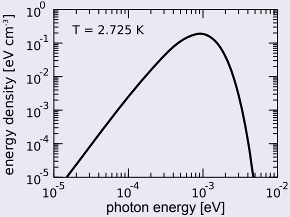



## CM energy

| $E_{lab}$[eV] | $E_{CM}$[TeV] | Exp |
|---|---|---|
| $10^{14}$ | 0.8 | SPS |
| $10^{15}$ | 2 | Tevatr. |
| $10^{16}$ | 7 | LHC |
| $10^{17}$ | 14 | LHC? |
| $10^{18}$-$10^{20}$ | 30-500 | Auger |

# Propagation of the Ultra High Energy CR

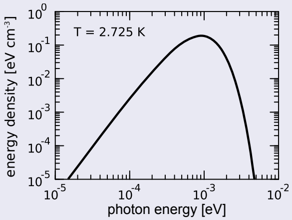
## They interact with the CMB - GZK cutoff



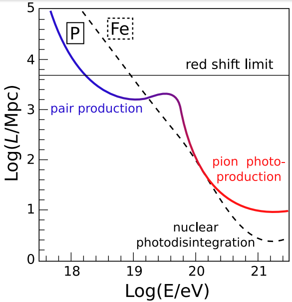

- pair production:
  $p + \gamma_{\mathrm{CMB}} \rightarrow p + e^{+} + e^{-}$
- pion photoproduction:
  $p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$ or $n + \pi^{+}$
  other resonances..
- nuclear photodisintegration.

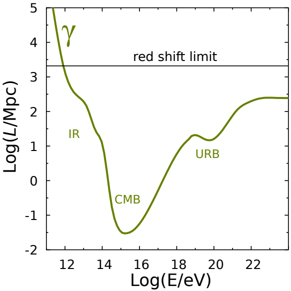
# Propagation of the Ultra High Energy CR

## They interact with the CMB - GZK cutoff

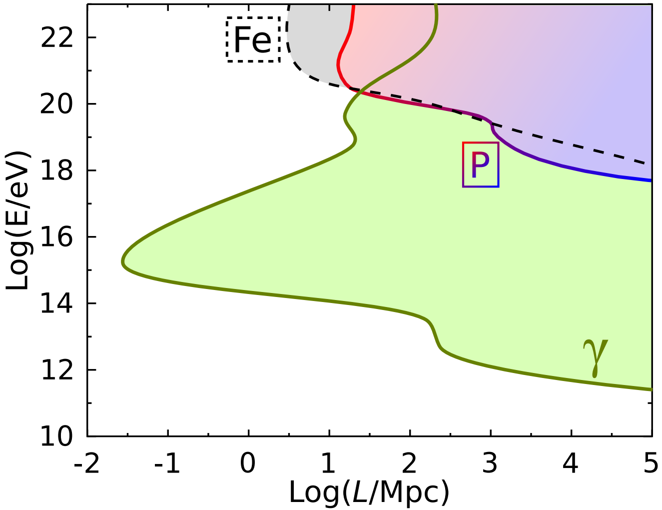



- pair production:
  $p + \gamma_{\mathrm{CMB}} \to p + e^{+} + e^{-}$
- pion photoproduction:
  $p + \gamma_{\mathrm{CMB}} \to \Delta^{+} \to p + \pi^{0}$ or $n + \pi^{+}$
  other resonances..
- nuclear photodisintegration.

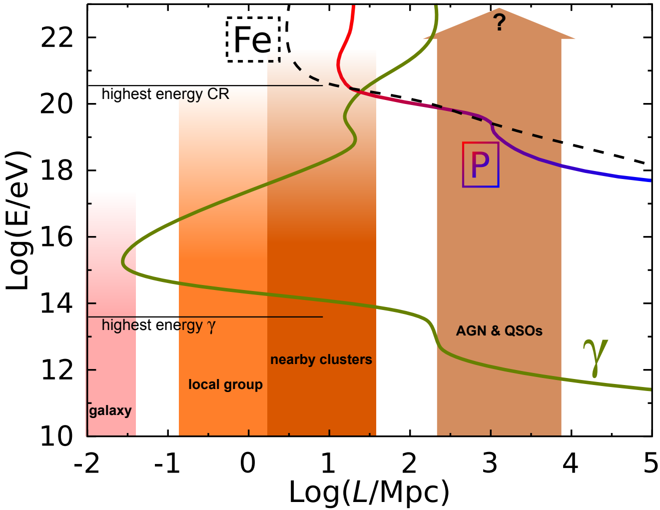


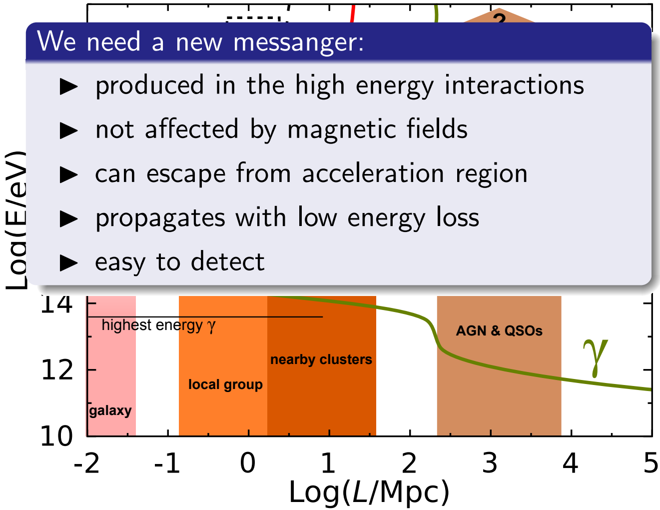
# Neutrino astronomy: objetives & motivation



# Neutrino astronomy: objetives & motivation



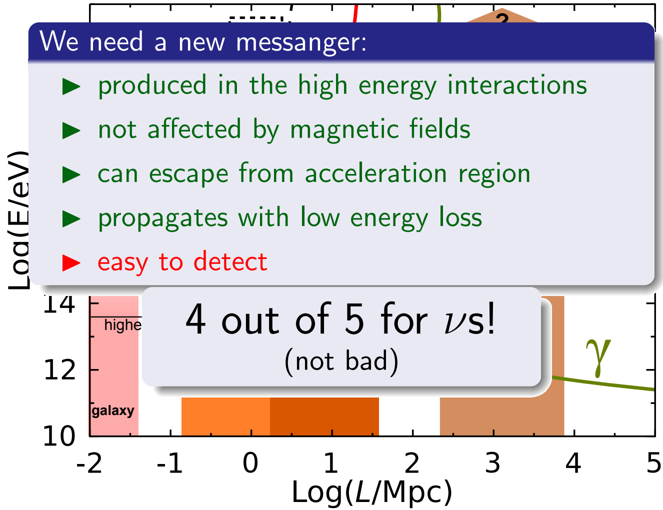
# Neutrino astronomy: objetives & motivation




## We need a new messanger:

- produced in the high energy interactions
- not affected by magnetic fields
- can escape from acceleration region
- propagates with low energy loss
- easy to detect

# Neutrino astronomy: objetives & motivation




**We need a new messanger:**

- produced in the high energy interactions
- not affected by magnetic fields
- can escape from acceleration region
- propagates with low energy loss
- easy to detect

4 out of 5 for $\nu$s!
(not bad)

# Origin of the UHE$\nu$

- Cosmogenic neutrinos/GZK neutrinos
  - Produced in UHECRs propagation.
    $p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow n + \pi^{+} \rightarrow n + \nu_{\mu} + \mu^{+}$
- 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, etc)
- New physics and "top-down" scenarios
  - Decay of ultra massive objects (topological defects, super heavy dark matter, $Z$ burst..).

# What kind of detector do we need?

## Back of the envelope calculation

- assume that the UHE$\nu$ flux is $\sim$ UHECR flux
  - $\phi \simeq 3 \times 10^3 \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$ for $E > 10^{17} \mathrm{eV}$
- neutrino cross-section $\sigma \sim 10^{-32}\ \mathrm{cm}^2$
- aim to detect $\sim$1 neutrino per year ($N = 1$ & $T = 1$ yr)

$$N \simeq \frac{\phi \sigma T}{m_p} M_{\mathrm{det}} \Rightarrow M_{\mathrm{det}} \simeq 5 \times 10^{11} \mathrm{kg}\ (0.5\ \mathrm{km}^3 \text{ of water!})$$

# What kind of detector do we need?

## Back of the envelope calculation

- assume that the UHE$\nu$ flux is $\sim$ UHECR flux
  - $\phi \simeq 3 \times 10^3 \mathrm{km}^{-2}\ \mathrm{yr}^{-1}$ for $E > 10^{17} \mathrm{eV}$
- neutrino cross-section $\sigma \sim 10^{-32}\ \mathrm{cm}^2$
- aim to detect ~1 neutrino per year ($N = 1$ & $T = 1\ \mathrm{yr}$)

$$N \simeq \frac{\phi \sigma T}{m_p} M_{\mathrm{det}} \Rightarrow M_{\mathrm{det}} \simeq 5 \times 10^{11} \mathrm{kg}\ (0.5\ \mathrm{km}^3 \text{ of water!})$$

⇒ we need huge detectors
⇒ it can only be a sparse instrumented detector

# Neutrino astronomy: dedicated experiments

| | Det. prin. | $V_{eff}$ [km$^3$] | $E_{min}$ [GeV] | $E_{max}$ [GeV] | Location | Op. period |
|---|---|---|---|---|---|---|
| RICE | Radio-ice | 4 | $10^8$ | $10^{11}$ | South Pole | 1997- |
| GLUE | Radio-moon | $10^5$ | $10^{11}$ | $10^{14}$ | California | 1999-2003 |
| FORTE | Radio-ice | $10^6$ | $10^{13}$ | $10^{17}$ | Satellite | 1997-2001 |
| ANITA | Radio-ice | $10^6$ | $10^9$ | $10^{14}$ | Balloon, Antartica | 2007- |
| Baikal | Cherenkov water | $10^{-4}$ | $10^4$ | $10^8$ | Lake Baikal, Siberia | 1993- |
| AMANDA | Cherenkov ice | $10^{-2}$ | $10^3$ | $10^6$ | South Pole | 1996-2005 |
| IceCube | Cherenkov ice | 1 | $10^2$ | $10^{10}$ | South Pole | 2006- ¡1¿ |
| ANTARES | Cherenkov water | $10^{-2}$ | $10^2$ | $10^5$ | Mediterranean sea -2500m | 2008- |
| Nestor | Cherenkov water | | $10^3$ | $10^7$ | Mediterranean sea -4000m | 2012? |

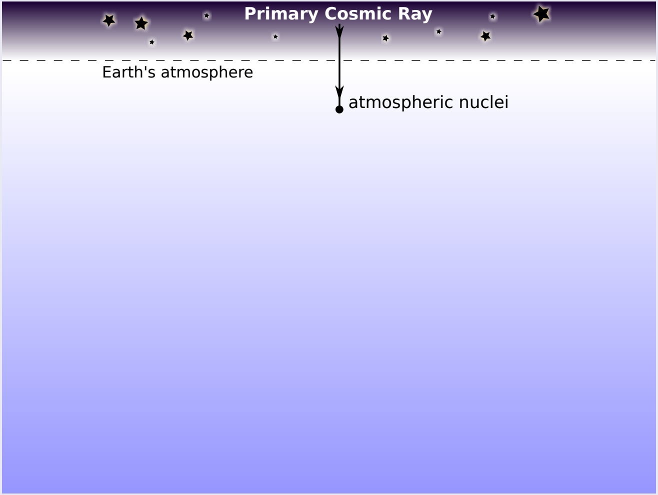
# Neutrino astronomy: dedicated experiments

| | Det. prin. | $V_{eff}$ [$km^3$] | $E_{min}$ [GeV] | $E_{max}$ [GeV] | Location | Op. period |
|---|---|---|---|---|---|---|
| RICE | Radio-ice | 4 | $10^8$ | $10^{11}$ | South Pole | 1997- |
| GLUE | Radio-moon | $10^5$ | $10^{11}$ | $10^{14}$ | California | 1999-2003 |
| FORTE | Radio-ice | $10^6$ | $10^{13}$ | $10^{17}$ | Satellite | 1997-2001 |
| ANITA | Radio-ice | $10^6$ | $10^9$ | $10^{14}$ | Balloon, Antartica | 2007- |
| Baikal | Cherenkov water | $10^{-4}$ | $10^4$ | $10^8$ | Lake Baikal, Siberia | 1993- |
| AMANDA | Cherenkov ice | $10^{-2}$ | $10^3$ | $10^6$ | South Pole | 1996-2005 |
| IceCube | Cherenkov ice | 1 | $10^2$ | $10^{10}$ | South Pole | 2006- ¡1¿ |
| ANTARES | Cherenkov water | $10^{-2}$ | $10^2$ | $10^5$ | Mediterranean sea -2500m | 2008- |
| Nestor | Cherenkov water | | $10^3$ | $10^7$ | Mediterranean sea -4000m | 2012? |

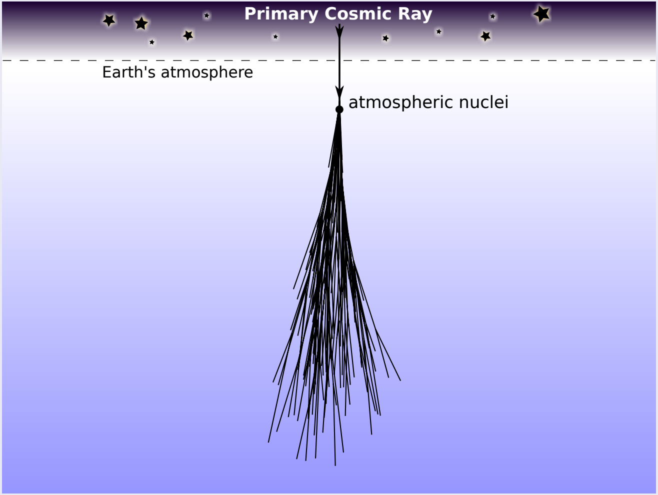
- **..and Auger!**
  - Phys. Rev. Lett. 101 (2008)
  - Phys. Rev. D 79 (2009)
  - Phys. Rev. D 84 (2011)

The Observatory has the capability to detect UHE $\nu$ using the atmosphere as a huge calorimeter.

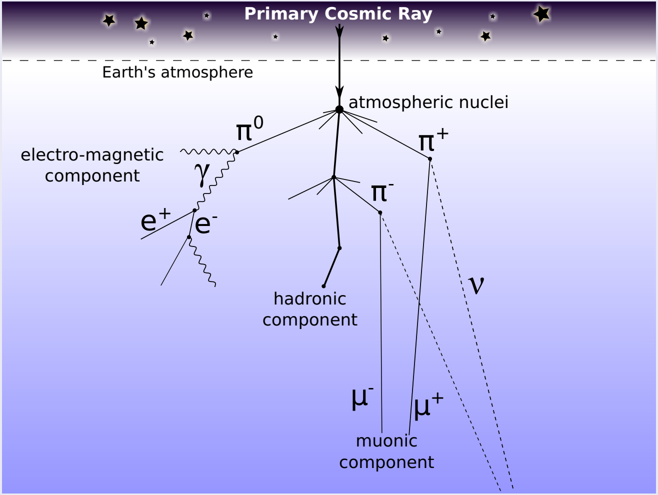
# Extensive air showers



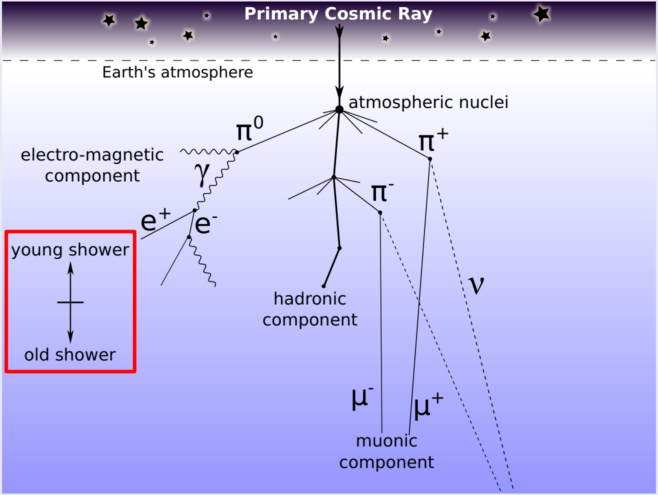
# Extensive air showers



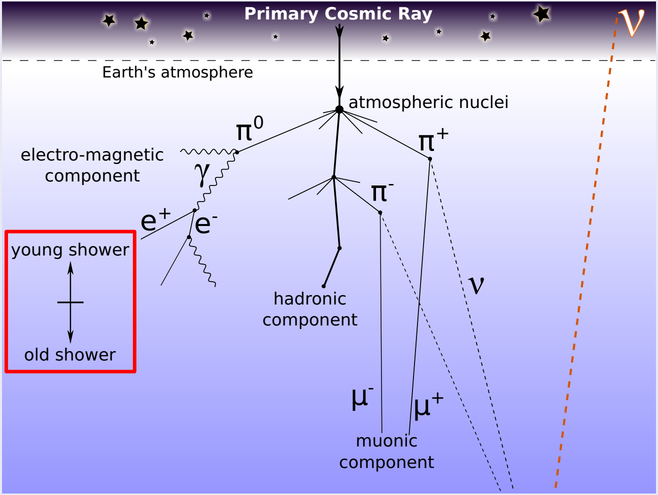
# Extensive air showers



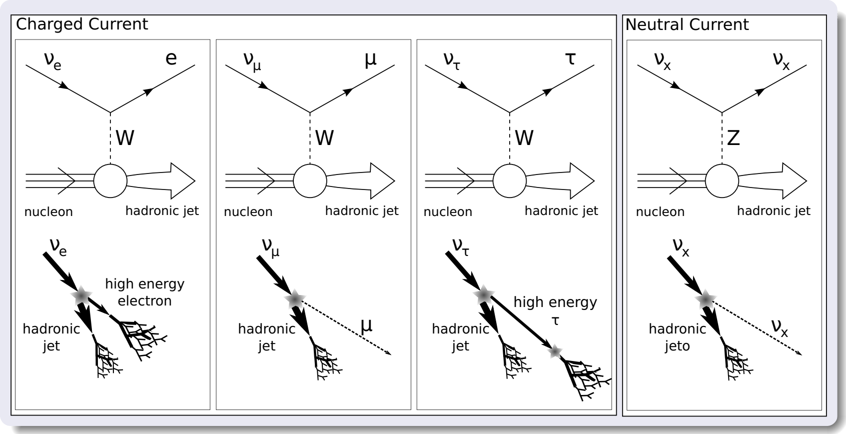
# Extensive air showers



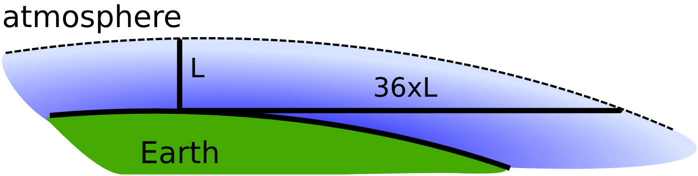
# Extensive air showers



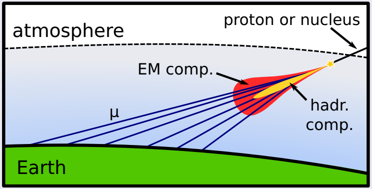
# Atmospheric showers initiated by neutrinos

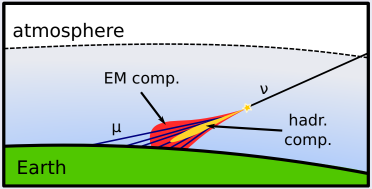


# Identification of neutrino induced showers

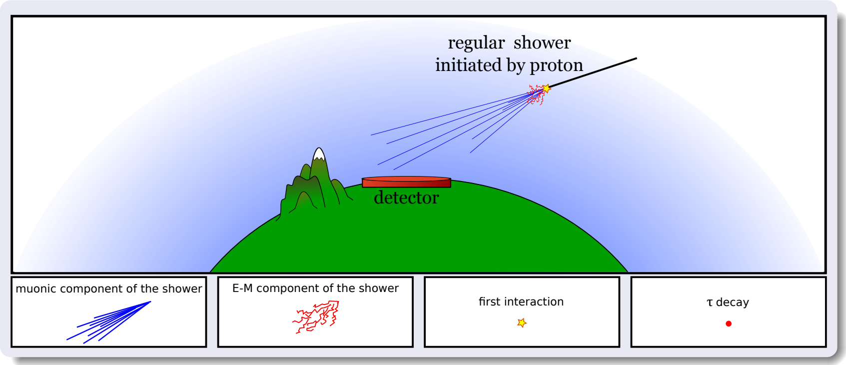



## High zenith angle showers

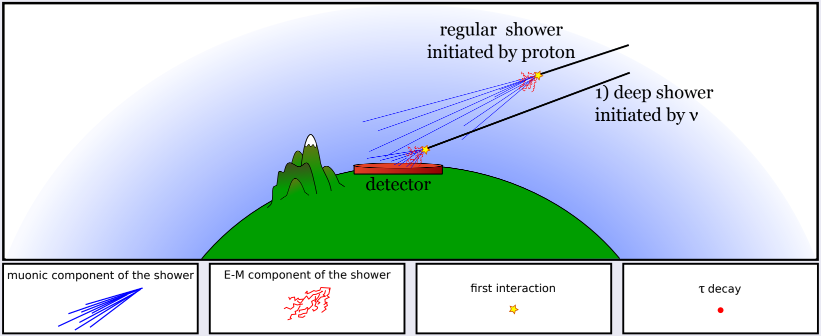


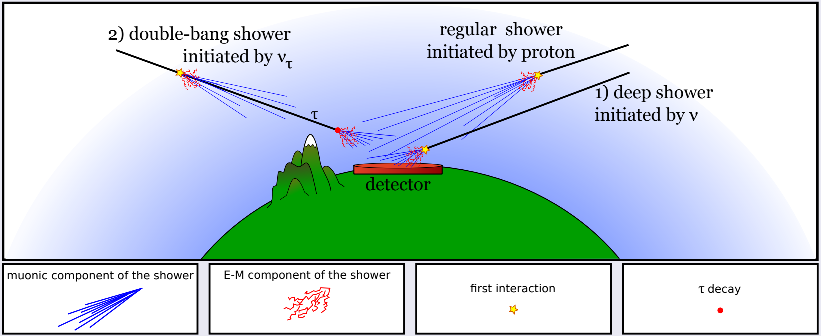
# Identification of neutrino induced showers



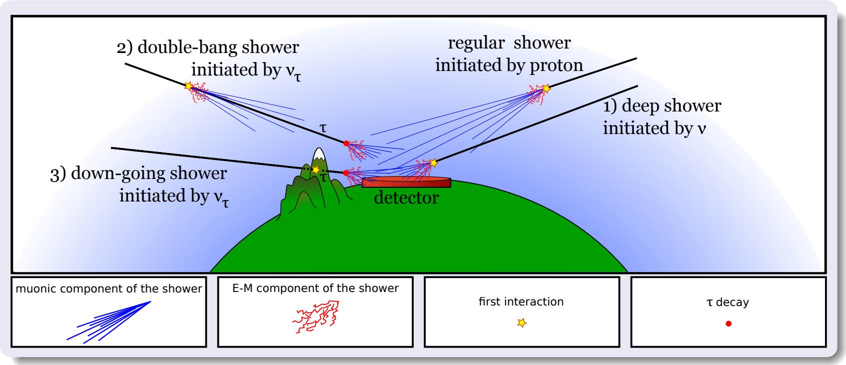
# Identification of neutrino induced showers



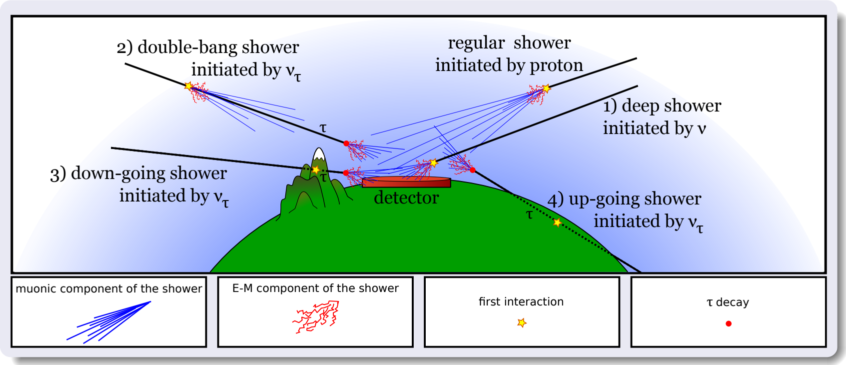
# Identification of neutrino induced showers



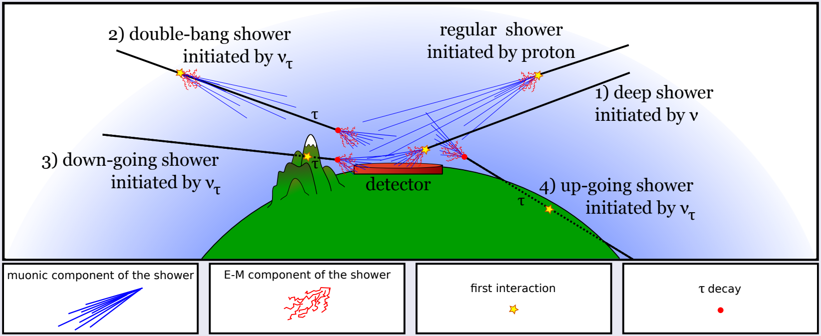
# Identification of neutrino induced showers



# Identification of neutrino induced showers



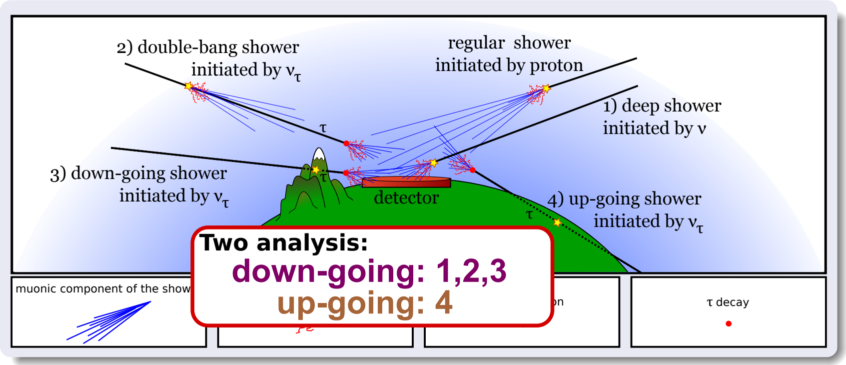
# Identification of neutrino induced showers




In the neutrino oscillation paradigm we expect the flavor ratio to be:

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$

# Identification of neutrino induced showers

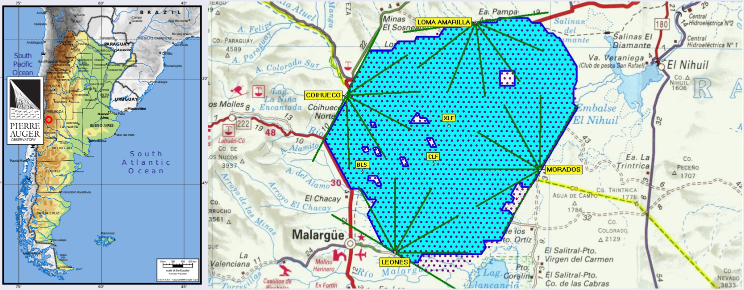



**Two analysis:**

**down-going: 1,2,3**

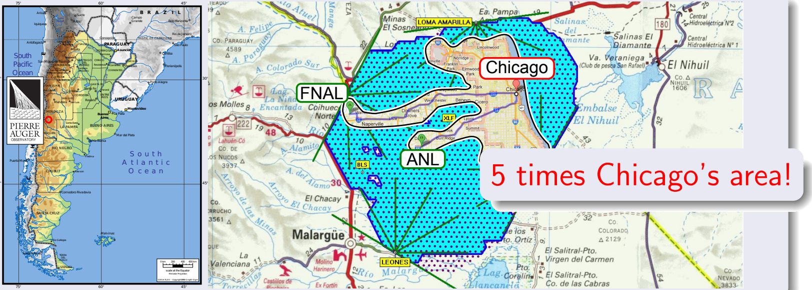
**up-going: 4**

# Pierre Auger Observatory



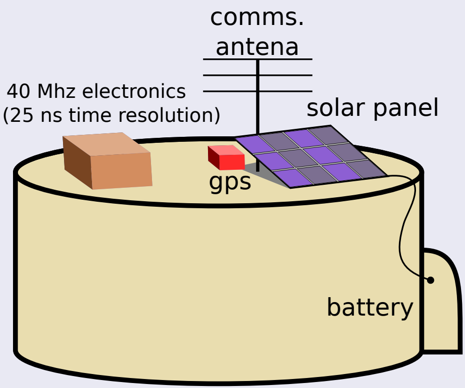

- hybrid detector.
  - Surface Detector (SD): $\sim$1600 stations over 3000 km$^2$.
  - Fluorescence Detector (FD): 4 eyes, 24 telescopes.
- construction completed in June 2008.

# Pierre Auger Observatory

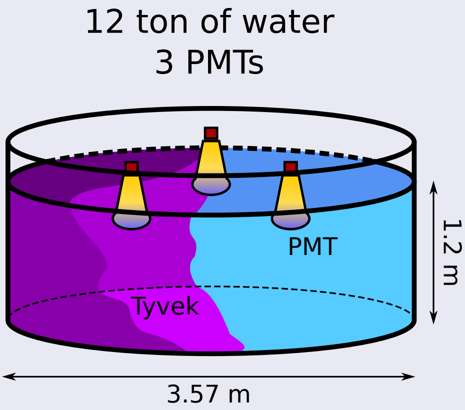



- hybrid detector.
  - Surface Detector (SD): ∼1600 stations over 3000 km$^2$.
  - Fluorescence Detector (FD): 4 eyes, 24 telescopes.
- construction completed in June 2008.

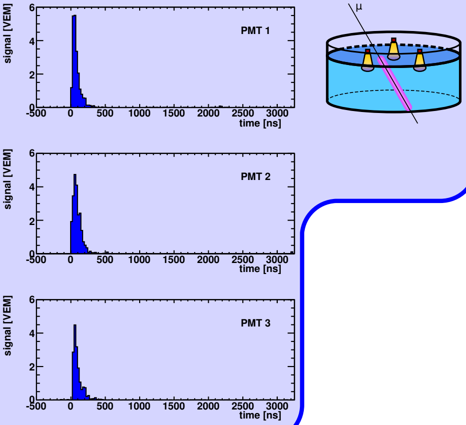
# Water Cherenkov detectors: autonomous units



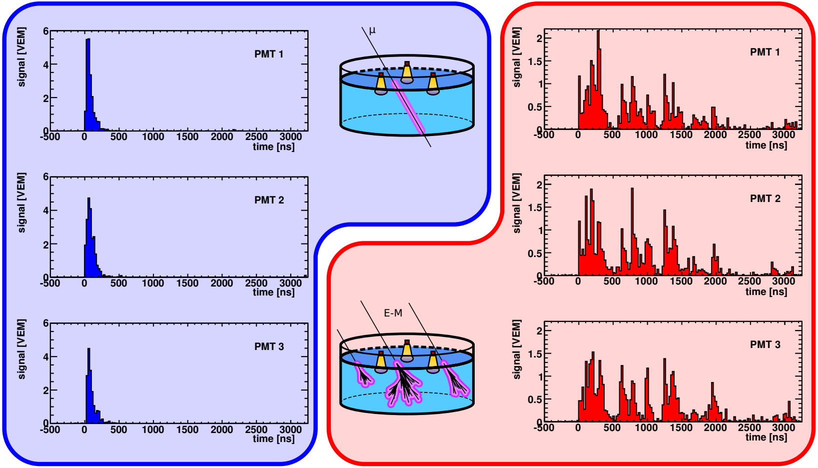
# Water Cherenkov detectors: autonomous units



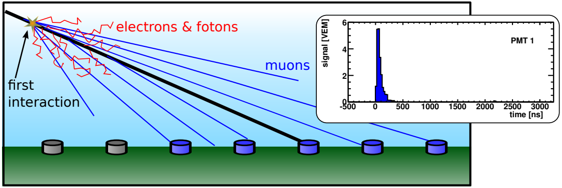
# Signals produced by muons / EM component

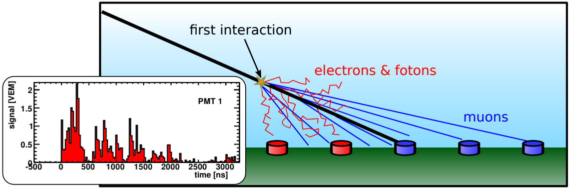


# Signals produced by muons / EM component



# Identification basis

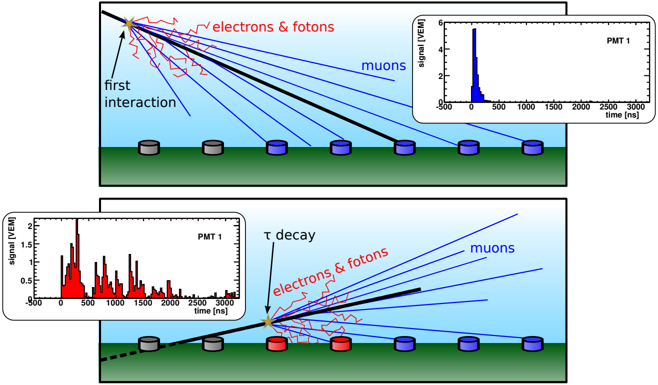



## SIGNATURE

inclined shower with significant electromagnetic content, in the **early** part of the shower.

# Identification basis



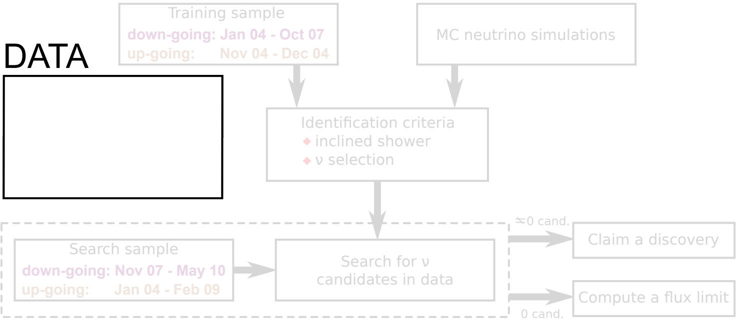

## SIGNATURE

inclined shower with significant electromagnetic content, in the **early** part of the shower.

# General neutrino search strategy

**down-going** & **up-going**

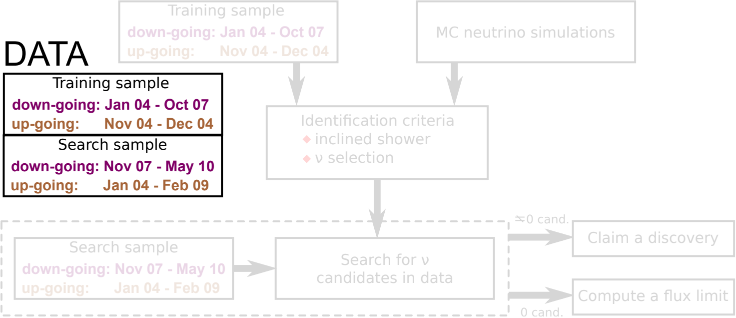
Two analysis, same approach



# General neutrino search strategy

**down-going** & **up-going**

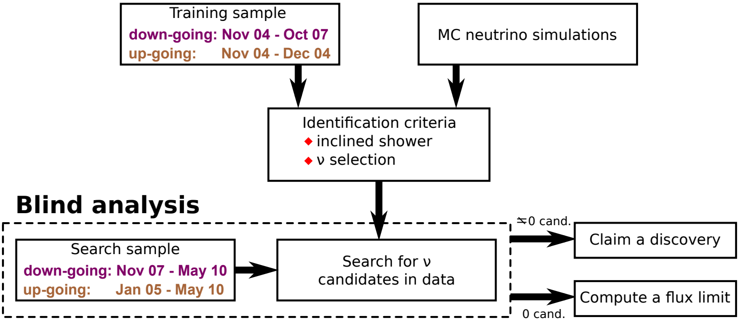
## Two analysis, same approach



# General neutrino search strategy

**down-going & up-going**

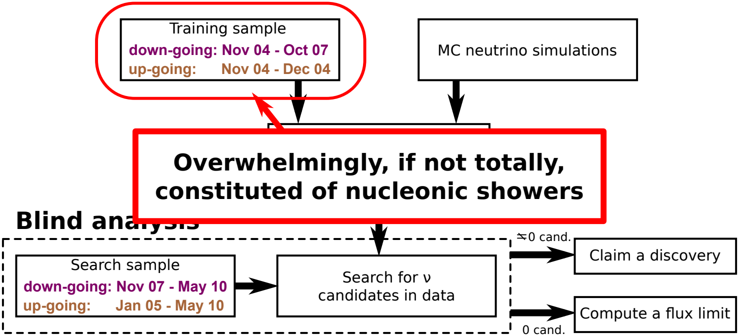
Two analysis, same approach



# General neutrino search strategy

**down-going** & **up-going**

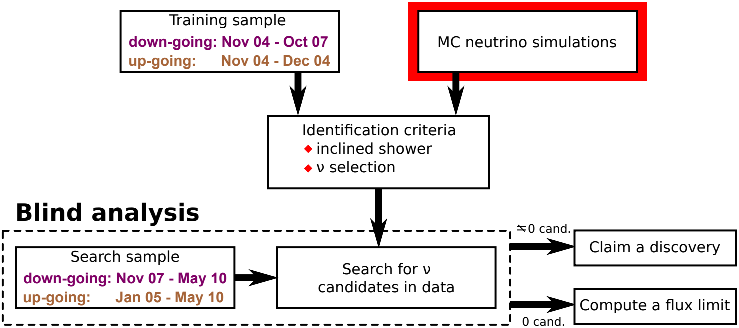
Two analysis, same approach



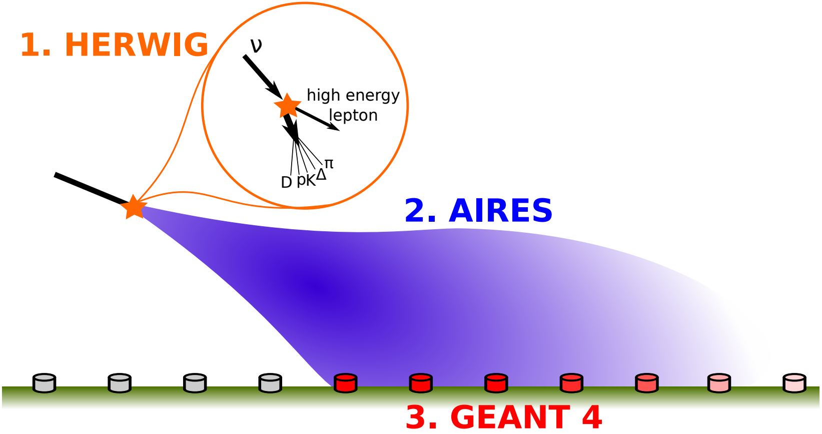
# General neutrino search strategy

**down-going & up-going**

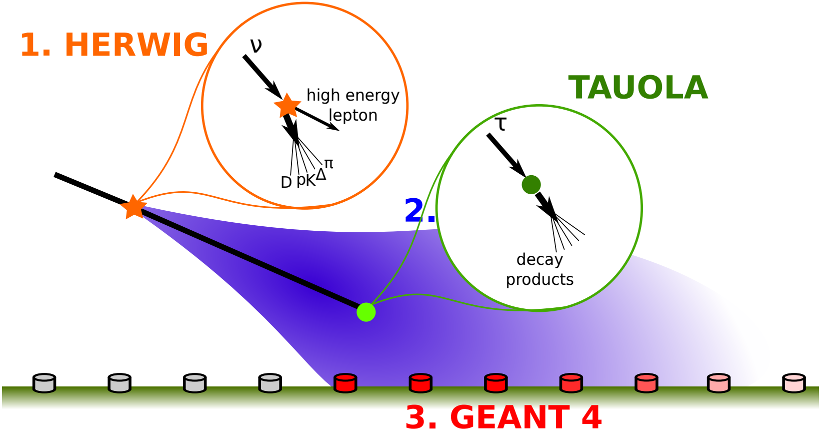
## Two analysis, same approach



# Monte Carlo simulations



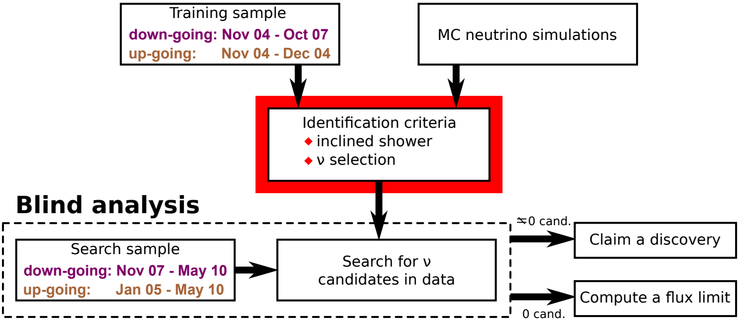
# Monte Carlo simulations



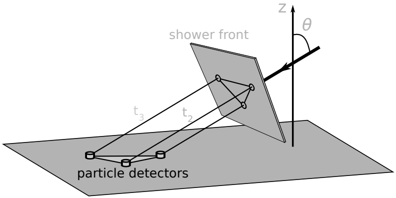
# General neutrino search strategy

**down-going** & **up-going**

Two analysis, same approach

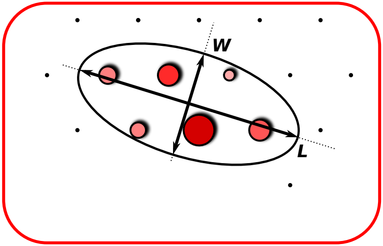


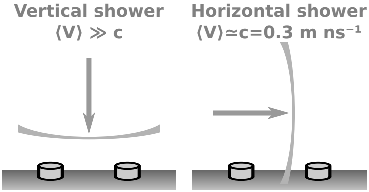
# Inclined showers selection




## Down-going

- elongated evt. $L/W \leq 3$
- signal speed $\langle V \rangle \leq 0.314$ m ns$^{-1}$
- $\langle V \rangle$ rel. err. $\leq 8\%$
- Rec. zenith angle $\theta \geq 75°$

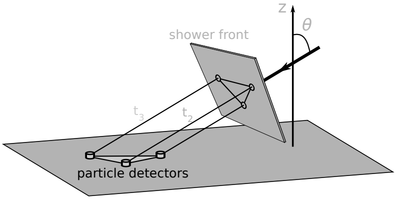


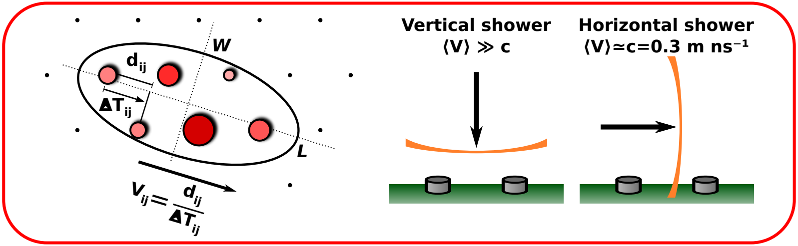



# Inclined showers selection

## Down-going

- elongated evt. $L/W \leq 3$
- signal speed $\langle V \rangle \leq 0.314\ \mathrm{m\ ns}^{-1}$
- $\langle V \rangle$ rel. err. $\leq 8\%$
- Rec. zenith angle $\theta \geq 75^\circ$

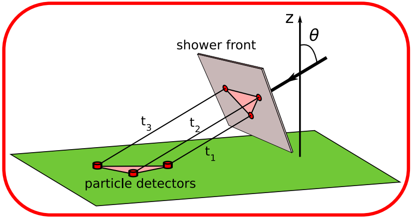


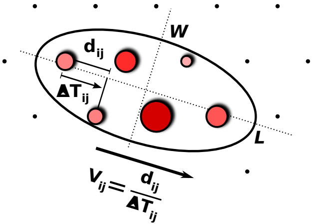



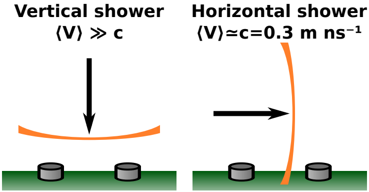
# Inclined showers selection

## Down-going

- elongated evt. $L/W \leq 3$
- signal speed $\langle V \rangle \leq 0.314$ m ns$^{-1}$
- $\langle V \rangle$ rel. err. $\leq 8\%$
- Rec. zenith angle $\theta \geq 75^\circ$

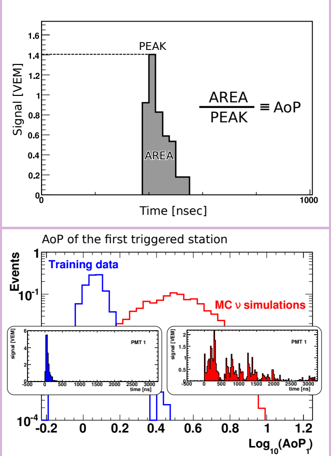


# Young showers selection: discriminating variables

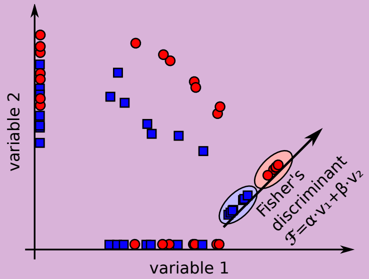
## Area Over Peak (AoP)




## MVA-Analysis: Fisher

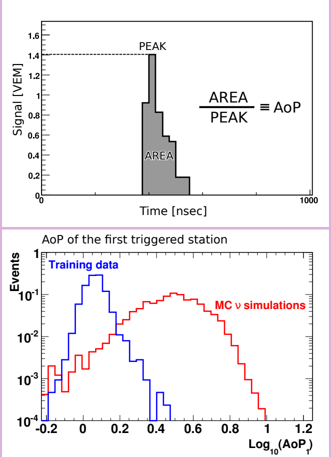
### 10 discriminating variables

- AoP of first 4 stations.
- Asym par: ⟨early AoP⟩-⟨late AoP⟩
- Non linear transf of them.



# Young showers selection: discriminating variables

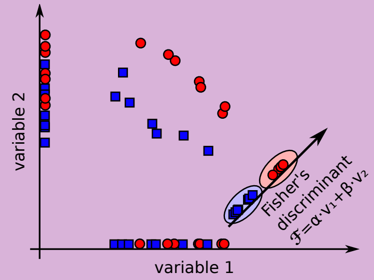
## Area Over Peak (AoP)



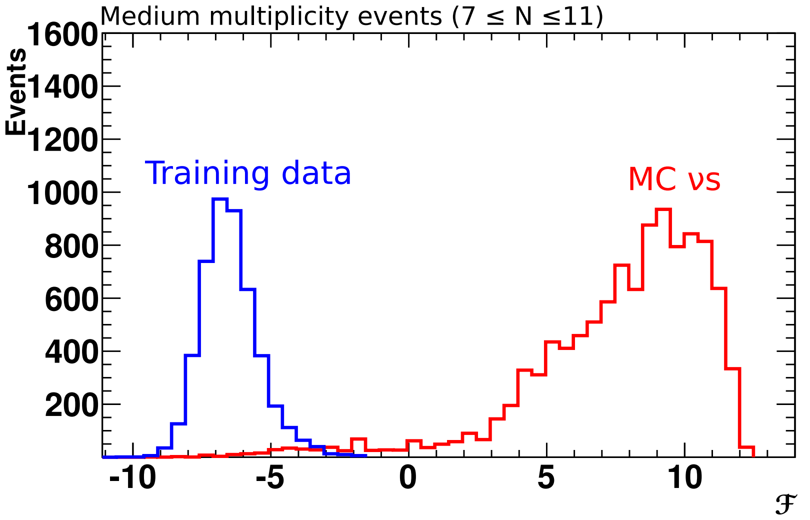

## MVA-Analysis: Fisher

**10 discriminating variables**

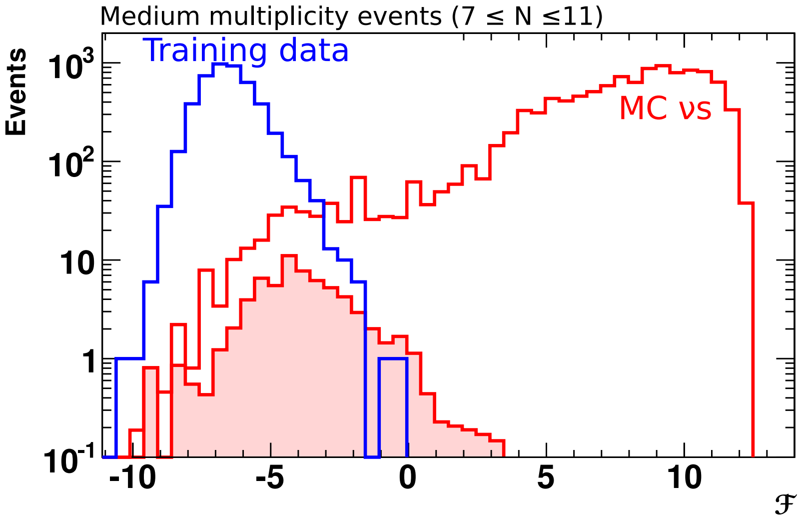
- AoP of first 4 stations.
- Asym par: ⟨early AoP⟩-⟨late AoP⟩
- Non linear transf of them.



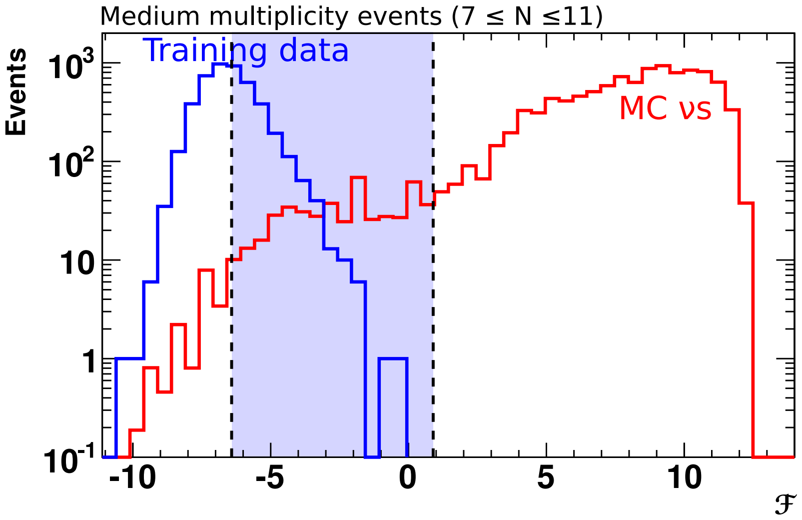
## Down-going: after training



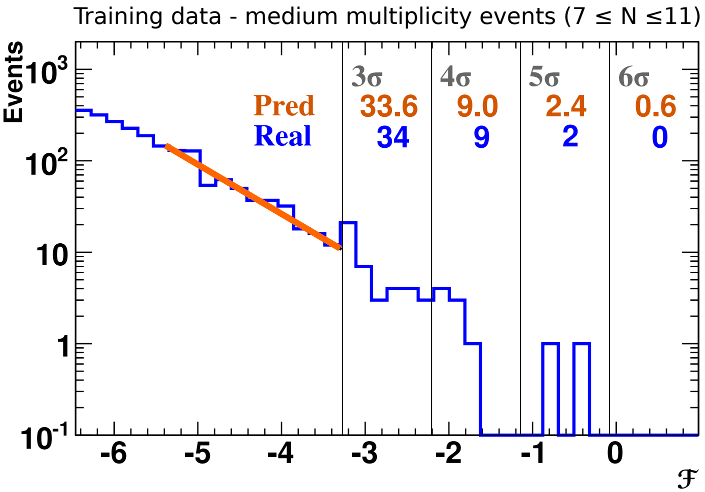
## Down-going: after training



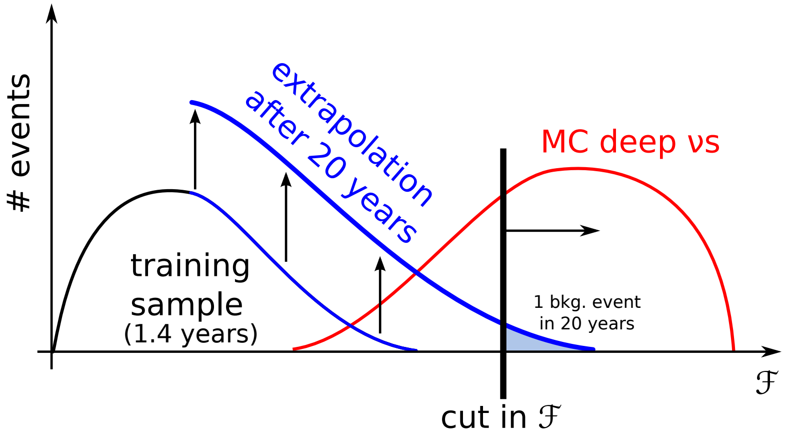
## Down-going: after training



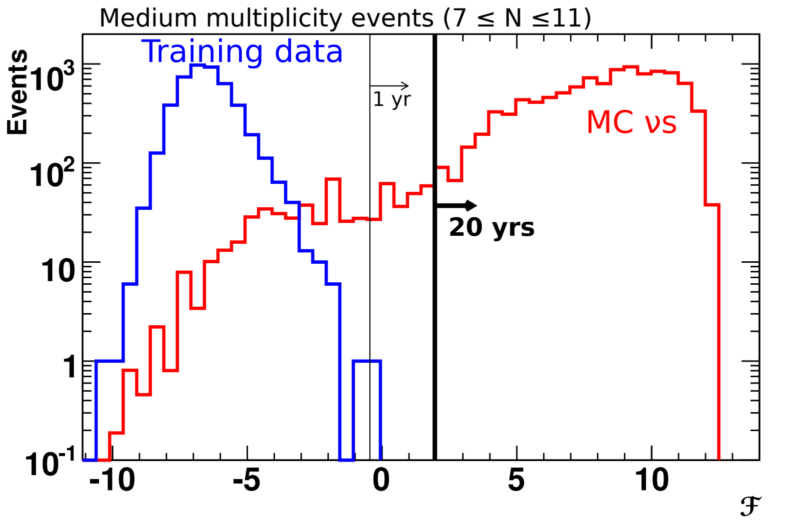
## Down-going: estimation of the background due to misclassification



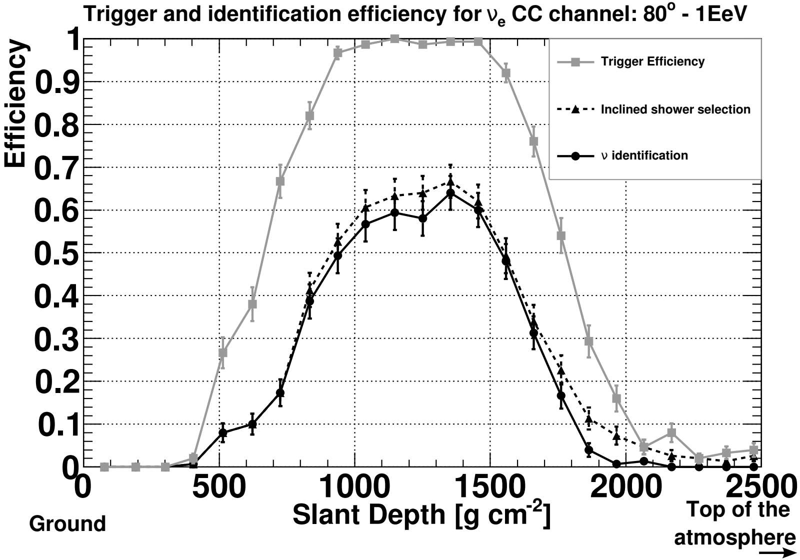
## Down-going: estimation of the background due to misclassification



## Down-going: estimation of the background due to misclassification



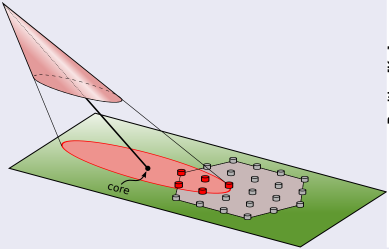
## Down-going: identification efficiency

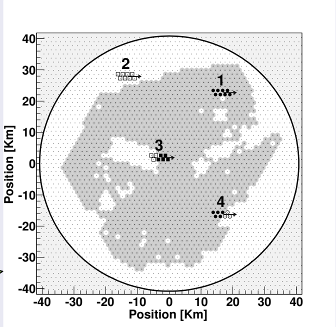


# Exposure

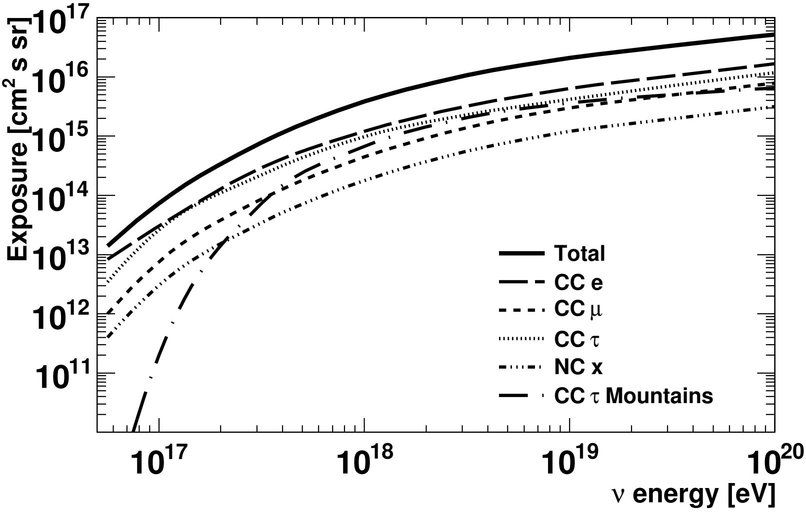
**MC $\nu$ events are used to compute the exposure of the SD**

- we take into account the contribution from showers falling outside the SD.
- that the array configuration varies with time.



## Down-going: exposure for the search period



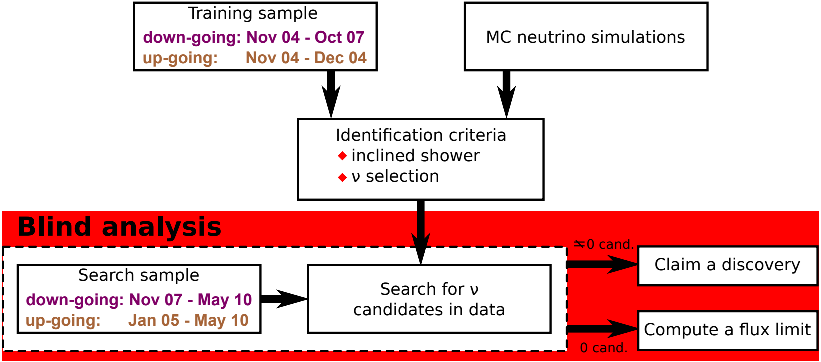
# Dominant systematic uncertainties

| Parameter | Reference (A) | Modification (B) | RD $\frac{\int B - \int A}{(\int B + \int A)/2}$ |
|---|---|---|---|
| Interaction generator | HERWIG | PYTHIA | -7% |
| | | HERWIG++ | -7% |
| PDF (generation level) | CTEQ06m | CTEQ66 | +2% |
| | | MSTW08nlo | -6% |
| | | MSTW08nnlo | -7% |
| Shower Simulator | AIRES | CORSIKA 6.9 | -17% |
| Hadronic Model | QGSJETII | QGSJETI | +2% |
| | | SIBYLL | -2% |
| | | SIBYLL ($E = 0.3$ EeV) | -1% |
| | | SIBYLL ($E = 3$ EeV) | -2% |
| | | SIBYLL ($\theta = 85^\circ$) | 0% |
| | | SIBYLL ($\theta = 89^\circ$) | +4% |
| Thinning | $10^{-6}$ | $10^{-7}$ | +7% |

# General neutrino search strategy

**down-going & up-going**

## Two analysis, same approach



# Opening the box

After unblinding:

**0**

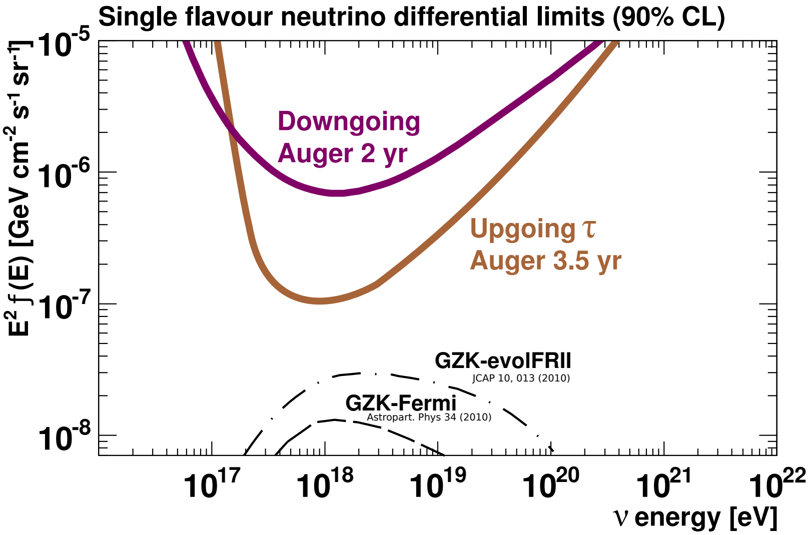
candidates for the search periods.

## search periods

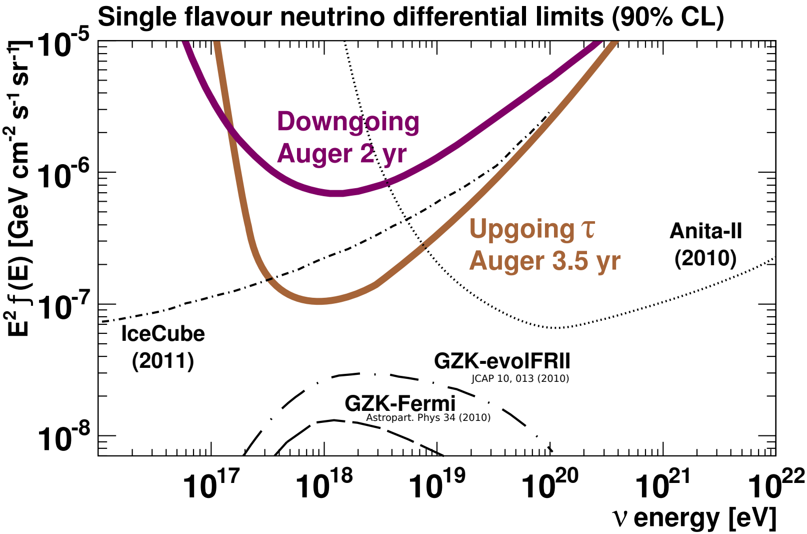
| | | | | |
|---|---|---|---|---|
| Down-going | : | Nov 07 | to | May 10 |
| Up-going | : | Jan 05 | to | May 10 |

equivalent to 2 yrs. and 3.5 yrs. of full Auger.

# Differential limit



# Differential limit



# Limit computation and systematics

For a 90% CL limit: $P(0 \mid N_{\mathrm{lim}}) = 0.1$

**Naive approach**

Poissonian probability

$\mathcal{P}(0 \mid N_{\mathrm{lim}}) = e^{-N_{\mathrm{lim}}} = 0.1$

---

$$N_{\mathrm{lim}} = 2.3$$

for a 0 bkd experiment

# Limit computation and systematics

For a 90% CL limit: $P(0 \mid N_{\rm lim}) = 0.1$

**Naive approach**

Poissonian probability

$\mathcal{P}(0 \mid N_{\rm lim}) = e^{-N_{\rm lim}} = 0.1$

$$N_{\rm lim} = 2.3$$

for a 0 bkd experiment

**Feldman-Cousins approach**

unified limit/discovery schema.

$$N_{\rm lim} = 2.44$$

for a 0 bkd experiment

# Limit computation and systematics

For a 90% CL limit: $P(0 \mid N_{\mathrm{lim}}) = 0.1$

**Naive approach**

Poissonian probability

$\mathcal{P}(0 \mid N_{\mathrm{lim}}) = e^{-N_{\mathrm{lim}}} = 0.1$

$N_{\mathrm{lim}} = 2.3$

for a 0 bkd experiment

**Feldman-Cousins approach**

unified limit/discovery schema.

$N_{\mathrm{lim}} = 2.44$

for a 0 bkd experiment

**Bayesian/frequentist mixed approach**

includes systematic uncertainties.

$N_{\mathrm{lim}} = 2.83$

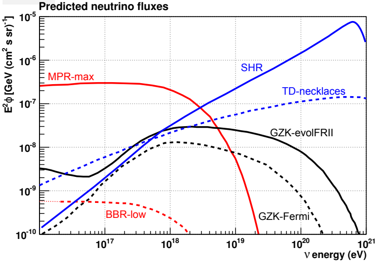
for this analysis!

# Expected event rate

Given a flux $\Phi(E_\nu)$ the expected number of events is:

$$N_{\mathrm{exp}}^{\nu} = \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} \Phi(E_\nu)\, \mathcal{E}(E_\nu)\, \mathrm{d}E_\nu$$

| Model | $N_{\mathrm{exp}}^{\nu}$ (DG + UG) |
|---|---|
| GZK-Fermi | 0.73 |
| GZK-evolFRII | 1.73 |
| MPR-max | 13.28 |
| BBR-low | 0.02 |
| TD-Necklaces | 2.56 |
| SHR | 11.07 |

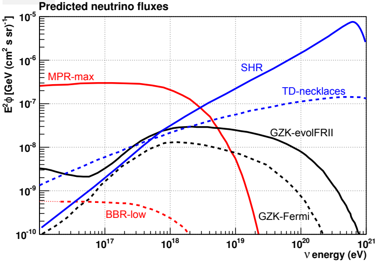


# Expected event rate

Given a flux $\Phi(E_\nu)$ the expected number of events is:

$$N^{\nu}_{\mathrm{exp}} = \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} \Phi(E_\nu)\,\mathcal{E}(E_\nu)\,\mathrm{d}E_\nu$$

| Model | $N^{\nu}_{\mathrm{exp}}$ (DG + UG) |
|---|---|
| GZK-Fermi | 0.73 |
| GZK-evolFRII | 1.73 |
| MPR-max | 13.28 |
| BBR-low | 0.02 |
| TD-Necklaces | 2.56 |
| SHR | 11.07 |



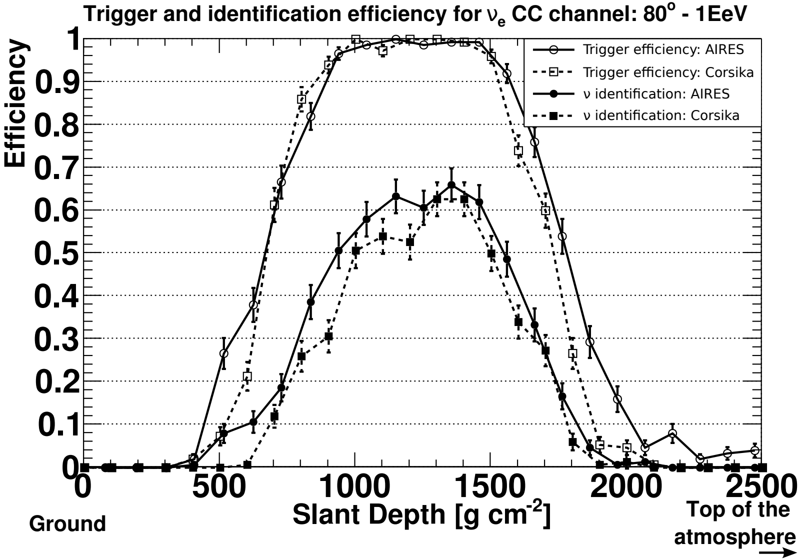

We reject a model with 90% CL if $N^{\nu}_{\mathrm{exp}} > 2.83$

# Summary

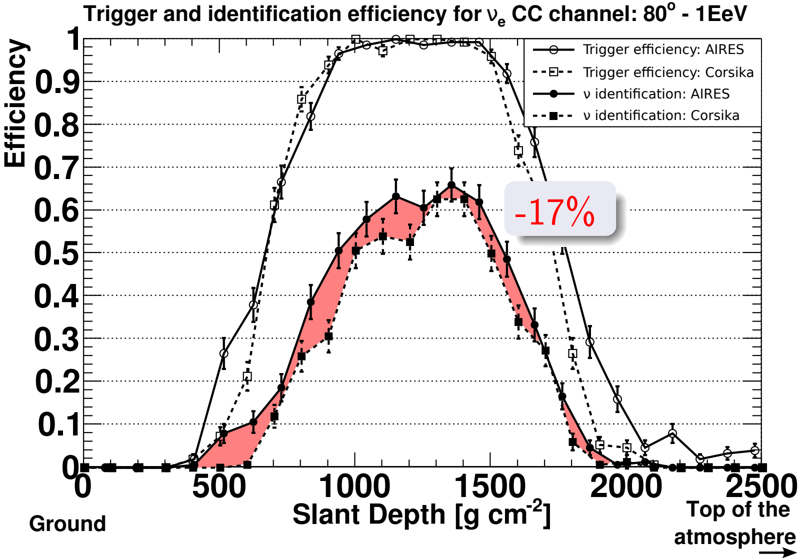
- The Pierre Auger Observatory is sensitive to UHE neutrinos:
  - down-going neutrinos ($\theta \in [75°, 90°]$): all flavours CC & NC.
  - up-going neutrinos ($\theta \in [90°, 95°]$): $\nu_\tau$ CC.
- Signature: very inclined showers with significant E-M content.
- ZERO neutrino candidate events found in data.
- Maximum sensitivity at the most relevant range for GZK neutrinos (1 EeV).
- Competitive limits on UHE fluxes.

# BACK UP SLIDES

# Example of systematic uncertainty computation



# Example of systematic uncertainty computation



# Simulations summary

**CC e neutrino & NC all flavours**

Energies (EeV): 0.06-0.1-0.3-1-3-10-30

| Zenith angle | #Inj. pt. | Max. slant depth (g cm$^{-2}$) |
|---|---|---|
| 75° | 30 | 2993 |
| 80° | 30 | 3066 |
| 85° | 30 | 3540 |
| 87° | 30 | 4469 |
| 88° | 30 | 5683 |
| 89° | 30 | 8599 |

**CC tau neutrino in the atmosphere**

Energies (EeV): 0.06-0.1-0.3-1-3-10-30

| Zenith angle | #Inj. pt. | Max. slant depth (g cm$^{-2}$) |
|---|---|---|
| 75° | 33 | 3325 |
| 80° | 48 | 4866 |
| 85° | 84 | 8803 |
| 87° | 123 | 12968 |
| 88° | 165 | 16570 |
| 89° | 218 | 22085 |

**CC tau neutrino in the mountains**

Energies (EeV): 0.1-0.3-1-3

| Zenith angle | #Inj. pt. | Max. slant depth (g cm$^{-2}$) |
|---|---|---|
| 89° | 20 | 8015 |
| 89.5° | 18 | 7222 |
| 89.7° | 12 | 4838 |

- $\sim$ one million events.
- weighted: $w \propto \cos\theta \sin\theta \, E^{-5/3}$