Assemblée Générale Enigmass2

Identification of ultra-high energy photons with Universality at the Pierre Auger Observatory for multi-messenger astronomy

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Enigmass
The enigma of mass

LPSC
GRENOBLE | MODANE

PIERRE AUGER
OBSERVATORY

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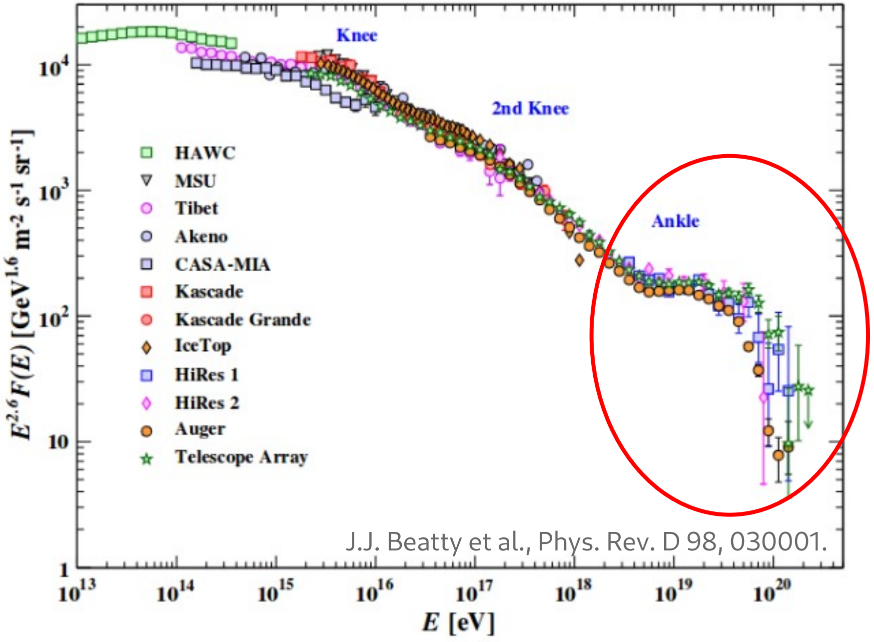
UHE Cosmic Rays and Air Showers

* CR spectrum : 11 decades of energy + 32 decades in flux

* CR + atmosphere –> Cascade of particles



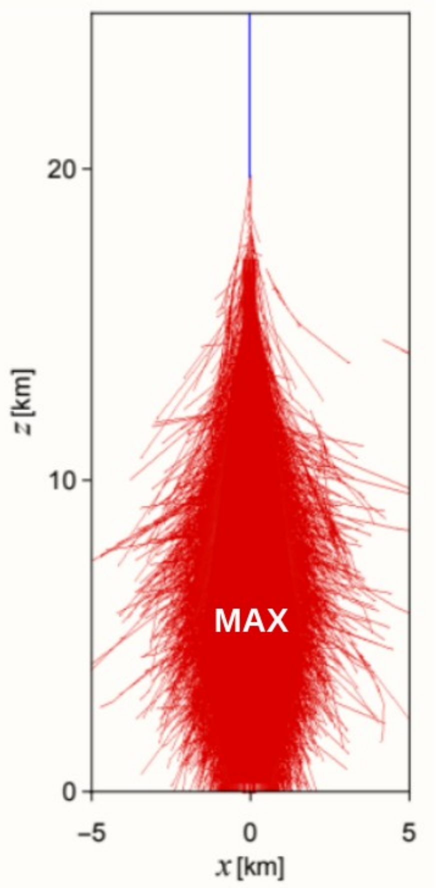
CR spectrum measured by ground detection experiments

At Ultra-High Energy :

* Flux of the order of 1 event /km²/yr
  ⇒ direct detection impossible

* Air showers particles reach the ground

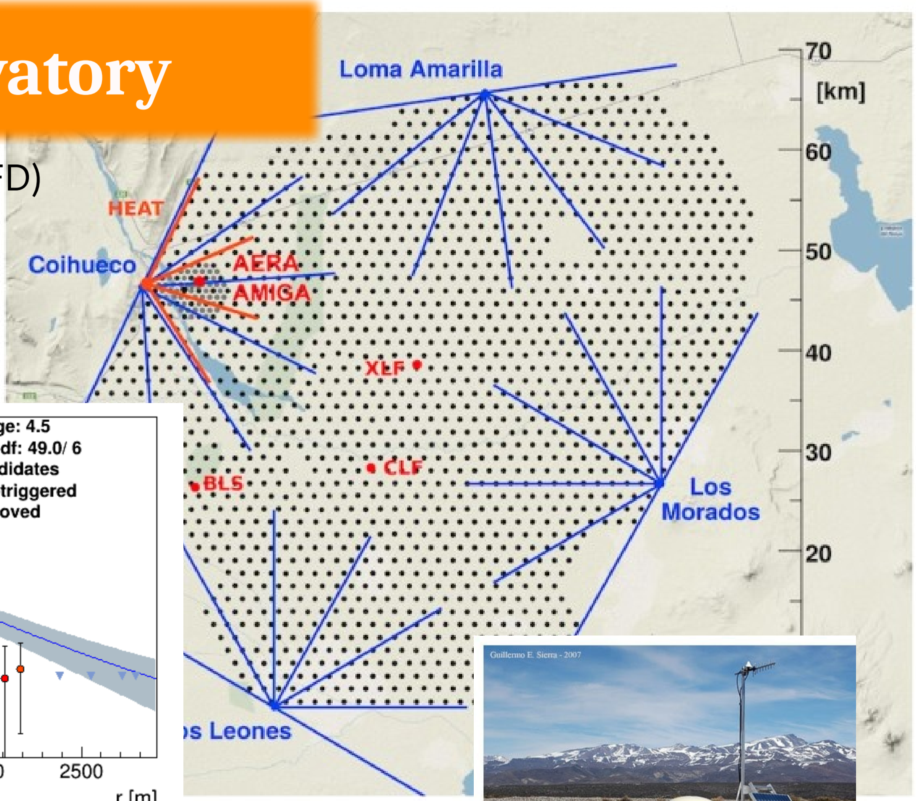
* Indirect detection of air showers



Two main components :
* muonic
* electromagnetic (e+/e-/photons)

Detection at the Pierre Auger Observatory

Hybrid detector ⇒ Surface Detector (SD) + Fluorescence Telescopes (FD)



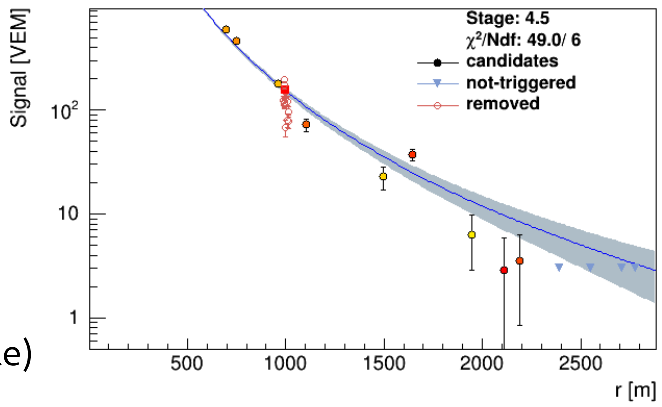
<u>Surface detector :</u> (100 % duty cycle)

* 1600 water cherenkov detectors (WCD) called stations

* triangular grid, spacing of 1.5 km

* spread over 3000 km²

⇒ lateral profile
+ direction and time information



<u>Fluorescence detector :</u> (14 % duty cycle)

* Detects the UV light emitted by excited nitrogen molecules

⇒ primary energy of the CR (calorimeter)
+ longitudinal profile of shower development

Interest of UHE photons

Origin of UHE photons :

1) During the production of UHECRs

* interaction of UHECRs near astrophysical sources ⇒ UHE photons
 ⇒ allows to point at these sources (multi-messenger astronomy)

* « top-down » models (SHDM,TD…) : most of them excluded by ULs

2) Along the propagation of UHECRs

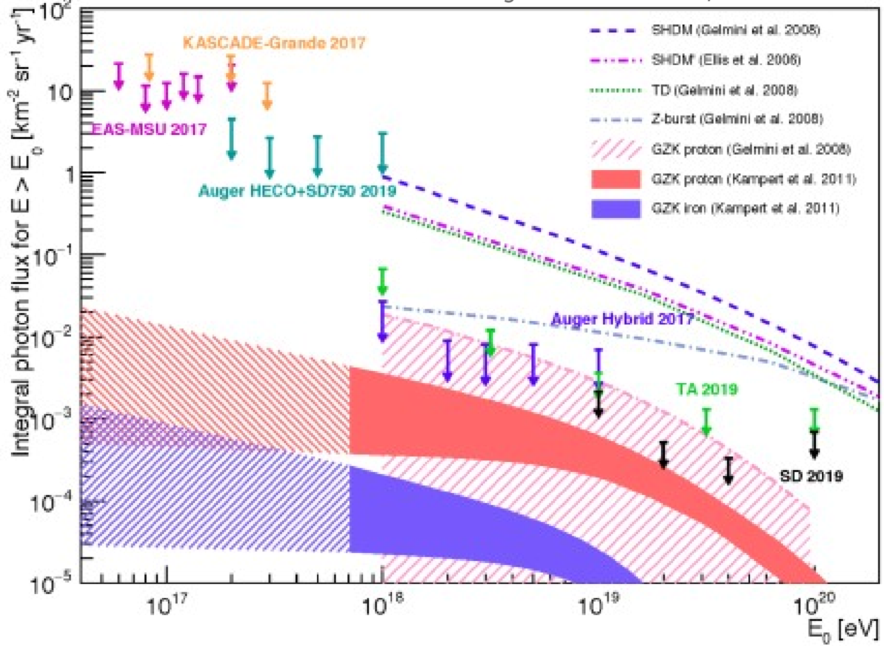
* GZK effect = interaction of UHECR – CMB photon

$$\gamma + p \rightarrow \Delta^+ \rightarrow \pi^0 + p$$

$$\gamma + p \rightarrow \Delta^+ \rightarrow \pi^+ + n$$

⇒ Flux suppression at $\sim 4.10^{19}$ eV
 (mass dependent)

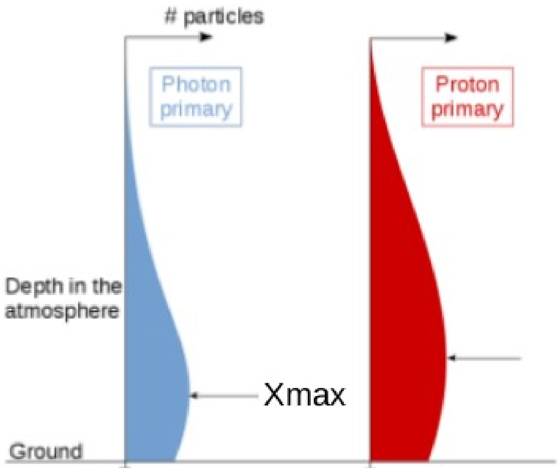
Auger Collaboration, ICRC 2019



Knowledge of the UHE photons flux
⇒ information on the sources + propagation of UHECRs

Identification of UHE photons

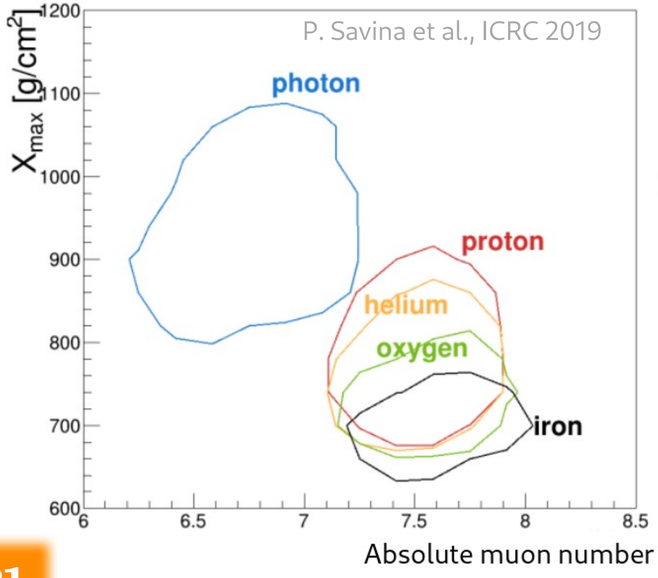
Based of the differences between photon-induced and nuclei-induced showers



1) late development for photons

* multiplicity of interactions

* larger Xmax [g/cm²] (maximum depth of development)



2) less muons in photon-induced showers

* properties of hadronic and electromagnetic interactions

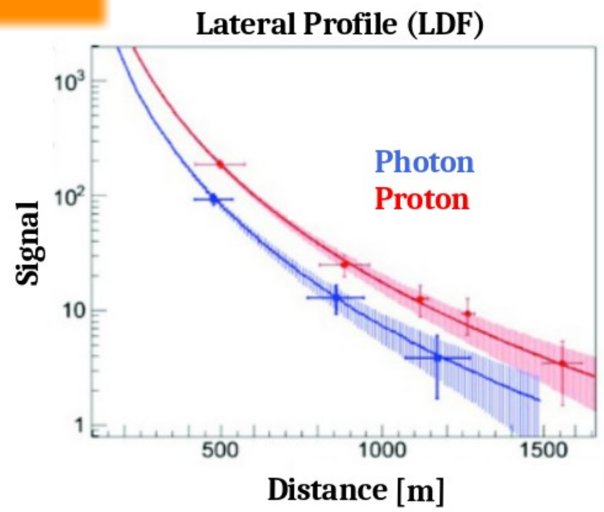
Identification of UHE photons

Based of the differences between photon-induced and nuclei-induced showers

⇒ steeper lateral profile

* large part of the energy goes in the EM component

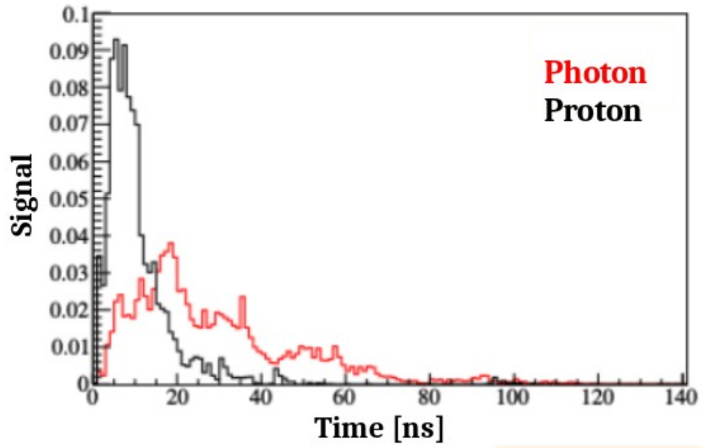
* lateral profile : steeper for the EM component (reinforced by large Xmax)



⇒ delay in the arrival times of the particles at ground for photons

* late development ⇒ larger delay in the arrival time of the particles

* EM component : undergoes more scattering
  ⇒ reach ground later



UHE photon search in the Auger Collaboration

Mass dependent observables ⇒ Discriminant Analysis + photon search selection cut

In this work : use of the SD only : no access to Xmax

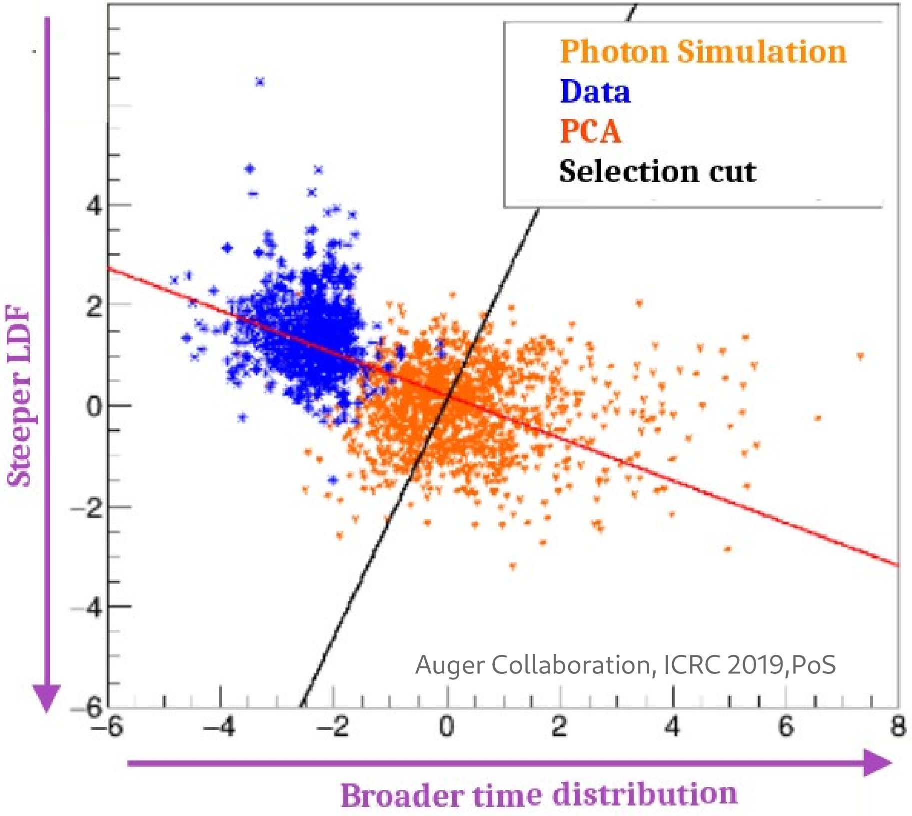
Current SD Analysis :

*Observables : LDF + Time Information

* Disavantages :

- background contamination
- restricted field of view (30°→60°)
- E = calibrated on data (LDF estimator)
  + converted into the photon energy using photon simulations
- observables = deviation of photons from data
  by looking at mass-dependent variables
  ⇒ no access to primary CR properties (Xmax,Nmu,E)

⇒ Use Universality to solve these problems
(reconstruct photon Energy and Xmax)



Concept of Air Shower Universality

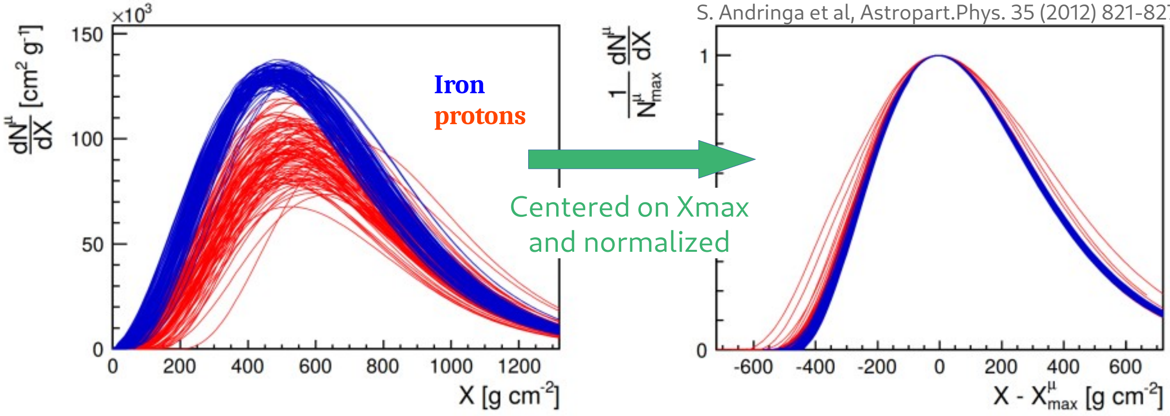
* Old concept from studies on EM cascades :
  The average properties of a shower can be described with E and the age only
  P. Lipari,Phys. Rev. D 79, 063001

* Concept extended to hadronic showers ⇒ $(Xmax, E, N_{\mu})$

Muon content : mass dependent

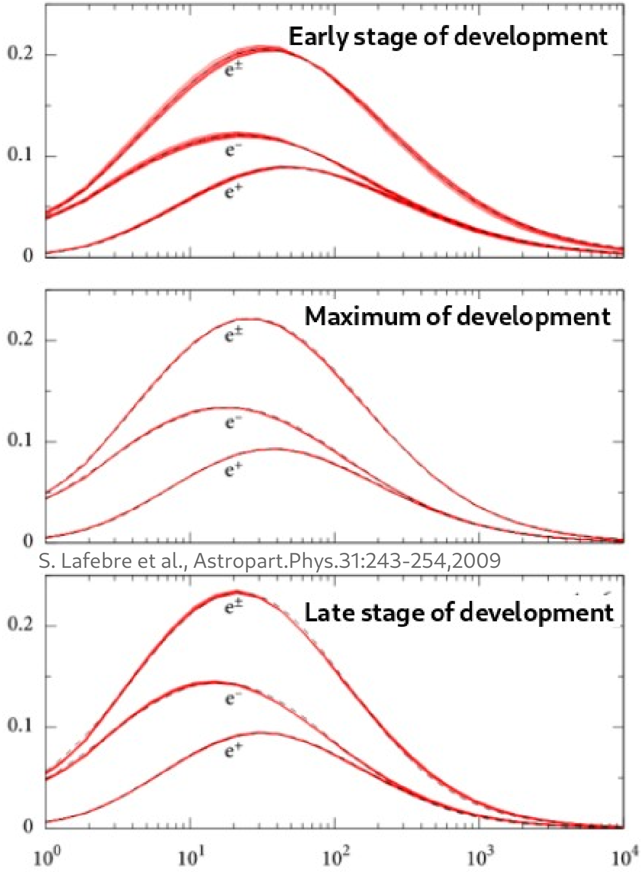
* universal features of secondary particles :
  - energy spectrum
  - angular and lateral distributions
  - longitudinal profile

S. Andringa et al, Astropart.Phys. 35 (2012) 821-827



Muons longitudinal profile

Normalized spectra of EM secondaries



S. Lafebre et al., Astropart.Phys.31:243-254,2009

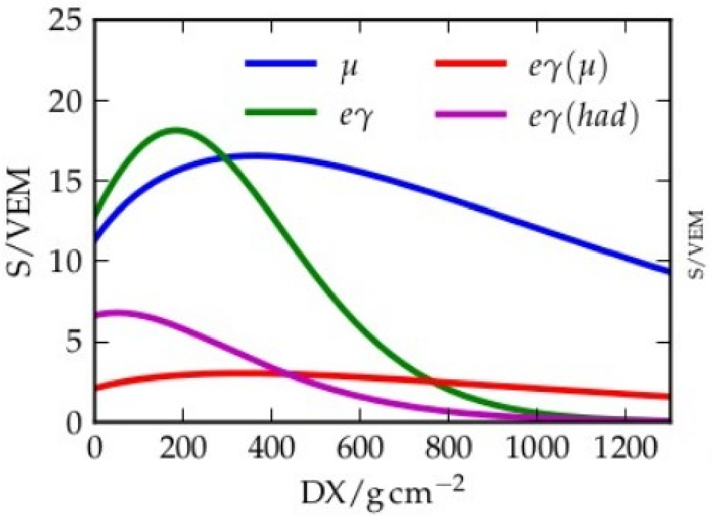
Universality Model

* **4 shower components** behaving universally : pure EM + muonic + EM from muon decay + EM from low energy hadrons

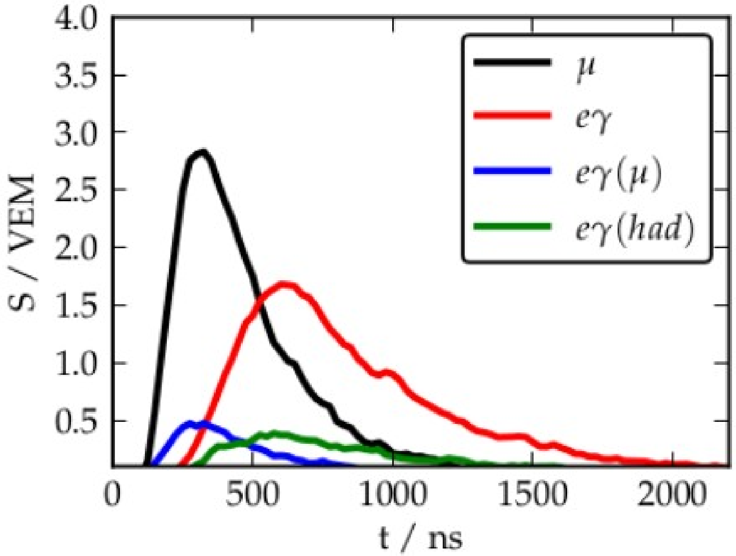
* The model describes the **shape and the normalization of the signal** for each component

Normalization : average signal in a WDC

$$S(r, \phi | E, X_{max}, N_{\mu}, \theta)$$



Shape : average time distribution of the signal



Reconstruction with Universality

Aim : use Universality to **reconstruct Xmax and the Energy** for photon showers, not directly accessible with the SD

Procedure : fix N_μ to its mean value that describes photon simulations

⇒ the reconstruction is **designed for photons** : Universality will follow the average behaviour of a photon.

E reconstruction
Xmax fixed to photons' mean
with signal model

→

Stations
Selection

→

E reconstruction
Xmax fixed to photons' mean
with signal model

→

Xmax reconstruction
with time model

First steps : * determine the mean N_μ

* validation of the Universality model

Working with : Photon simulations

Energy : $[10^{18.5}, 10^{20.5}]$ eV

The mean Nmu for photon showers

N_μ = the muon density at 1000m relative to QGSJetII-03 protons (hadronic interaction model)

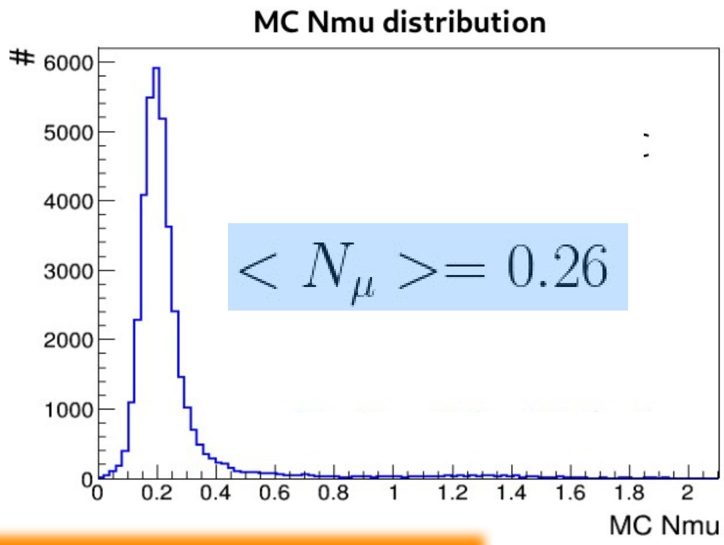
Computation of the individual N_μ of the shower :

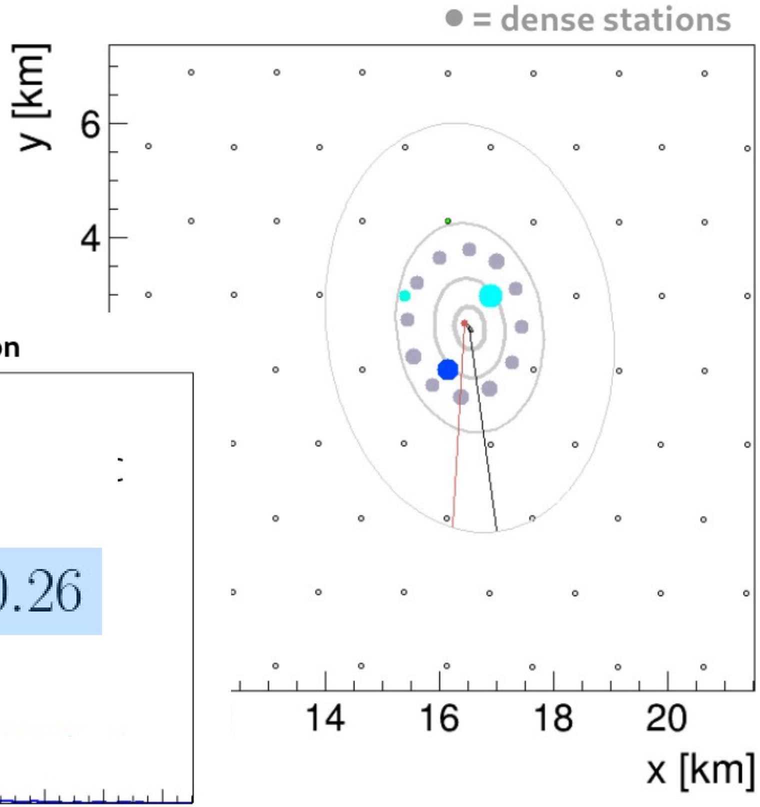
With the 12 dense stations + signal model
(Dense stations : ring of 12 simulated stations at 1000m from the axis)

Muonic signal in a dense station

$$N_\mu = \frac{1}{12}\sum_{i=1}^{12}\frac{S_\mu(i)}{S_{ref}(N_\mu = 1)}$$

Muonic signal predicted from Universality for QGSJetII-03 protons





Validation of the Universality Model

Verify if the model describes well the photon simulations

⇒ Dependence on the predicted signal

Predicted values = Function (MC parameters)

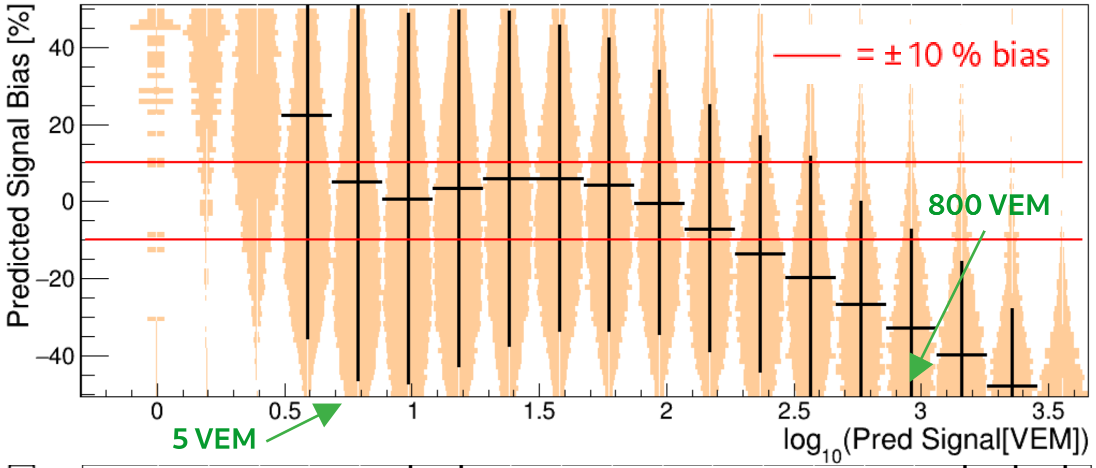
* For the signal model ⇒ look at the predicted signal

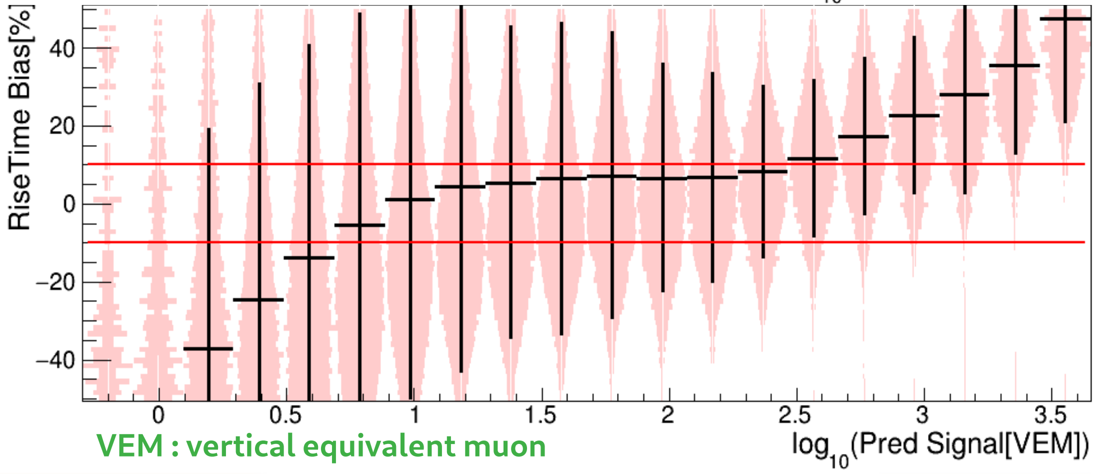
* For the time model ⇒ look at the RiseTime

* Strong bias for small and high predicted signals

⇒ cut at 5 VEM : removes trigger effects
⇒ cut at 800 VEM : removes saturation effects

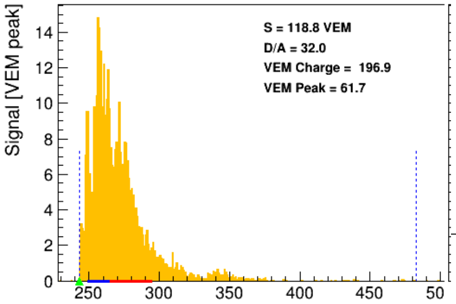
⇒ keep stations with predicted signals between 5 and 800 VEM for the reconstruction



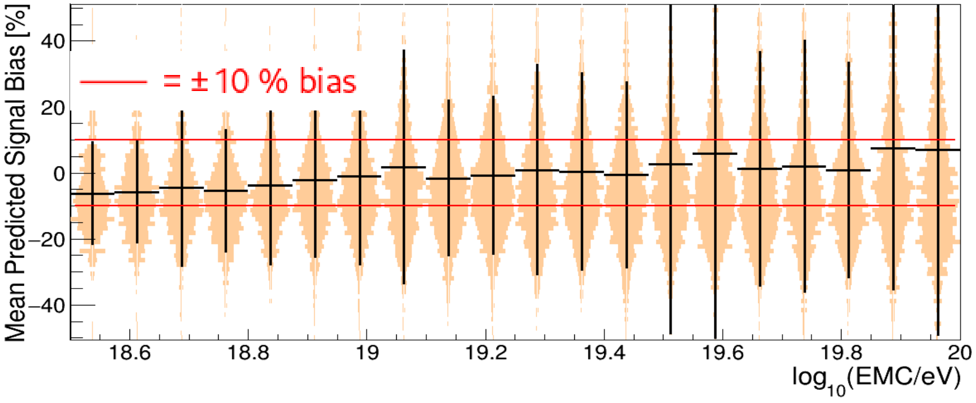


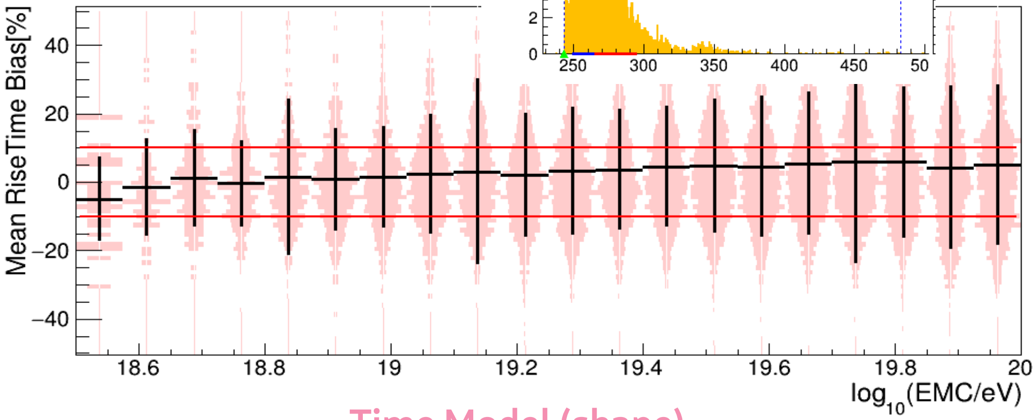
VEM : vertical equivalent muon

Validation of the Universality Model



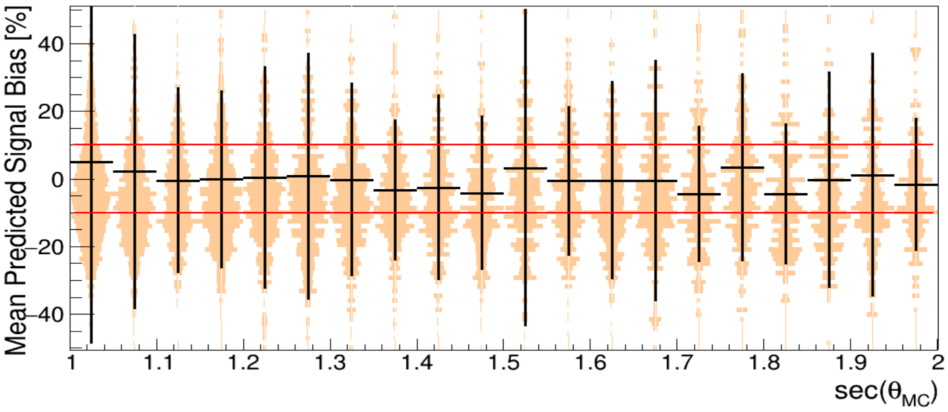
The model describes well the photons simulations : mean value within 10 % bias.

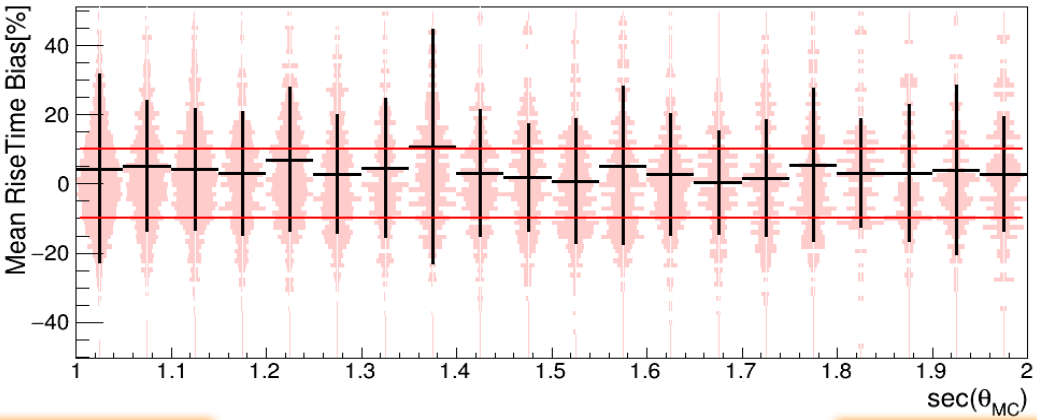




Signal Model (normalization)

Time Model (shape)





Ongoing and future works

* **Different reconstructions** are tested/investigated :

- example : originally the direction of the shower was reconstructed : fixed it to the standart Auger one

- exploring adding iterations until convergence of the reconstructed parameters

E reconstruction
Xmax fixed to photons' mean
with signal model → Stations Selection → E reconstruction
Xmax fixed to photons' mean
with signal model → Xmax reconstruction
with time model ⇒ $E_\gamma, Xmax_\gamma$

*Currently checking the **likelihood function** maximized for the Signal Model

Future :

* Reconstruct the whole photon/proton showers libraries :
compare results and discriminating power of the reconstructed parameters

* Could the analysis be extented to more vertical showers ? To lower energies ?
(current analysis : above 10 EeV)

Expected photon flux for the Milky Way

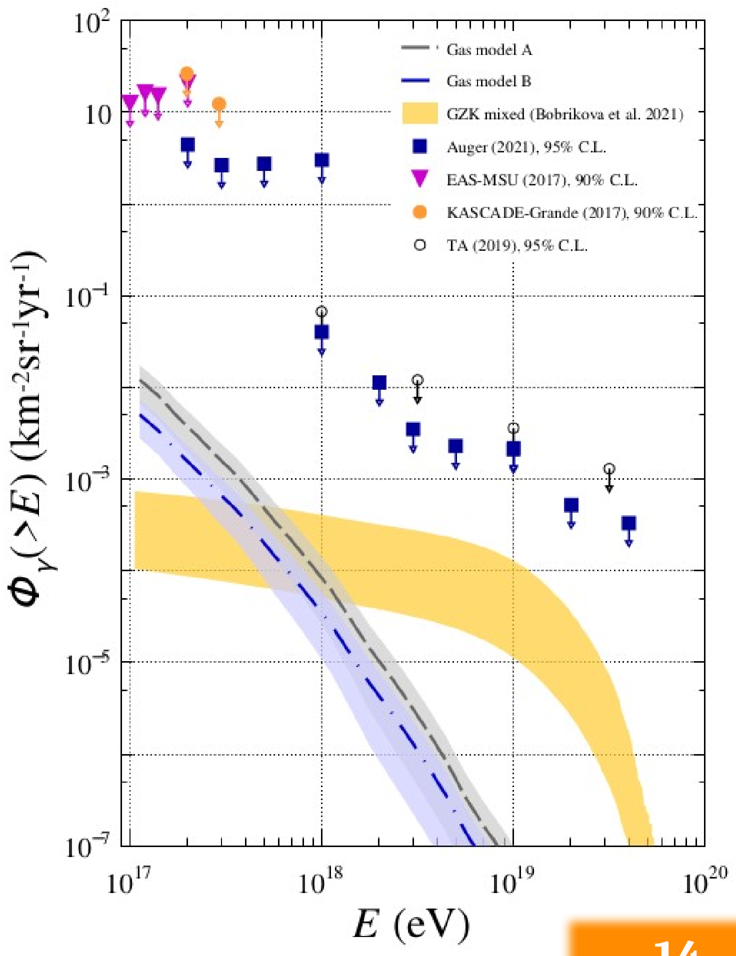
Diffuse flux of UHE photons from CR interactions in the disk of the Galaxy and implications for the search for decaying super-heavy dark matter

Z. Torrès et al.

Paper in preparation

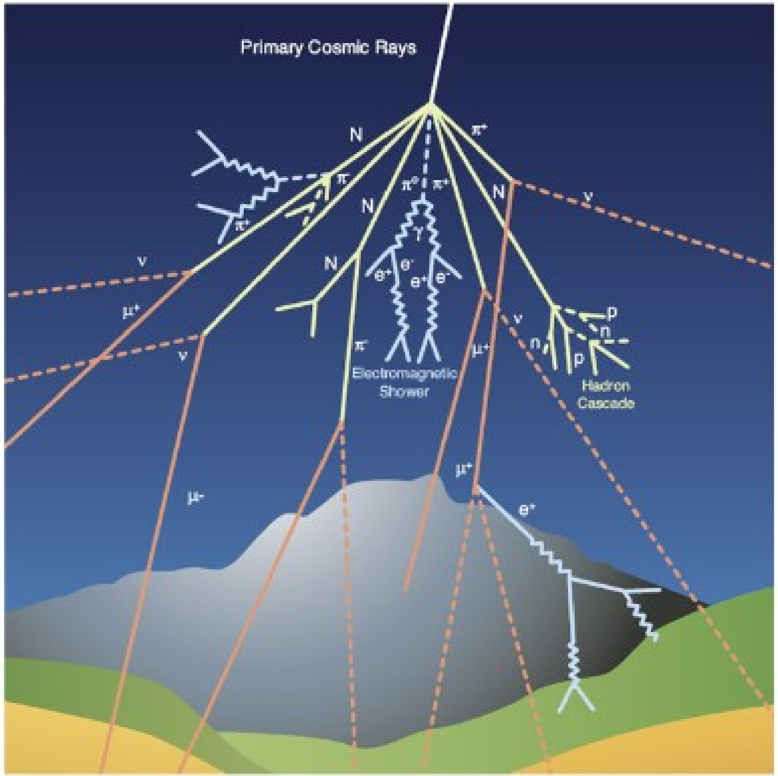
- local gas density
- CR flux
- cross section of (CR + gas)
- photon yield of the interaction

→ Expected UHE photon flux



Back up slides

Air showers



First interaction = mainly pions

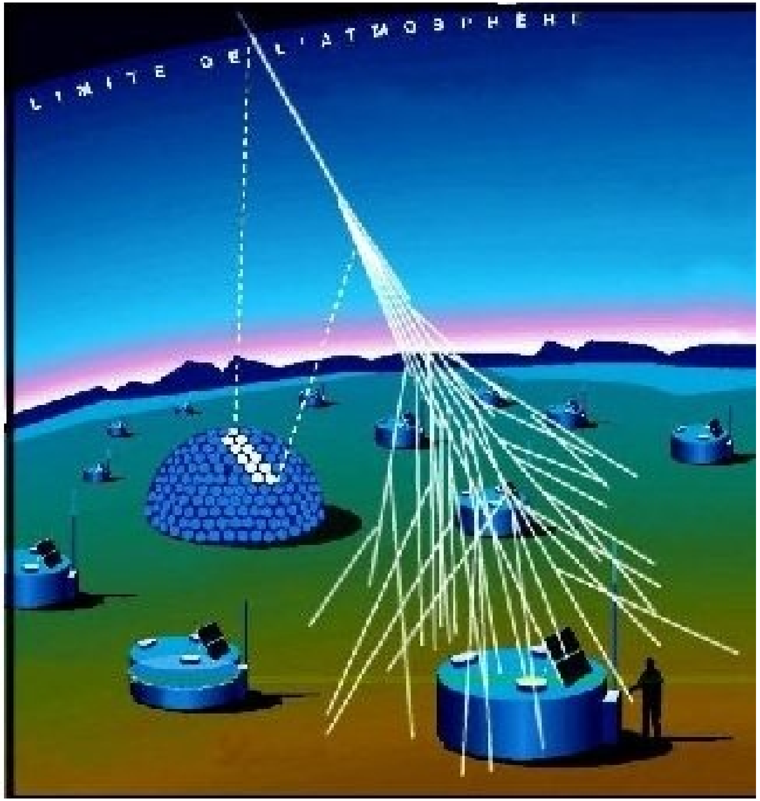
Charged pions ⇒ hadronic cascade : stops when they decay before interacting

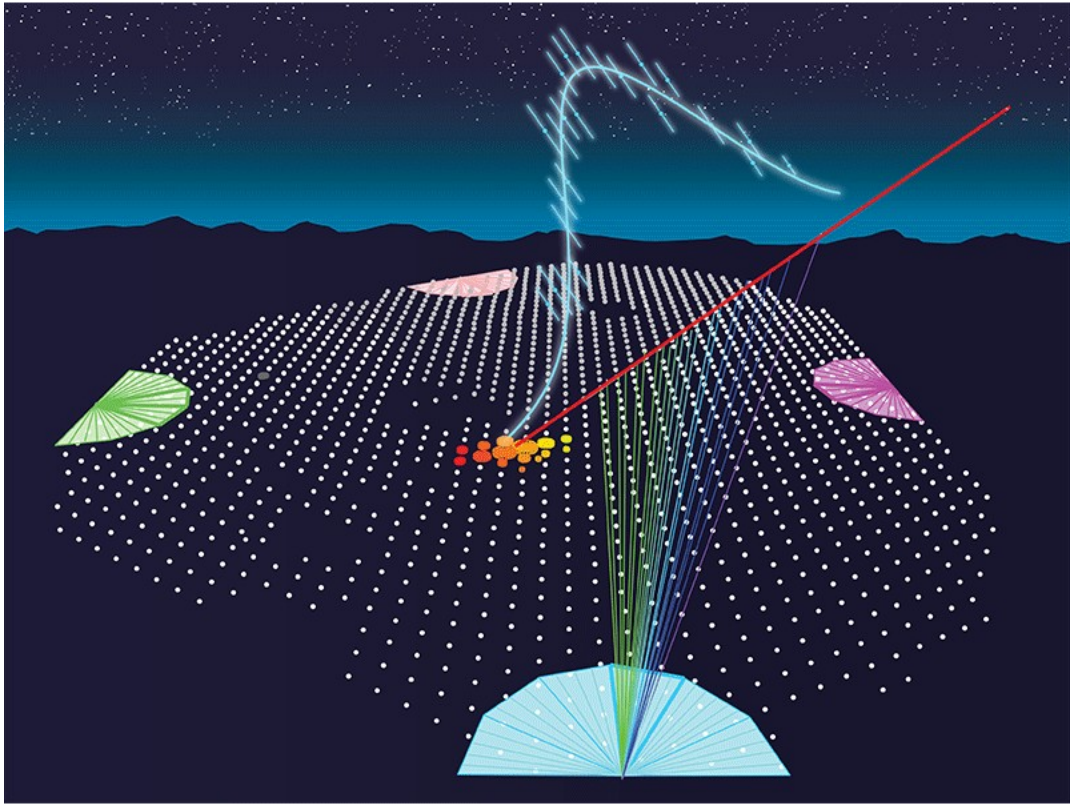
Neutral pions ⇒ decay into photons

EM cascade : e+/e- pair production (small ratio of muons) + Bremsstrahlung

Stops when the ionisation process is dominant

Fluorescence Telescopes





Top-down models

Z-burst :

UHE neutrino + cosmic neutrino background –> Z boson –> UHECRs

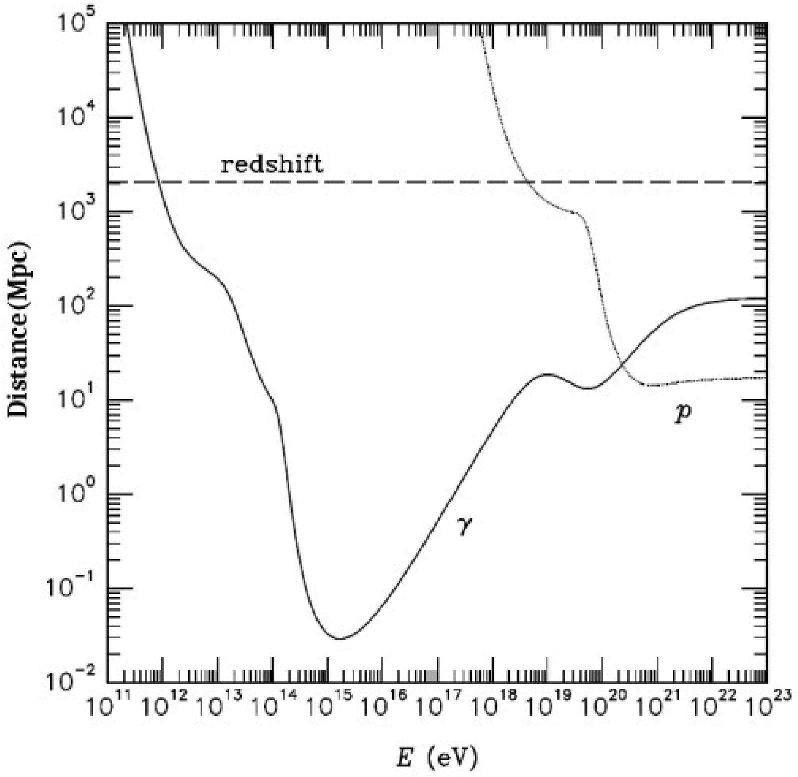
SHDM :

SHDM observed if long engough life time

Cosmological long lifetime only explained by non pertubative phenomena

SHDM metastable particles decay –>UHE CRs + photons

Photon mean free path



Identification of photons

Smaller number of muons :

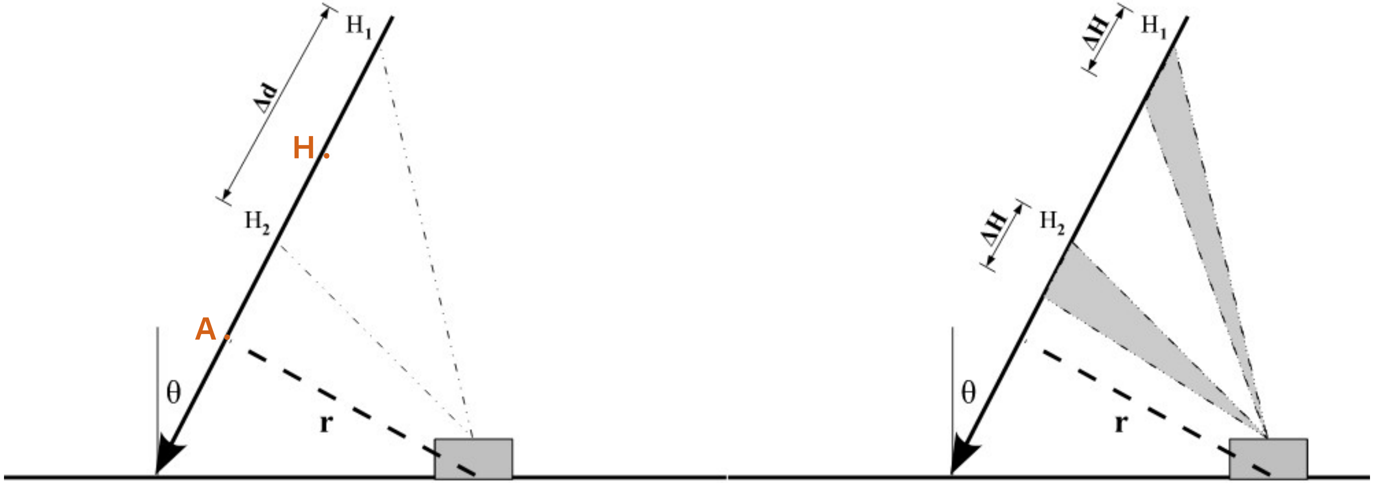
Mean path of photo-nuclear interaction and muon pair production is smaller than the radiation length

Arrival time distribution :

Particles produced at higher ernergies arrive sooner than the one produced closer to ground

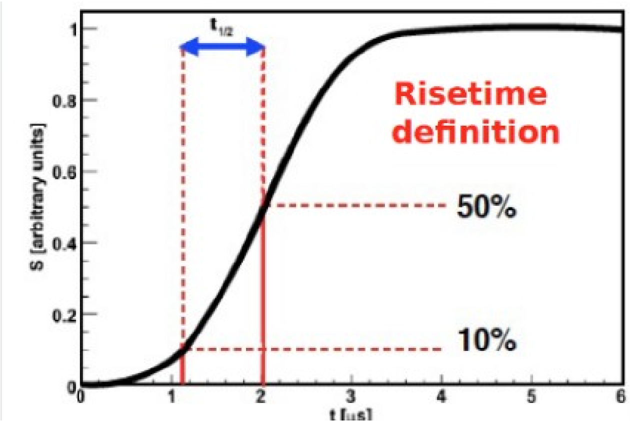
Delay t between a particle produced at A and H :

$$t = \frac{1}{c}\left(\sqrt{H^2 + r^2} - H\right) \propto \frac{r^2}{H}(r \ll H).$$

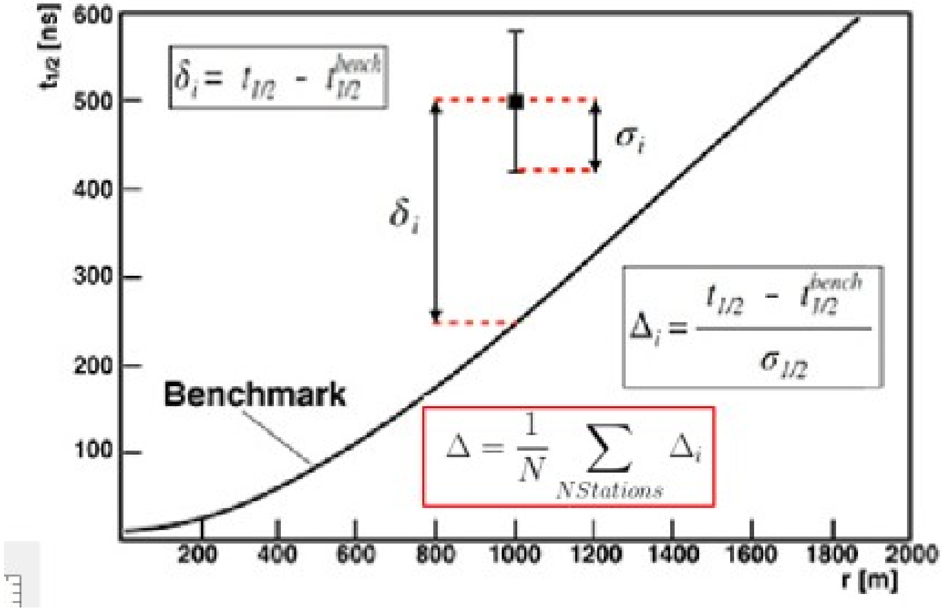


SD Analysis observables

Rise Time : Computed for each stations



Delta Rise Time : mean diviation of the rise time from a benchmark parametrized on data



RNKG :

-based on a LDF parametrized on data

-mean ratio : Signal/Signal LDF

- photons : steeper LDF / smaller footprint ⇒ less signal ⇒ smaller RNKG

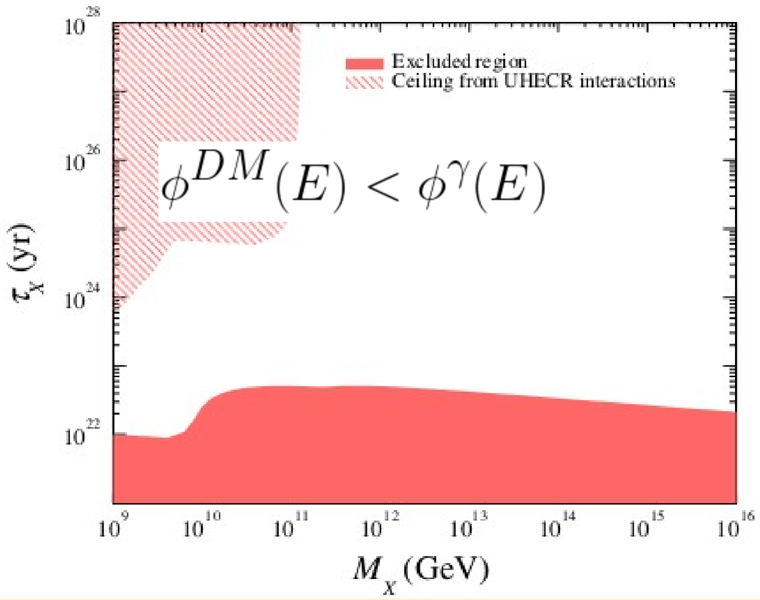
Expected photon flux for the Milky Way

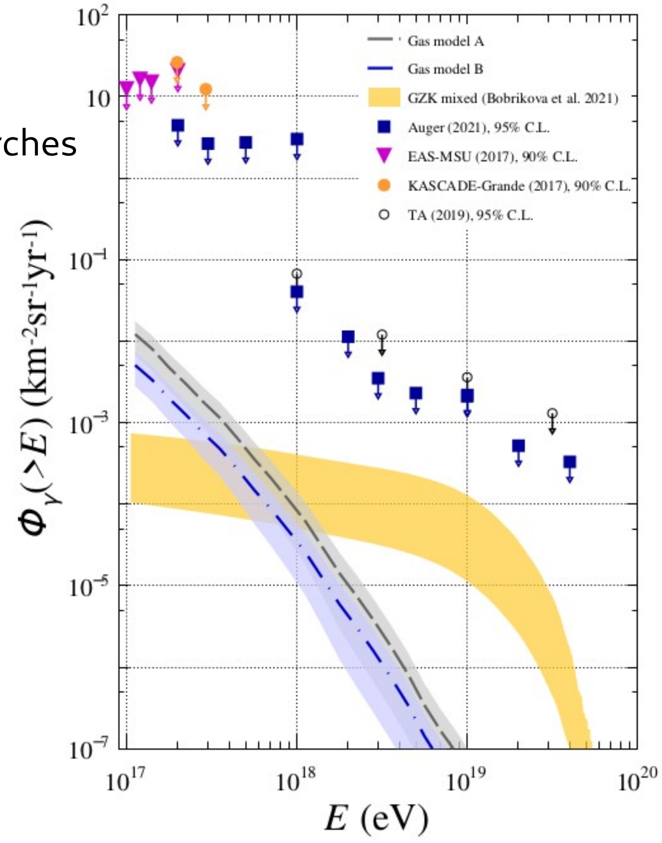
* it is the dominant cosmogenic flux between 0.1 EeV and 1 EeV

* out of reach with current observatories

* sets a floor below which other signals will be overwhelmed : relevant for SHDM searches

* sets a ceiling region for the lifetime of SHDM particles





Reconstruction Outputs