GRAND simulation scheme

What is and what should ever be

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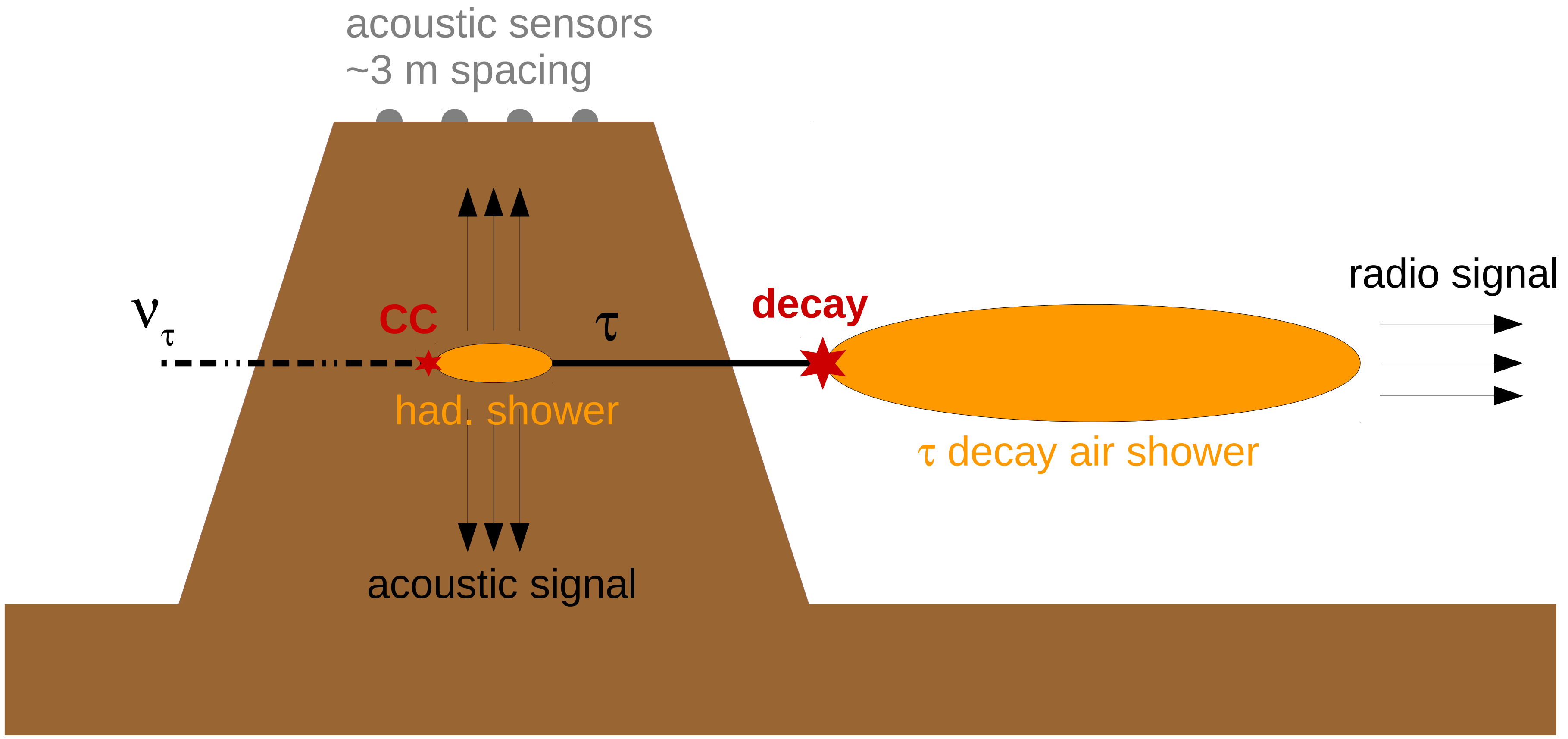
Early simulations

- Simulation work started in Jully 2008, **not for radio** detectors, but … for **acoustic** ones!
- Triggered by a question from F. Vannucci : « *would it be possible to reconstruct simultaneously the hadronic deposit of the* ν_τ *converting in the rock with acoustic sensors and the EM part from the in flight* τ *decay in air, with radio antennas?* »
- So I started some quick and dirty simulations using toy models. But, unfortunatelly this **work was lost** in Gare de Lyon, as my laptop was acquired by a gang of pickpockets.
- Nevertheless, **from pure geometric considerations**, it is quite obvious that such a **hybrid detection** would be **very ineficient**. Indeed, the acoustic signal of the in rock shower propagates orthogonaly to the shower axis, within 0.5 deg and ~10m extent, whereas the radio part is boosted forward along the axis.

Hybrid detection scheme



The GRAND simulation : key items

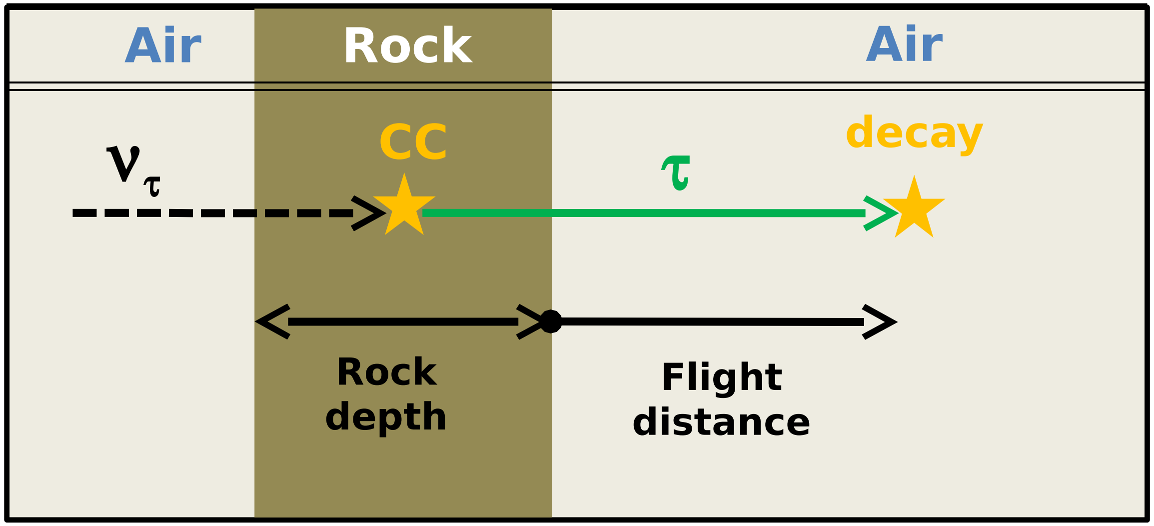
- **The neutrino simulation** : from the ν_τ to the τ decay products.
  - Custom 1D simulation scheme. Written in C++. External dependencies : Pythia6.4 and TAUOLA /FORTRAN, gnuplot (optional). Transverse transport *is neglected.*

- **The radio E-field computation** : from the τ decay products to the radio E-field.
  - Ideally, we would use existing referenced/tested/validated code(s). BUT ...
  - There is a trade to play between accuracy and CPU time / a minimalistic toy model based on the τ energy at decay and the full simulation scheme used for TREND: EVA conex+EVA.

- **The antenna response computation**: from the radio E-field to the antenna current/voltage response.
  - The TREND simulation scheme relies on a NEC2 implementation in C hacked in order to allow longitudinal polarization components.

The neutrino simulation illustrated with a toy experiment

- **The toy experiment** :
  - A ν_τ of energy E_ν incoming normal to a rectangular wall of Standard rock.
  - Look for τ's decaying in the air after the wall.

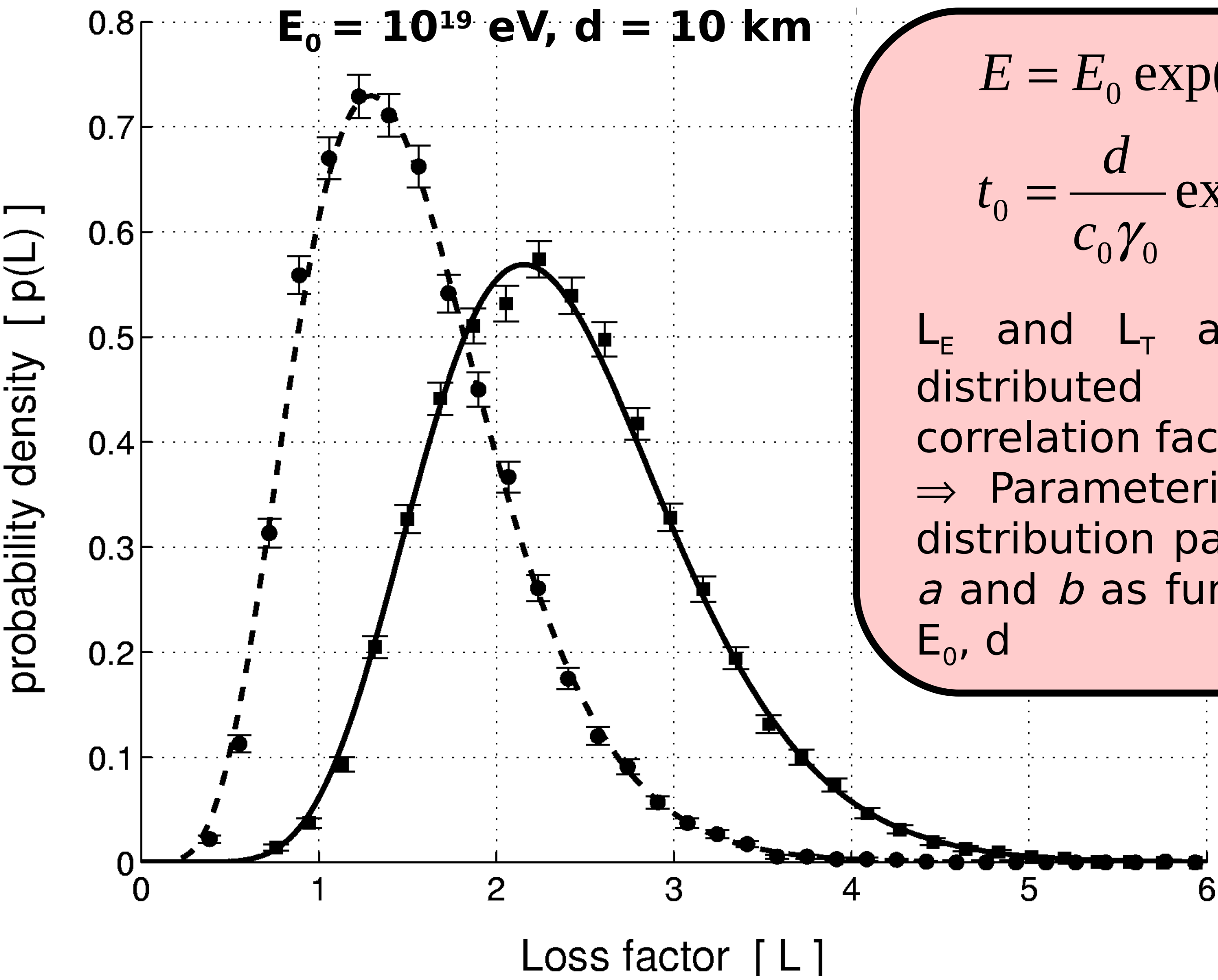


- **Compute** :
  - The **conversion efficiency** to τ leptons decaying in the air.
  - The **energy spectrum** of τ leptons at decay.
  - The **flight distance** in the air of the decaying τ leptons.

The neutrino simulation ingredients

- **ν Deep Inelastic Scattering (DIS)** in the rocks:
  - Integrated cross sections from Gandhi et al. (CTEQ4-DIS), but inelasticity randomised with Pythia CTEQ5d pdf.
  - The neutrino is tracked until a CC interaction occurs, its energy falls below a threshold (1 PeV typically) or it escapes the simulation volume.
- **τ propagation in rocks (energy loss+proper time)** :
  - **Detailed studies** of the τ energy loss in rocks **with GEANT4 simulations** for various τ initial energies. The τ photonuclear interactions, dominant energy loss process at UHE, have been coded in GEANT4 following Dutta et al.
  - **Parameterisation** of the τ energy loss and of the proper time spectrums according to the distance d (0-60 km) and the initial energy, E_0.
  - For the simulation, use an **hybrid Monte-Carlo scheme** for the τ propagation in rocks (energy loss, decay) according to the parameterisations derived from GEANT4.
- **τ decays** :
  - Simulated with Pythia+TAUOLA.
  - The decay daughters are logged to a file which would be served as input to the shower simulation. The daughter ν_τ is further simulated.

Parametrisation of τ energy loss and proper time in Standard rocks

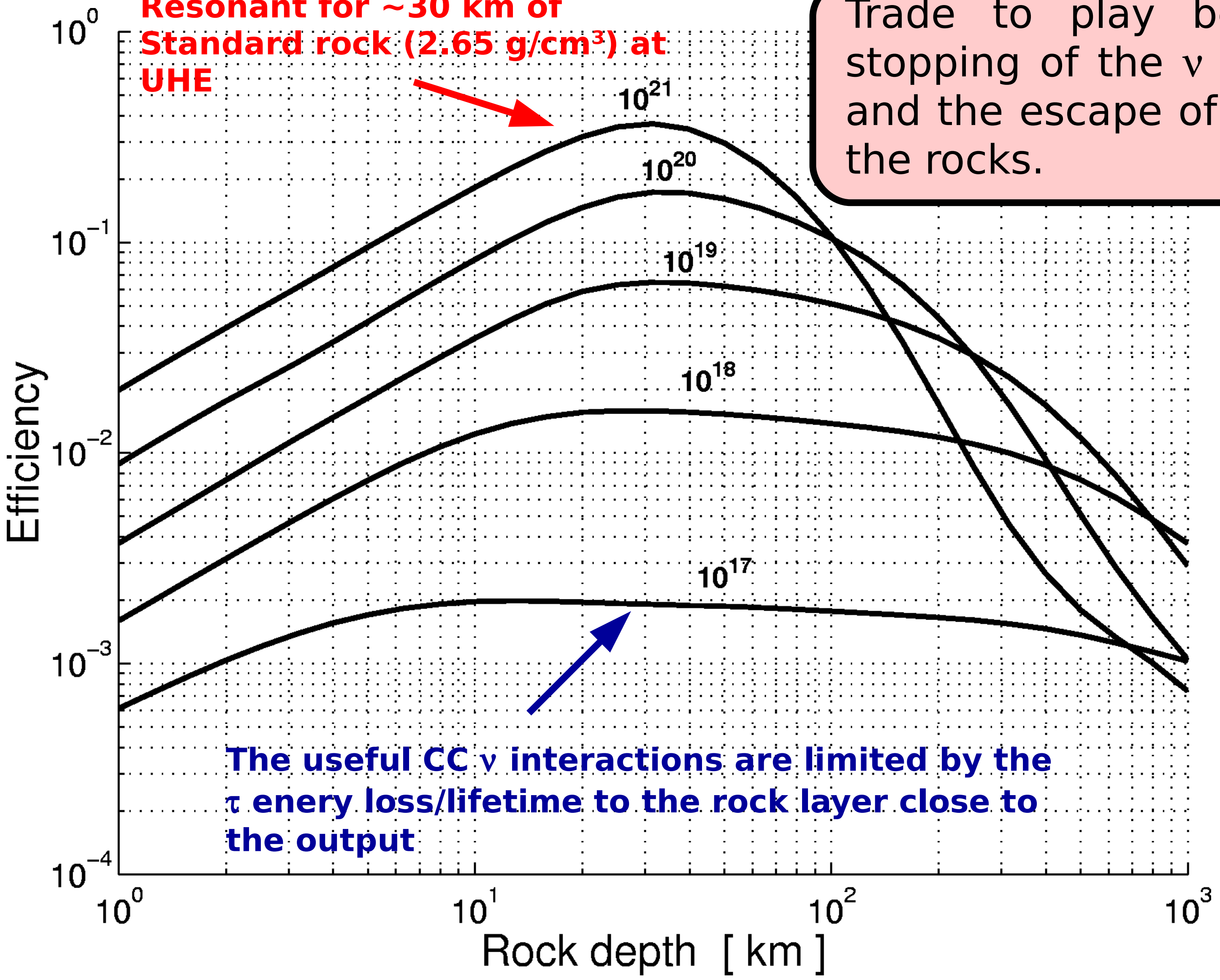


$$E = E_0 \exp(-L_E)$$

$$t_0 = \frac{d}{c_0 \gamma_0} \exp(L_T)$$

L_E and L_T are $\gamma(a,b)$ distributed with a correlation factor ~ 0.9 ⇒ Parameterise the γ distribution parameters *a* and *b* as functions of E_0, d

Result : conversion efficiency as rock depth

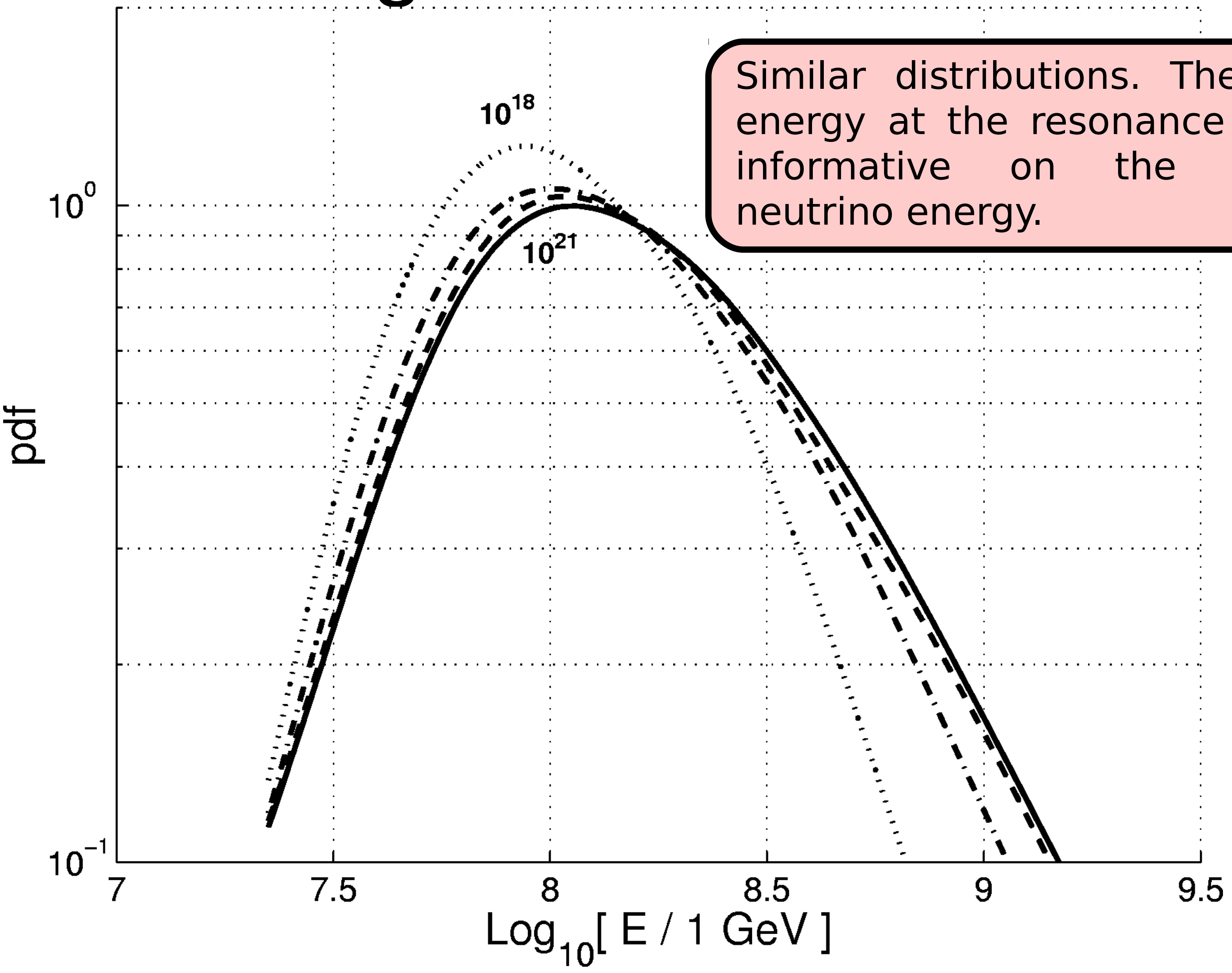


Resonant for ~30 km of Standard rock (2.65 g/cm³) at UHE

Trade to play between the stopping of the ν in the rocks and the escape of the τ out of the rocks.

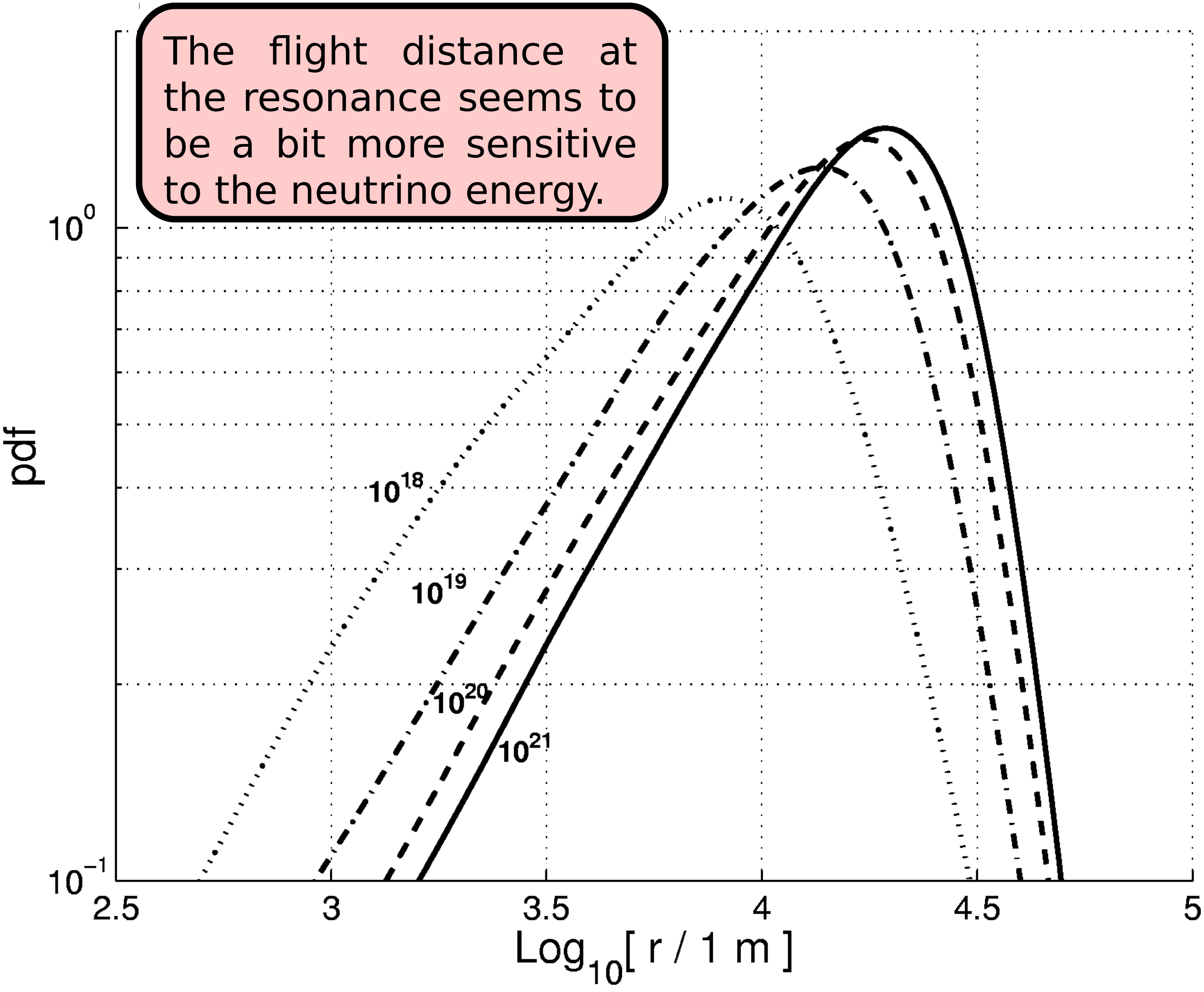
The useful CC ν interactions are limited by the τ enery loss/lifetime to the rock layer close to the output

Result : energy distribution at decay through 30 km of rocks



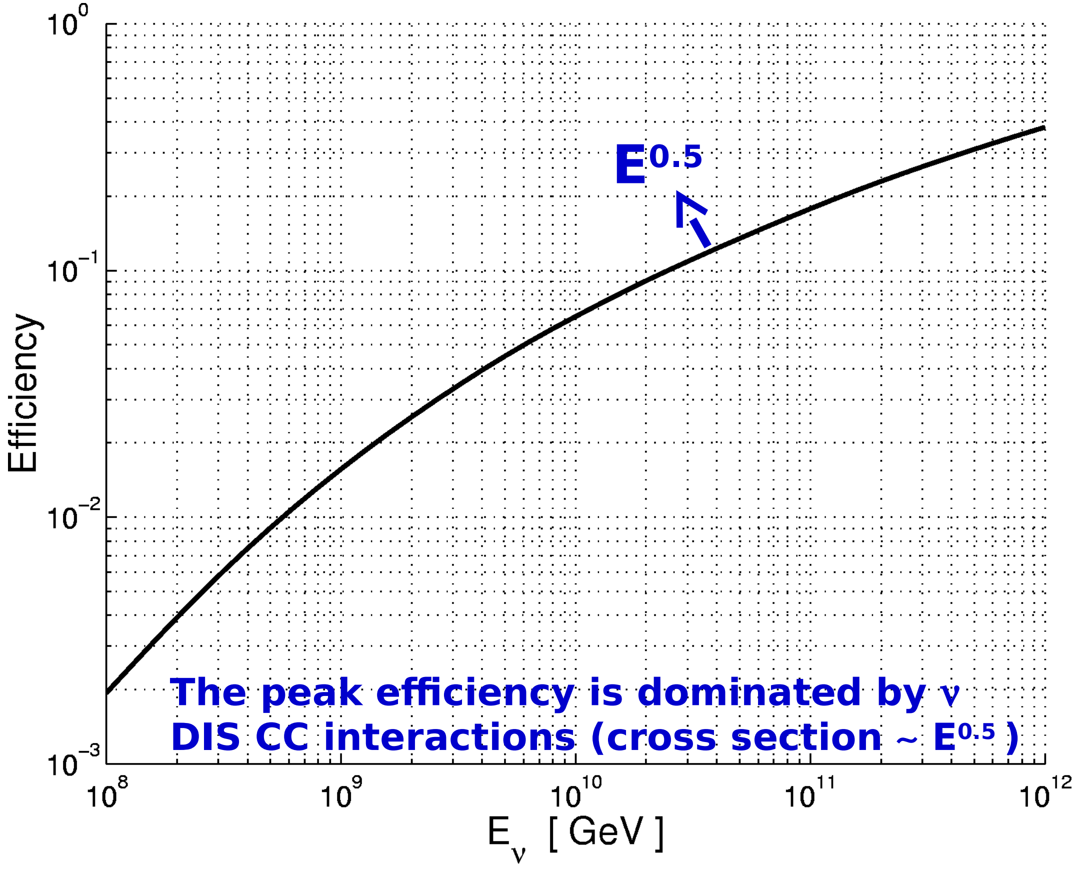
Similar distributions. The decay energy at the resonance is little informative on the primary neutrino energy.

Result : flight distance distribution through 30 km of rocks



The flight distance at the resonance seems to be a bit more sensitive to the neutrino energy.

Result : peak efficiency through 30 km of rocks as energy

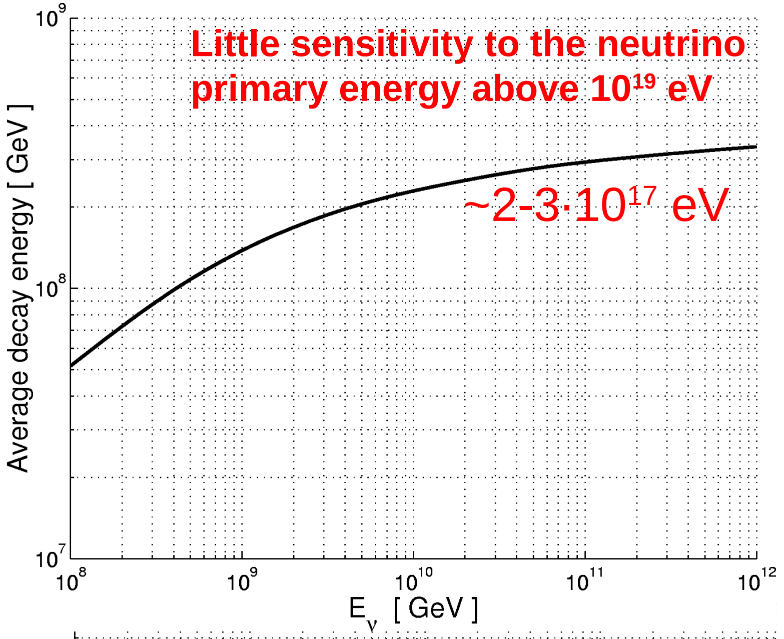


The peak efficiency is dominated by ν DIS CC interactions (cross section ~ $E^{0.5}$)

Asymptotic limit for a 1/E² flux, ϕ:

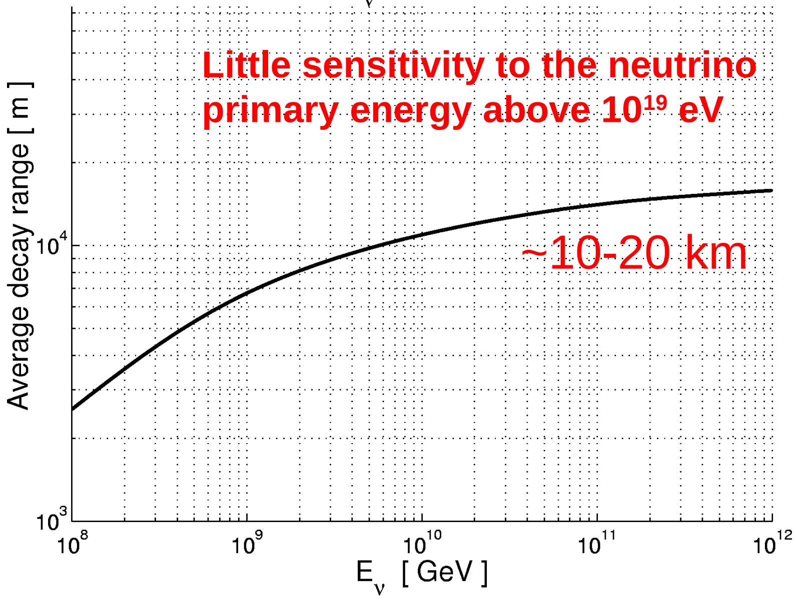
$$E^2\phi \le \frac{9.3\cdot 10^{-8}}{S\cdot\Omega\cdot T}\,\mathrm{GeV}\cdot\mathrm{cm}^{-2}\cdot\mathrm{sr}^{-1}\cdot\mathrm{s}^{-1}$$

with S in km², T in year, Ω in sr and E>100 PeV



Little sensitivity to the neutrino primary energy above 10^{19} eV

~2-3·10^{17} eV

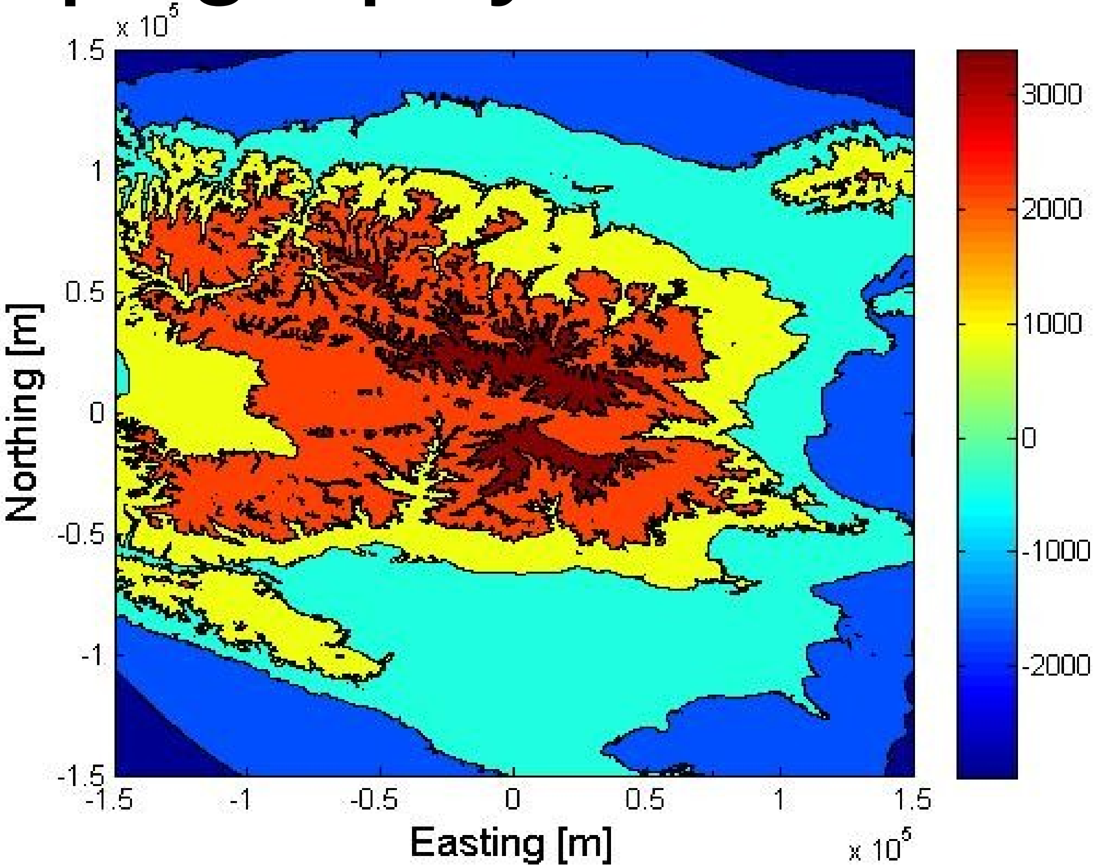


Little sensitivity to the neutrino primary energy above 10^{19} eV

~10-20 km

Extending the neutrino simulation with a topography

- Topographic data from the Shuttle Radar Topographic Missions (**SRTM**), downloaded from the NASA (free public access).
- We use a **200x200 km** wide area, centered on Ulastai, with a sample stepping of **100m**. The map is projected over a **curved Earth**.
- For upgoing neutrinos, the **Earth core** is rendered with the Preliminary Reference Earth Model (**PREM**).



- **Preselection** of in flight tau decay events based on *arguable* topological criteria:
  - There must be at least 1 antenna within a forward cone of 30 deg centered on the shower axis.
  - There must be at least 1 antenna in sight of the decay vertex, with no rocks on the line of sight.

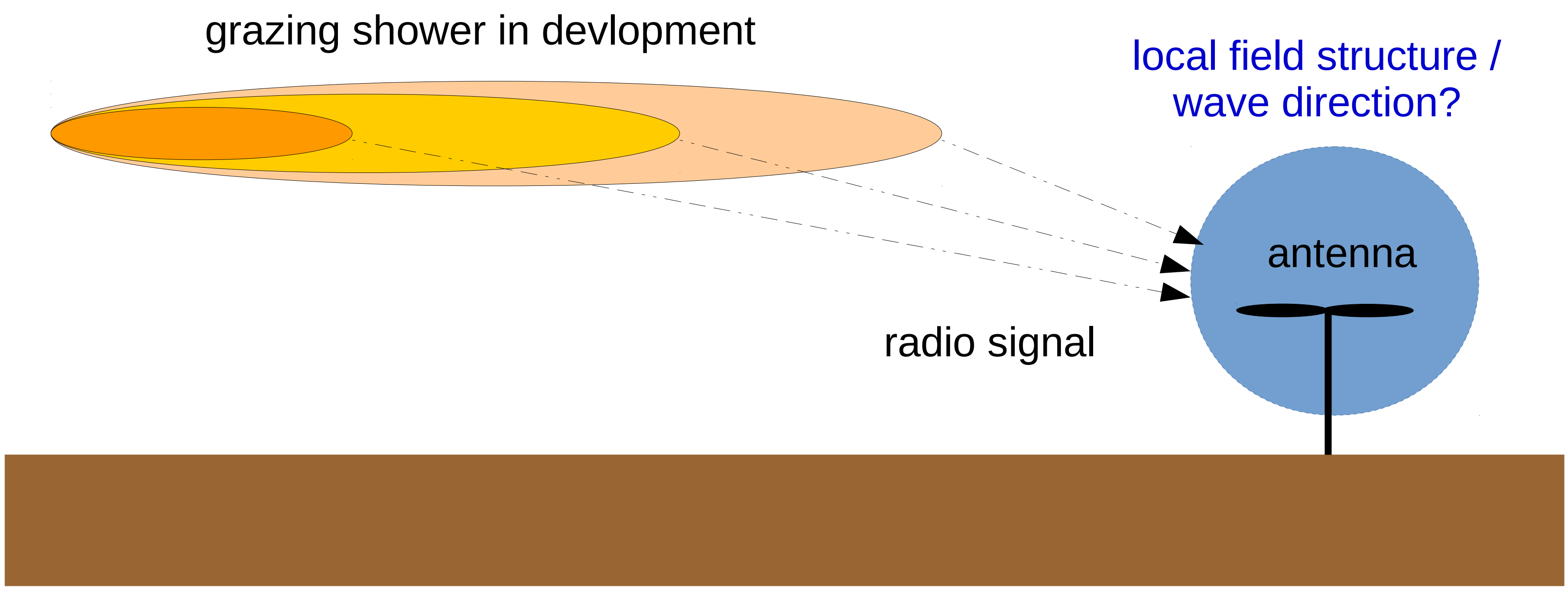
The shower and radio simulation(s)

- For TREND/cosmic ray radio signals we use the detailled **computation code EVA Conex+EVA**/FORTRAN. It does a **good job for our prototype array**, however, there are **several issues** for using it **for the neutrino simulation**:
  - **CPU time** would be prohibitive. It takes a few hours to compute a radio field for a single antenna, using a single core. **We currently use the france-asia GRID for TREND**. Simulating the 3x3 km wide prototype setup takes months …
  - We have **horizontal showers starting at ground level**, whereas some parts of the code were designed/hardcoded for downgoing atmospheric showers. A few **hacks have been introduced** to tackle this, but validation/debugging is still required.
  - The shower develops close to the ground. To what extent **can we factorize out ground boundary effects in the shower simulation/radio computation?** And what about hybrid events, that would split over air and rock. Do they matter at the end?
- **Three main strategies** foreseen:
  - Use a **toy model** based on the sole energy and direction of the τ at decay. **This is what has been done sofar**. Its easy, cheap, but … we don't have a valid estimate of how (in)accurate it can be?
  - Use a **detailled computation** scheme as for TREND, *à la* EVA Conex+EVA/FORTRAN. Get thousands of CPUs over a year to do the job.
  - Use a **simplified *1D* computation** where the lateral spread of the shower is factorised, *à la* conex 1D+MGMR. It captures the relevant features of the detailed computation at low frequencies (~100 MHz). However, it is not accurate for simulating the high frequency (>GHz) radio Cerenkov/refraction effects.
  - Other approximation/optimized computation schemes on the market?

The antenna response simulation

- The straightforward way for us would be to rely on the **ready to use TREND computation scheme**:
  - The antenna **frequency response** to plane waves is computed with **NEC2**.
  - We rely on a C implementation of NEC2 that was hacked in order to allow transverse polarization components.
  - The time voltage/current response is obtained by convolution/multiplication in the frequency domain, and summing up the polarisation components.
  - In addition, we can simulate various samplings, introduce minimum bias **measured background** at Ulastai, a real measured DAQ gain shapes, ect …
- But … **the receiving antennas are not in the far field of the shower source**. For example, which incoming wave direction should we consider?
  - Sofar we **approximate the wave direction by the direction from the antenna to the point of maximum of radio emission** on the shower axis. This should be OK for distant showers assuming that the radio emission is focused within a few degrees.
  - But what about grazing showers above the antennas? can we really **factorise the E-field computation and the antenna response?**

Grazing showers and antenna response



Conclusion and outlooks

- Some work already done :
  - ν_τ to τ decay simulation chain ~OK.
  - Antenna response, background, event selection could be taken from on field TREND data.
  - A CPU wise pratical and accurate computation scheme is rquired to finalise this work.
- Quite some work left to get the exact right numbers/uncertainties.
- To be continued ...