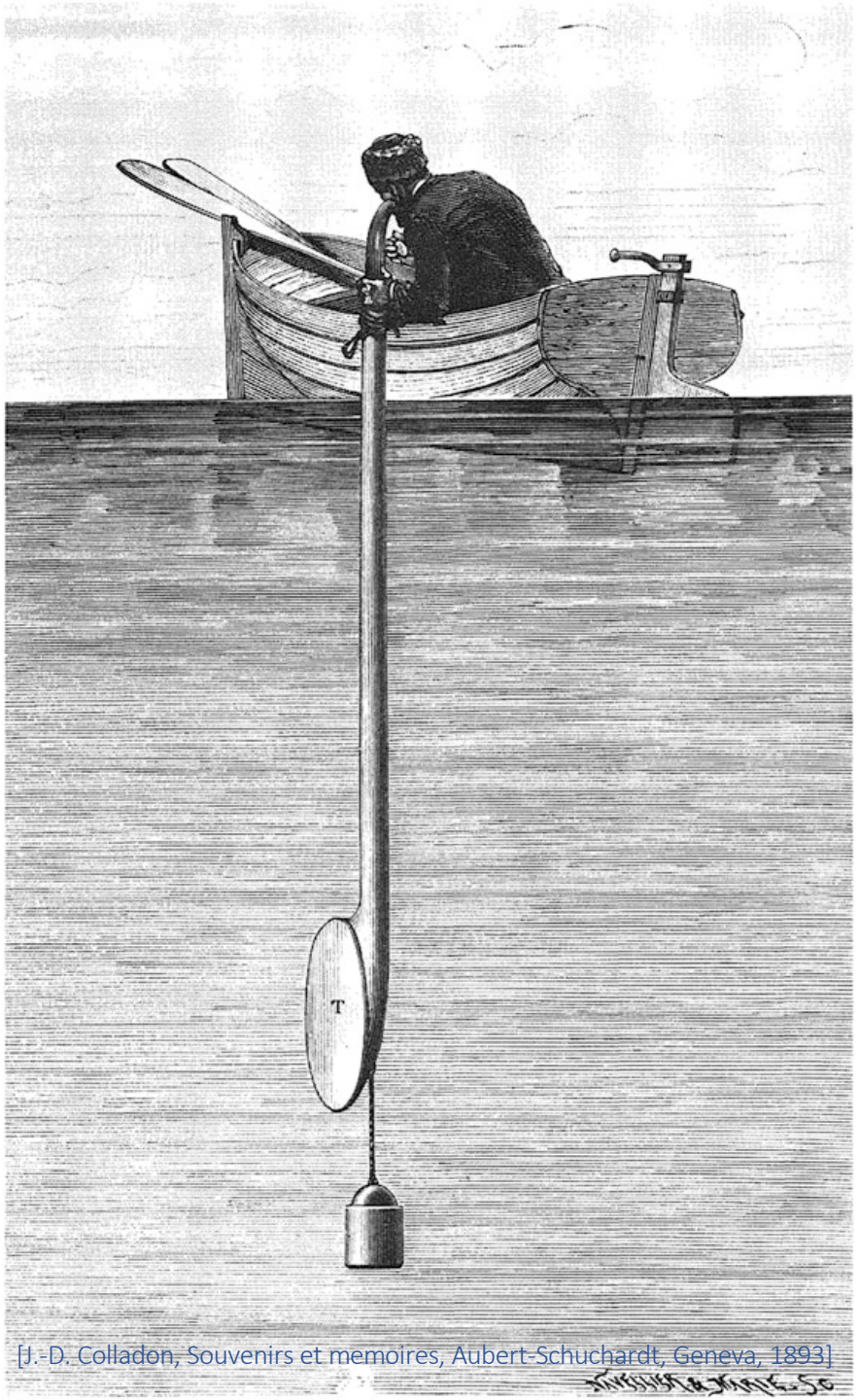


[J.-D. Colladon, Souvenirs et memoires, Aubert-Schuchardt, Geneva, 1893]

Acoustic signals from Ultra High Energy cosmic neutrinos

Ernst-Jan Buis, **Clara Gatius Oliver**
c.gatius@nikhef.nl

ARENA 2022

Find thesis at:
https://drive.google.com/file/d/1ZGaIkAOW8QeTwzDzMYBxxw7H6qFt8-RF/view?usp=sharing

1. MOTIVATION: Study of Ultra High Energy (UHE) cosmic neutrinos

WHY ?

$E > 10^{18}$ eV = 1 EeV

1) **Excellent messengers of the highest energy events in the Universe**

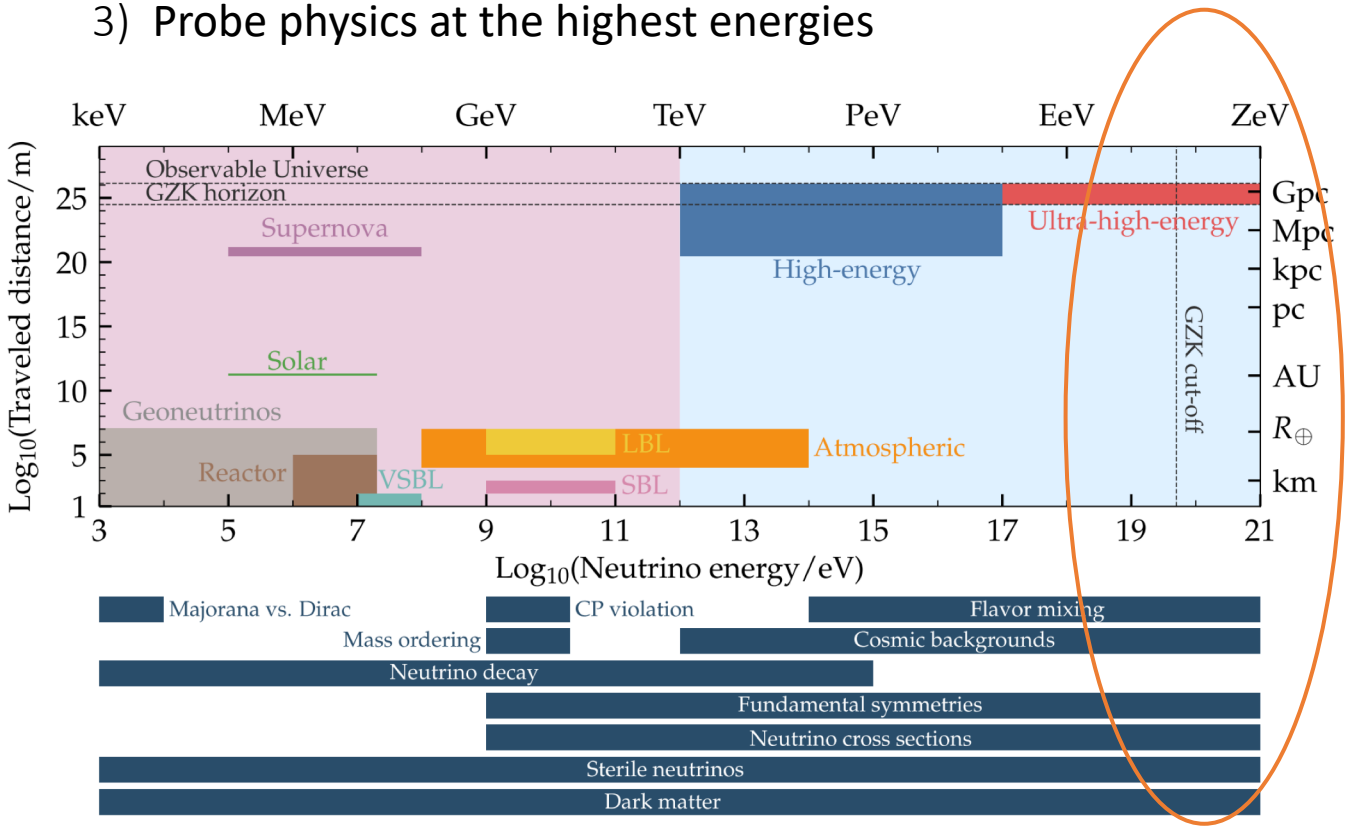
In contrast to other CRs, which lose energy when interacting with the cosmic microwave background (CMB)

2) **Cosmogenic neutrinos: from cosmic rays interactions with the CMB**

Valuable information of cosmic ray sources

Probe GZK cut-off

3) **Probe physics at the highest energies**



[Argüelles, C. A. *et al.,* Fundamental physics with high-energy cosmic neutrinos today and in the future. *Bull. Am. Astron. Soc.* 51, 185 (2019)]

What is the impact of the LPM effect on neutrino acoustic signals?

1) Simulation of neutrino induced showers

CORSIKA-IW (adaptation of CORSIKA-66)

2) Study of the energy deposition profiles in water

3) Computation and study of the acoustic signals

Implementation of the thermo-acoustic mechanism by the ACoRNE Collaboration

[Bolmont, J. CORSIKA-IW: a Modifed Version of CORSIKA for Cascade Simulations in Ice or Water. 1–20 (2008)]
[Bevan, S. *et al.* Simulation of ultra high energy neutrino induced showers in ice and water. *Astropart. Phys.* 28, 366–379 (2007)]

Landau-Pomeranchuk-Migdal (LPM) effect

Suppression of the high energy electromagnetic cross-sections (Bremsstrahlung and pair production) at high densities or energies.

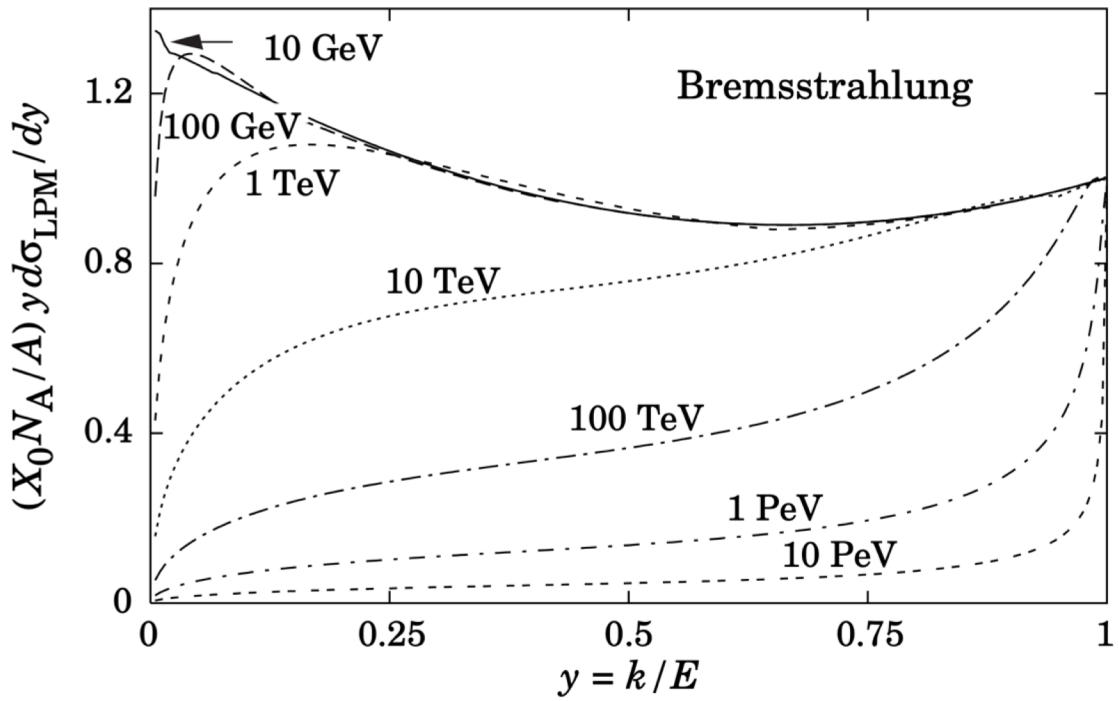
$$E_{LPM} = 7.7 \frac{TeV}{cm} \rho X_0 \sim 3 \cdot 10^5 \text{ GeV}$$ (in water)

ρ = medium density, X_0 = radiation length

Room for other interactions to happen:

→ Photonuclear and electronuclear interactions

Normalised cross-sections in lead



[Klein, S. Suppression of bremsstrahlung and pair production due to environmental factors. *Rev. Mod. Phys.* 71, 1501–1538 (1999)]
[Zyla, P. A. *& et al*. Particle Data Group. *to be Publ. Prog. Theor. Exp. Phys.* 083C01, (2020)]
[Landau, L. D. & Pomeranchuk, I. J. The limits of applicability of the theory of bremsstrahlung by electrons and of the creation of pairs at large energies. *Dokl. Akad. Nauk SSSR* 92, (1953)]
[Landau, L. D. & Pomeranchuk, I. J. Electron- cascade processes at ultra-high energies. *Dokl. Akad. Nauk SSSR* 92, (1953)]
[Migdal, A. B. Bremsstrahlung and pair production in condensed media at high energies. *Phys. Rev.* 103, 1811–1820 (1956)]

Simulated showers

- **Hadronic showers:** proton primary, average profile from 100 showers, energies $10^9 - 10^{13}$ GeV
- **Electromagnetic showers:** e^- primary, individual shower profiles, energies $10^9 - 10^{13}$ GeV

CORSIKA parameters

Hadronic models

QGSJETII-03, GHEISHA 2002d

Energy deposition binning

- Longitudinal slices: $20\ g/cm^2$

  $L_{total} = 2 \cdot 10^4$ g/cm^2 ~ 200 m (hadronic)
  $L_{total} = 3.748 \cdot 10^4$ g/cm^2 ~ 375 m (e.m.)

- Annular cylinders:

$$1.025\ g/cm^2 \text{ for } r \in (0, 10.25)\ g/cm^2$$
$$10\ g/cm^2 \text{ for } r \in (10.25, 112.75)\ g/cm^2$$

Energy cuts

Shower energy (GeV)	$E_{cut}^{hadrons}$ (GeV)	E_{cut}^{μ} (GeV)	$E_{cut}^{e^{\pm}}$ (GeV)	E_{cut}^{γ} (GeV)
$\leq 10^{11}$	0.05	0.05	0.001	0.001
$> 10^{11}$	0.05	0.05	0.1	0.1

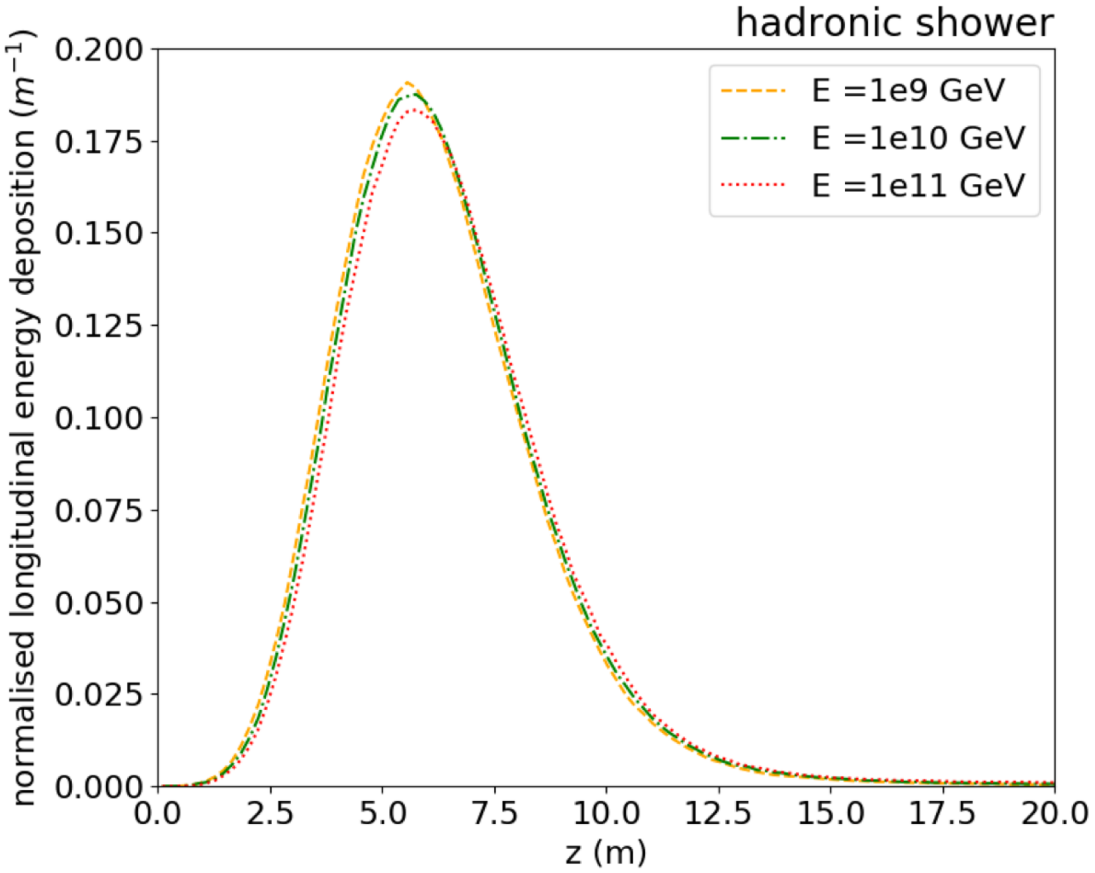
Table B.1: Energy cuts

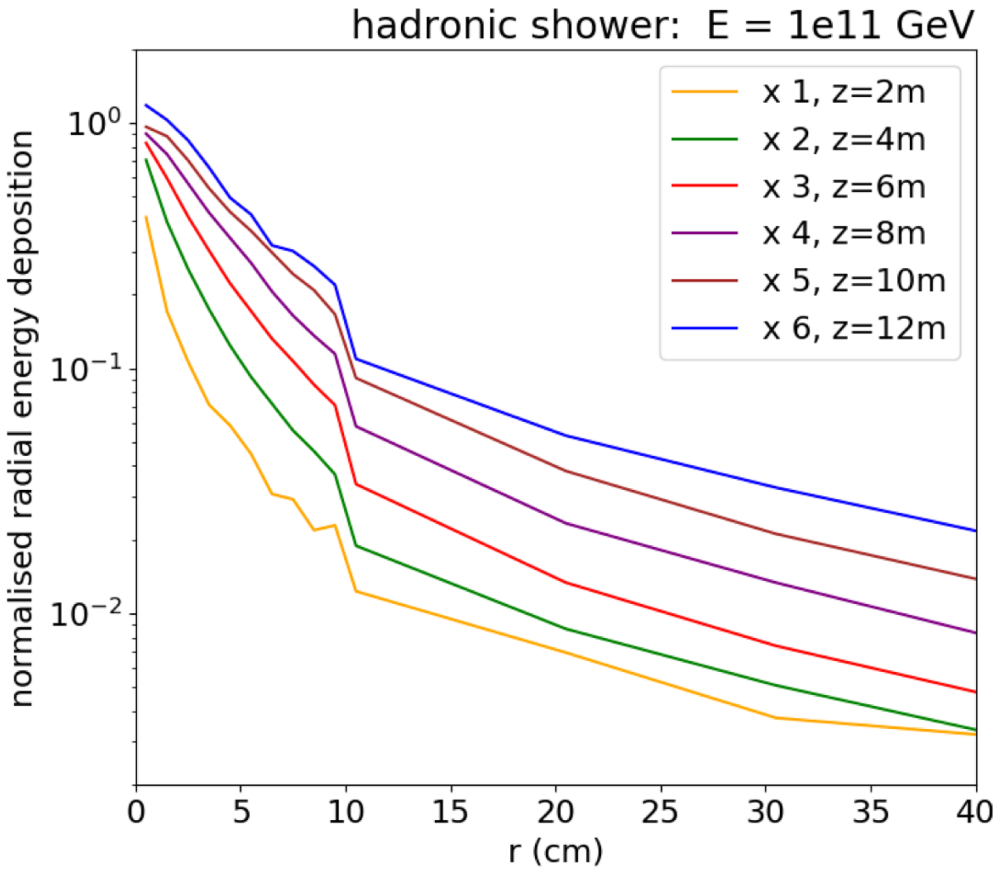
Thinning

THIN	$\epsilon_{th_{hadr}} = 10^{-4}$	$W_{max} = 10^{-4} E_0$
THINEM	THINRAT $= \frac{5 \cdot 10^6}{E_0} \frac{1}{\epsilon_{th_{hadr}}}$	WEITRAT $= 1$

Table B.2: Thinning parameters, where E_0 is the primary energy of the shower. For $E_0 < 10^{11}$, THINRAT = 1.

Energy deposition profiles (average of 100 shower profiles)



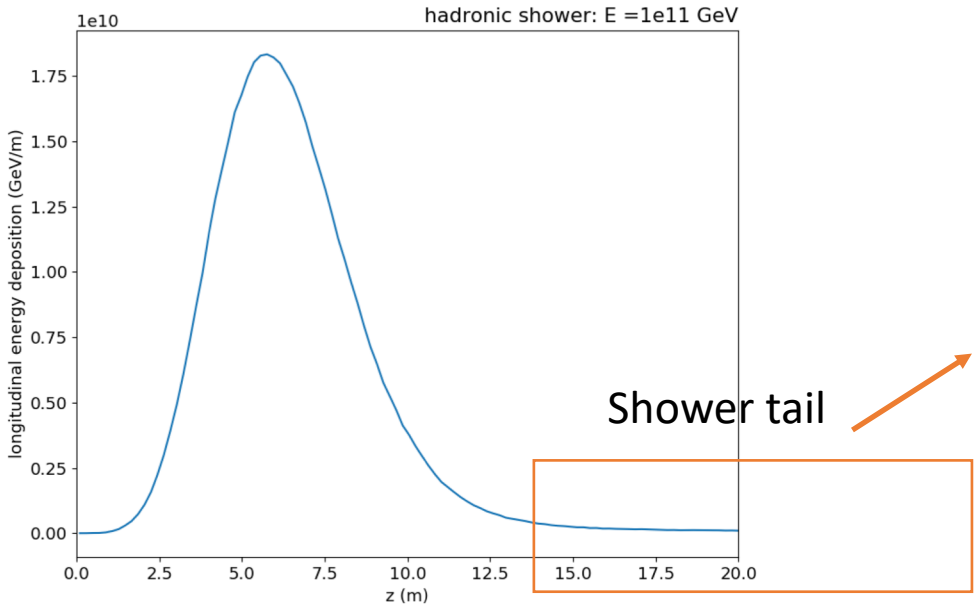


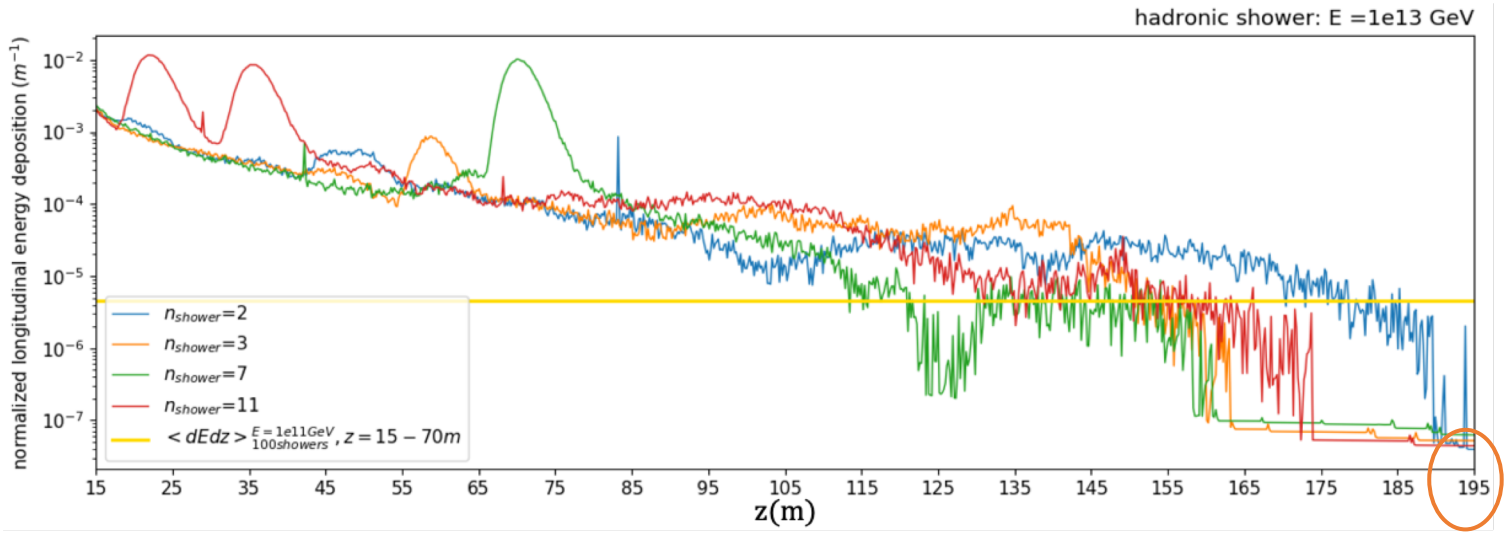
- Small shower to shower fluctuations
- Not dependent on shower energy

} **Minor impact LPM effect**

Energy deposition profiles

However, if we look at the shower tail…

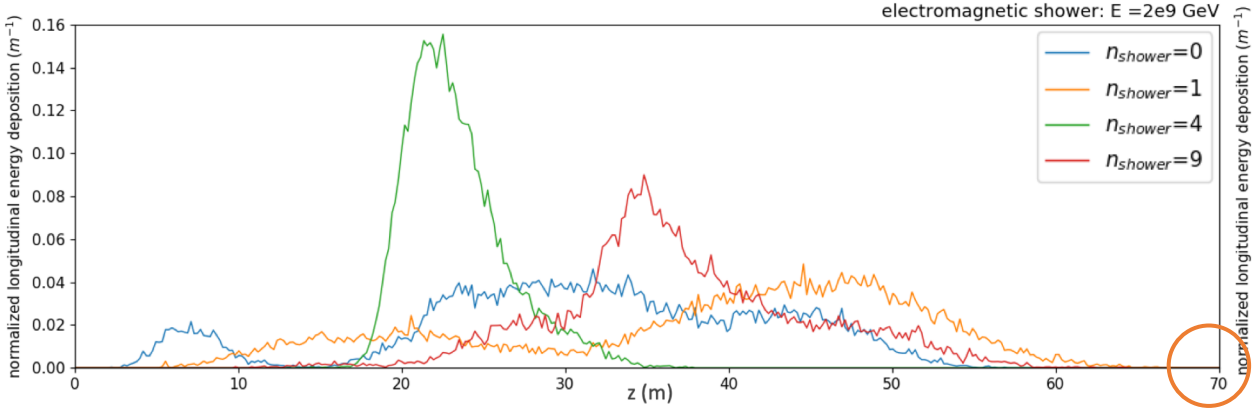


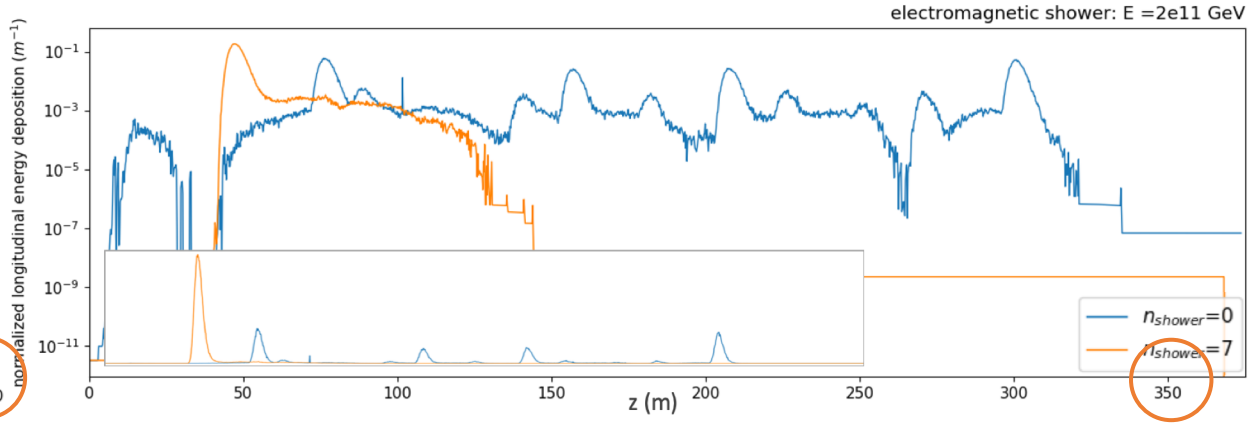


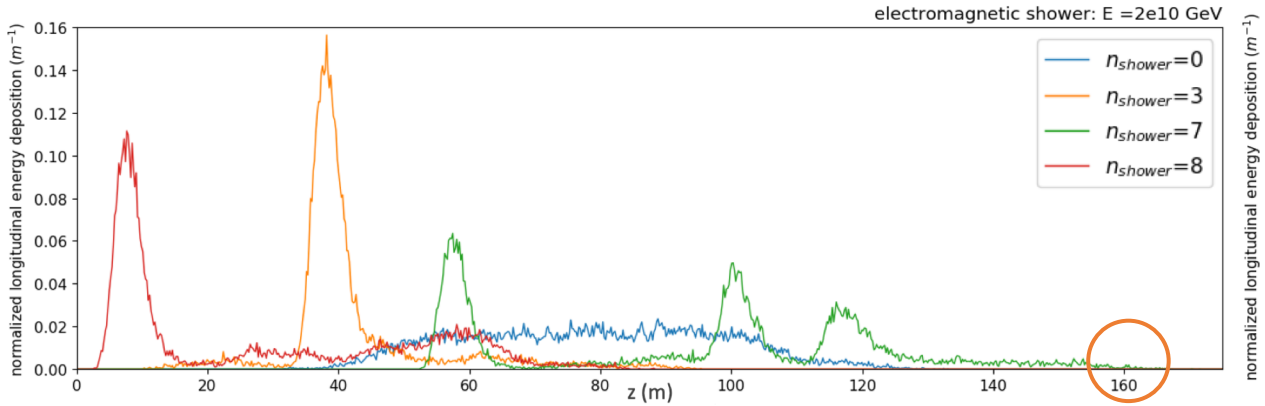
- Relevant fluctuations from shower to shower
- Elongation showers increases with energy due to LPM effect

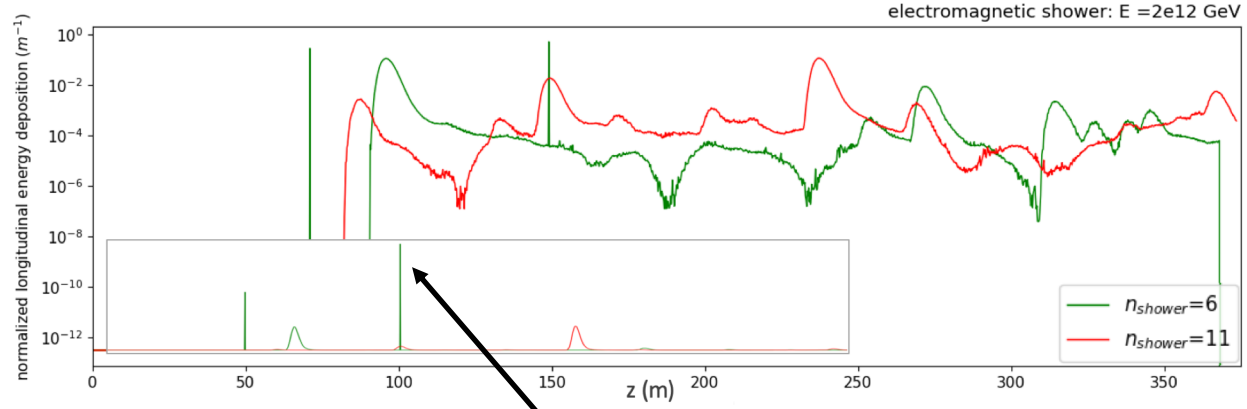
} **Larger impact LPM effect**

Longitudinal energy deposition profiles









- Increase of shower to shower fluctuations
- Presence of multiple sub-showers
- Elongated showers

Large impact LPM effect

Not proper treatment of hadronic particles from photonuclear and electronuclear interactions. These interactions seem to decrease the multi-shower structure

Thermo-acoustic mechanism

$$\nabla^2 p - \frac{1}{c_s^2}\frac{\partial^2 p}{\partial t^2} = -\frac{\alpha}{c_p}\frac{\partial^2 q(\bar{r},t)}{\partial t^2}$$

Energy deposition density

Solution:

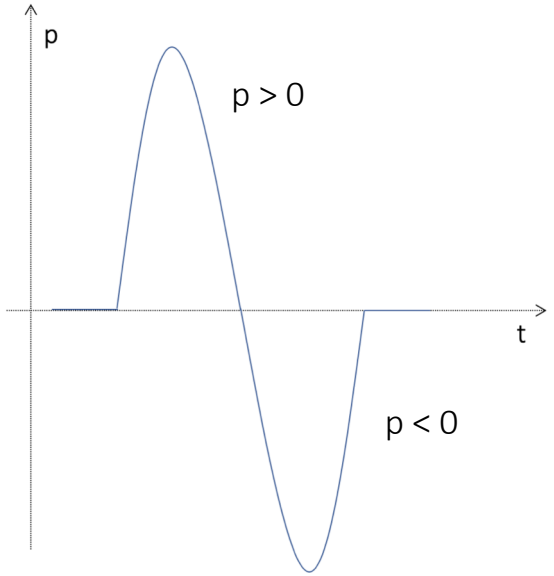
$$p(\bar{r},t) = \frac{c_s^2}{4\pi}\frac{\alpha}{c_p}\frac{\partial}{\partial R}\int_{S_{\bar{r}}^{Rt_0}} \frac{dS'}{R_{t_0}} q(\bar{r}')$$

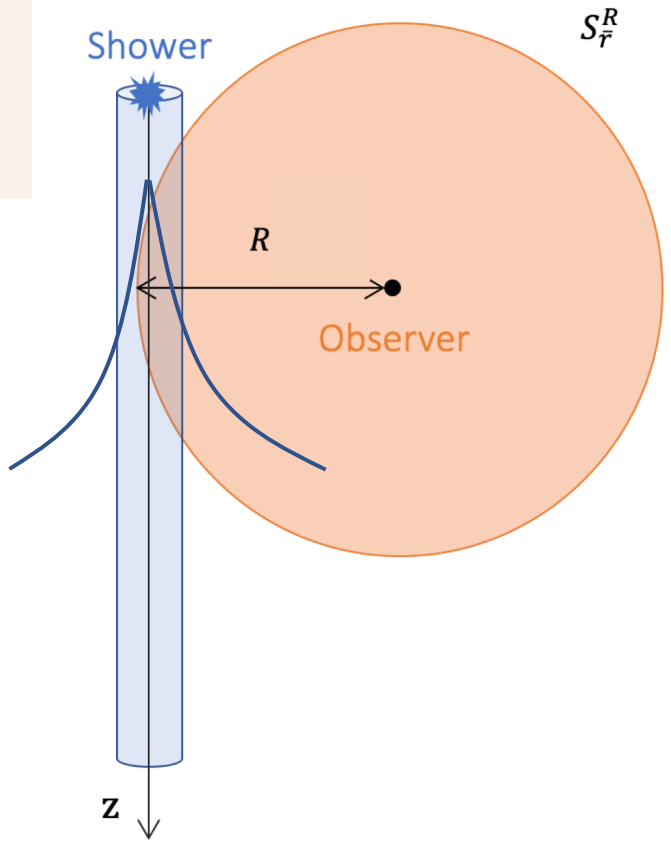
$q(\bar{r}',t') = q(\bar{r}')\Theta(t'-t_0)$ (Instantaneous energy deposition)

Depends on:

- Medium properties
- Change of energy deposition with respect observer distance

Creation of a bipolar pulse:





[Askariyan, G. A *et al.*, Acoustic detection of high energy particle showers in water. *Nucl. Instruments Methods* 164, 267–278 (1979)]

Characteristics of the pulse depend on observer position

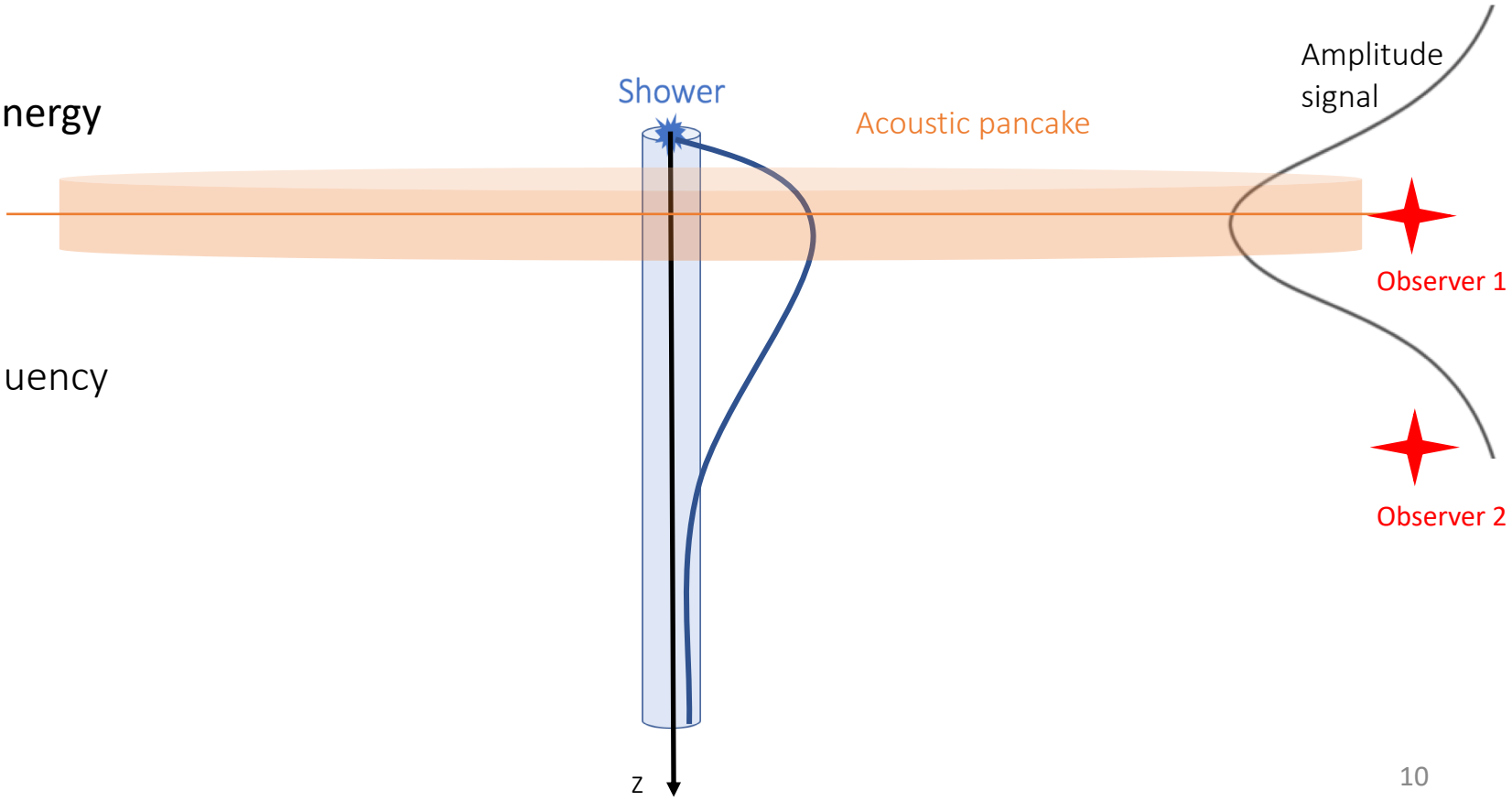
1) as further from the shower axis…

- Larger part of the shower contributing to the pulse (transition from near field to far field)
- Larger impact absorption

2) as further from the maximum energy deposition plane of the shower…

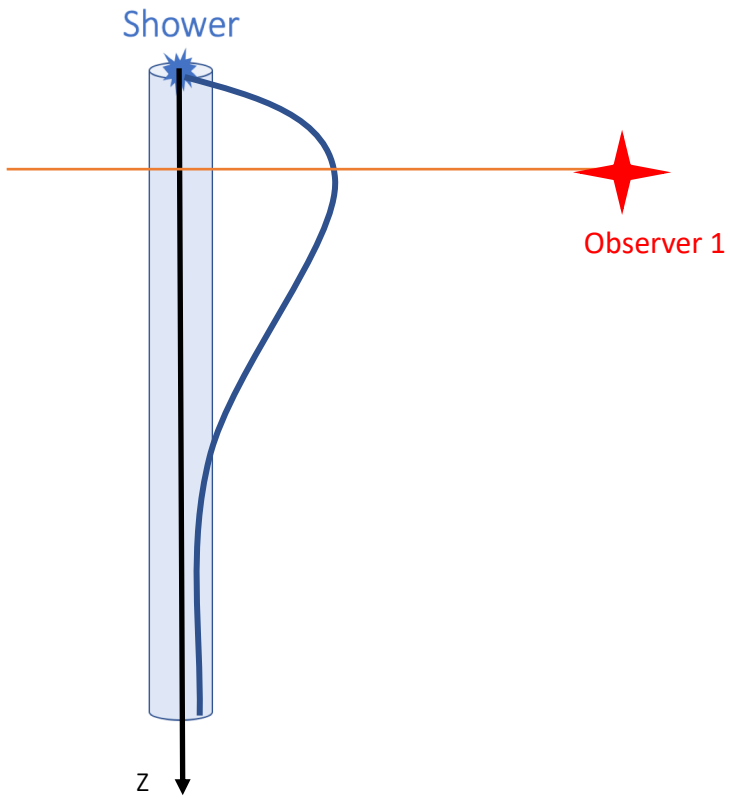
Coherence decreases

- Decrease in amplitude and frequency

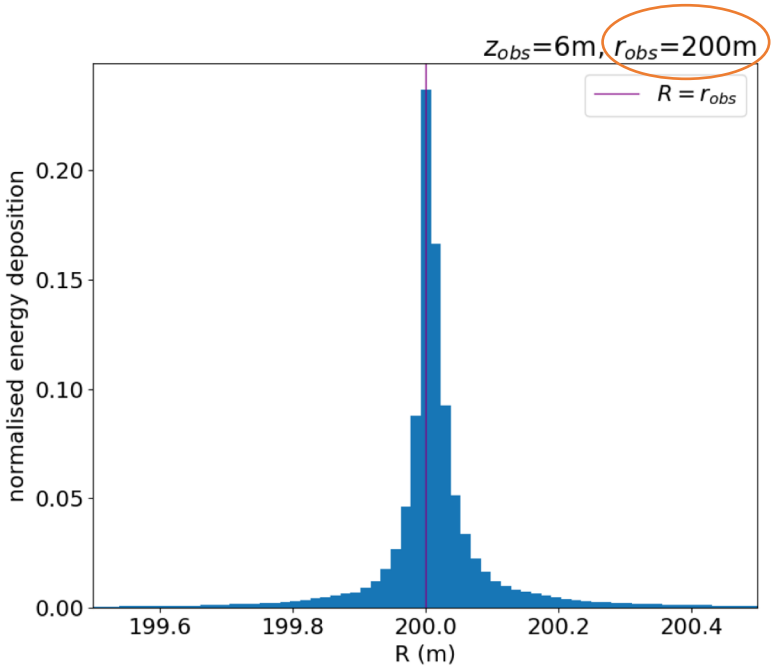


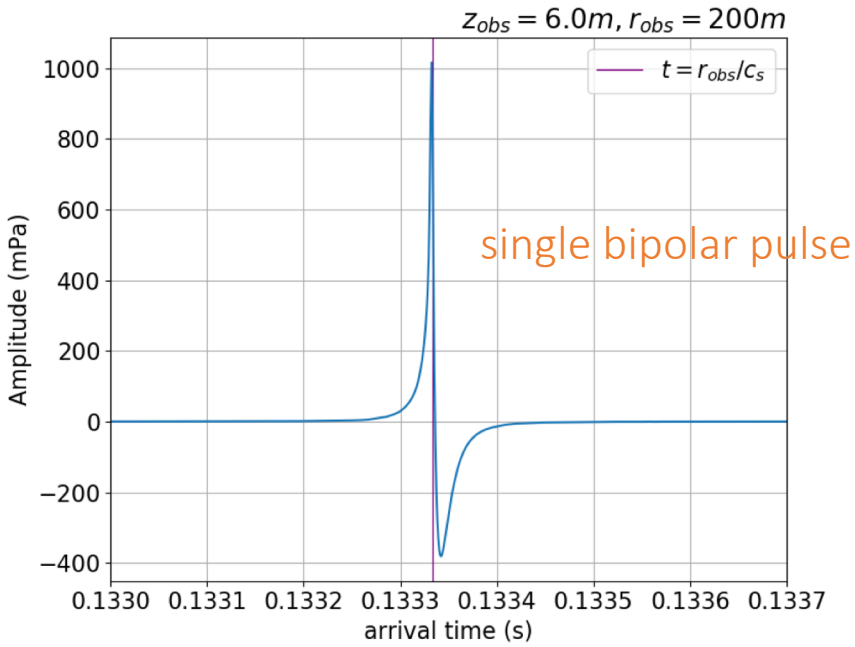
Observation close to the shower axis

(10^{11} GeV shower)



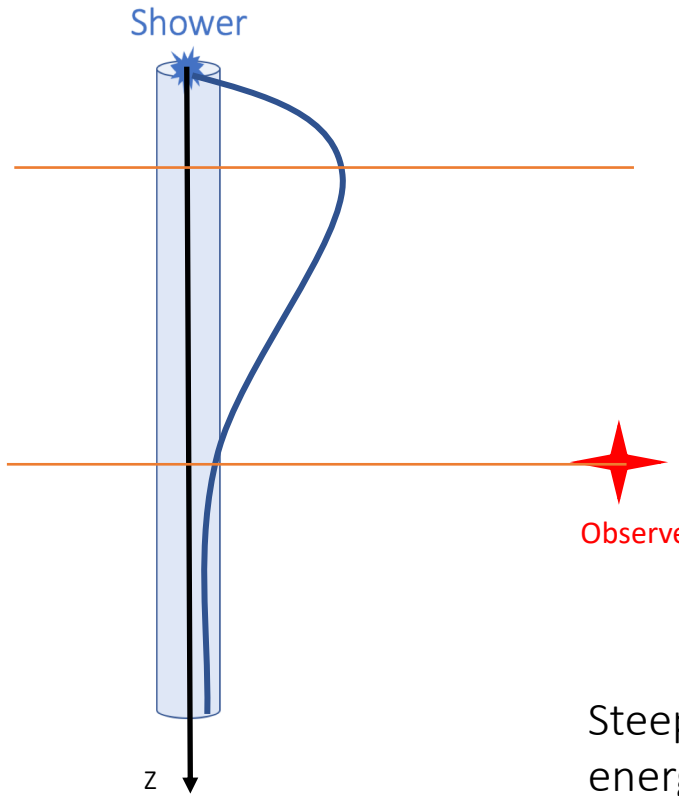
Energy deposition wr distance from observer

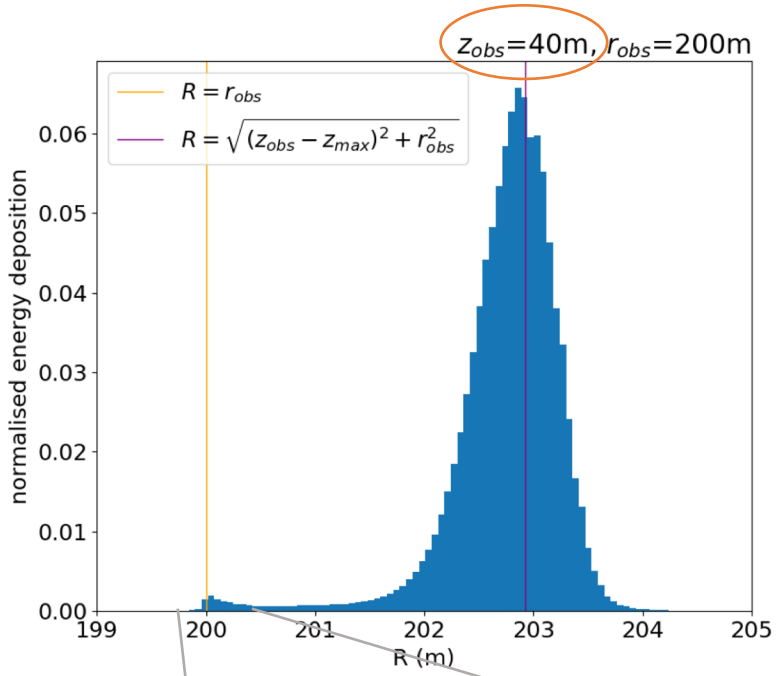


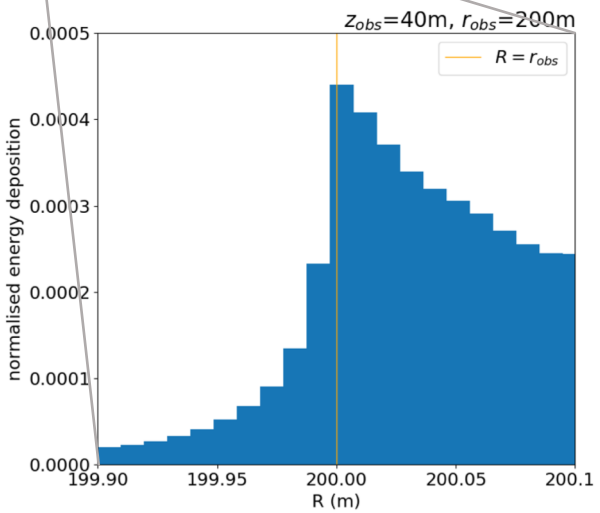


Observation close to the shower axis

(10^{11} GeV shower)



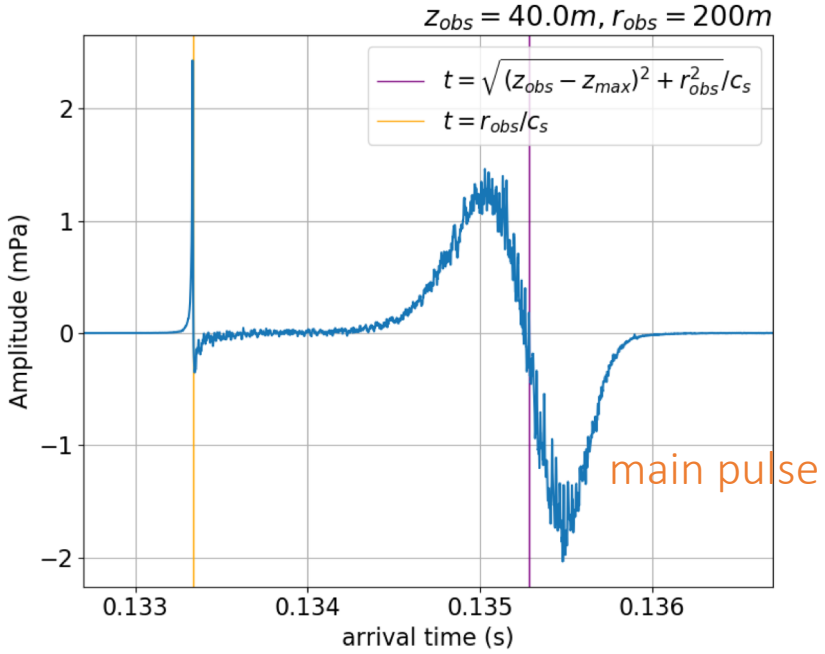




Steep increase of energy deposition

(due to radial energy profile at z = 40m)

early pulse

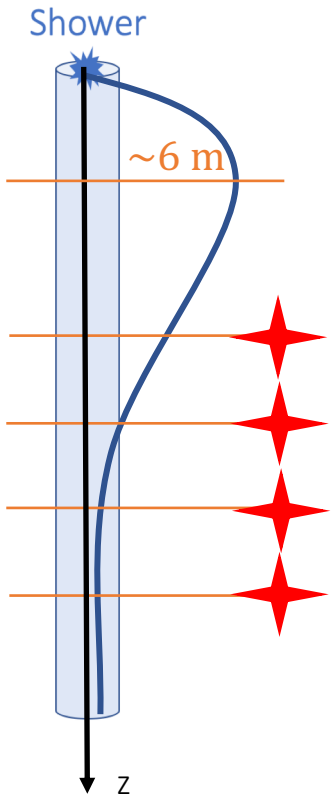


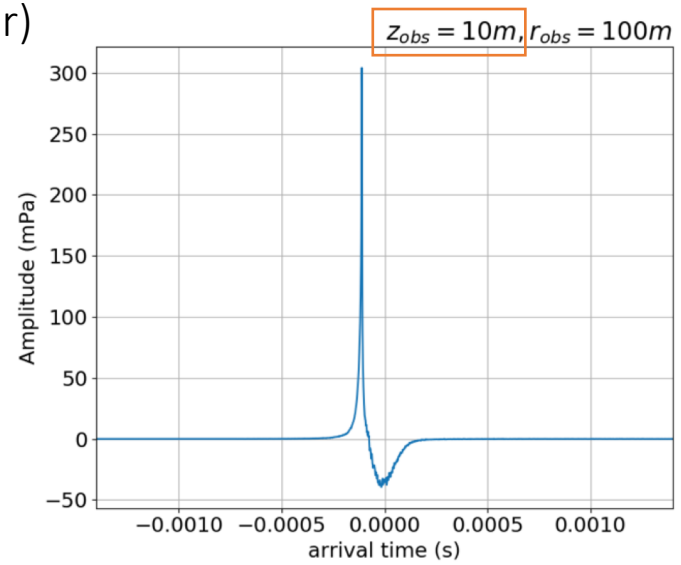
main pulse

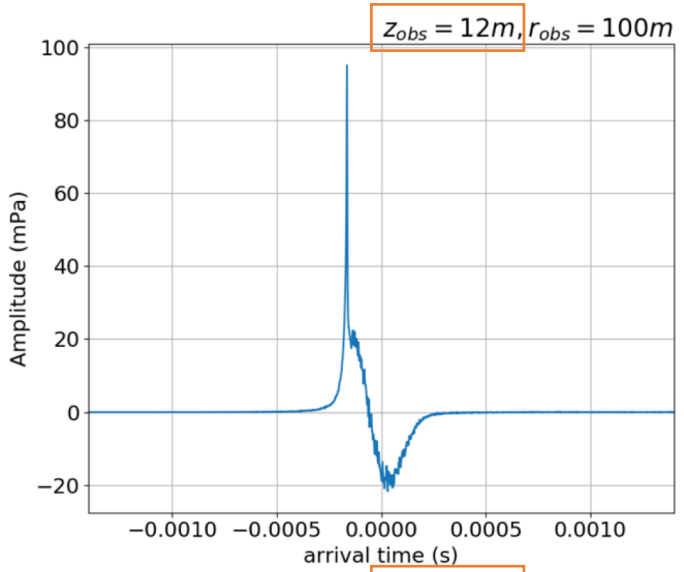
6. SIMULATION OF NEUTRINO ACOUSTIC SIGNALS: Pulses hadronic showers

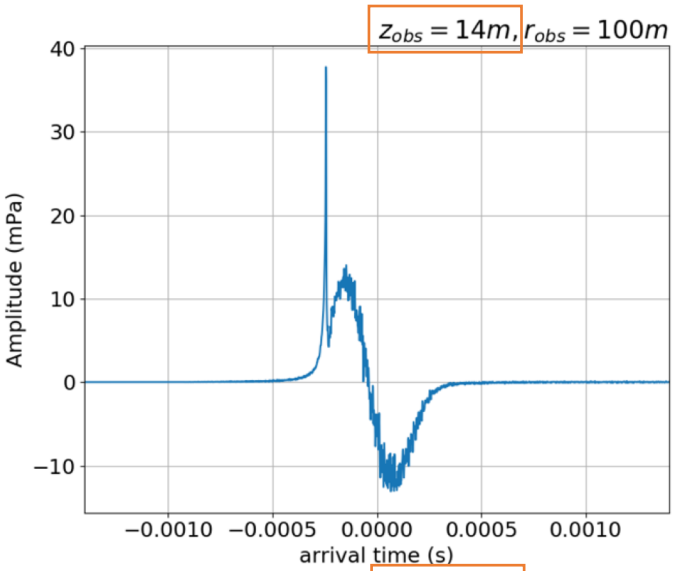
Observation at near field

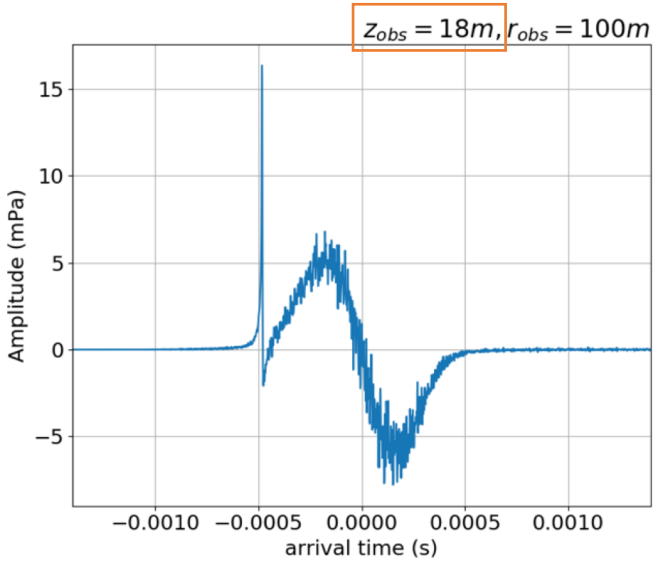
(10^{11} GeV shower)

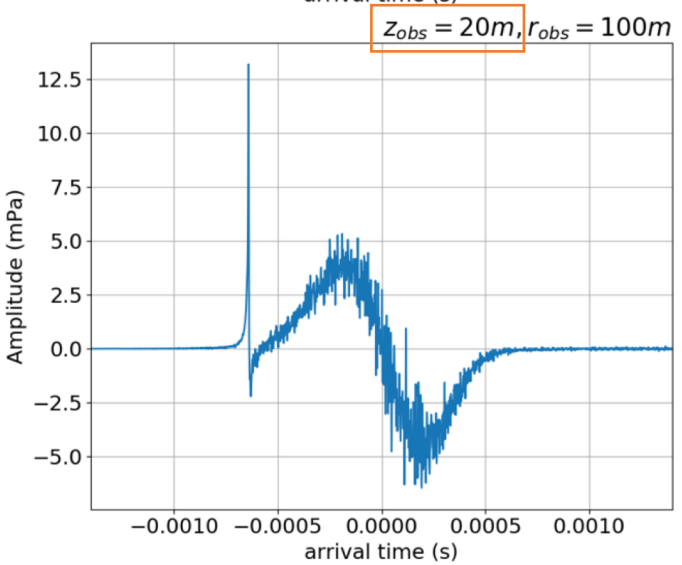


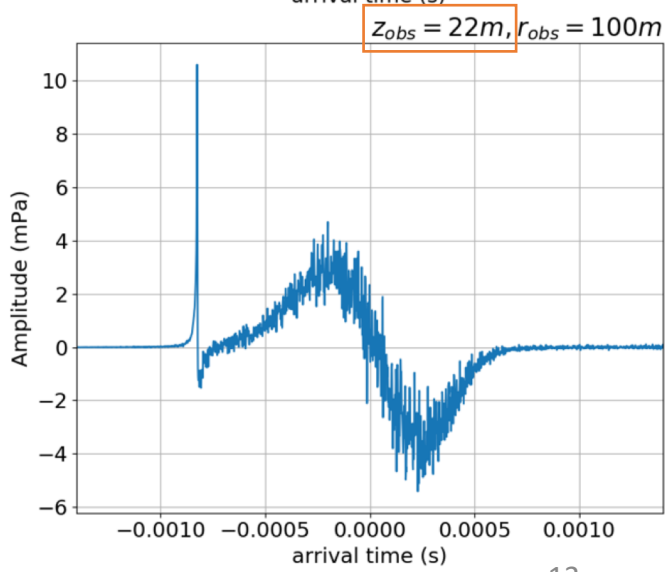






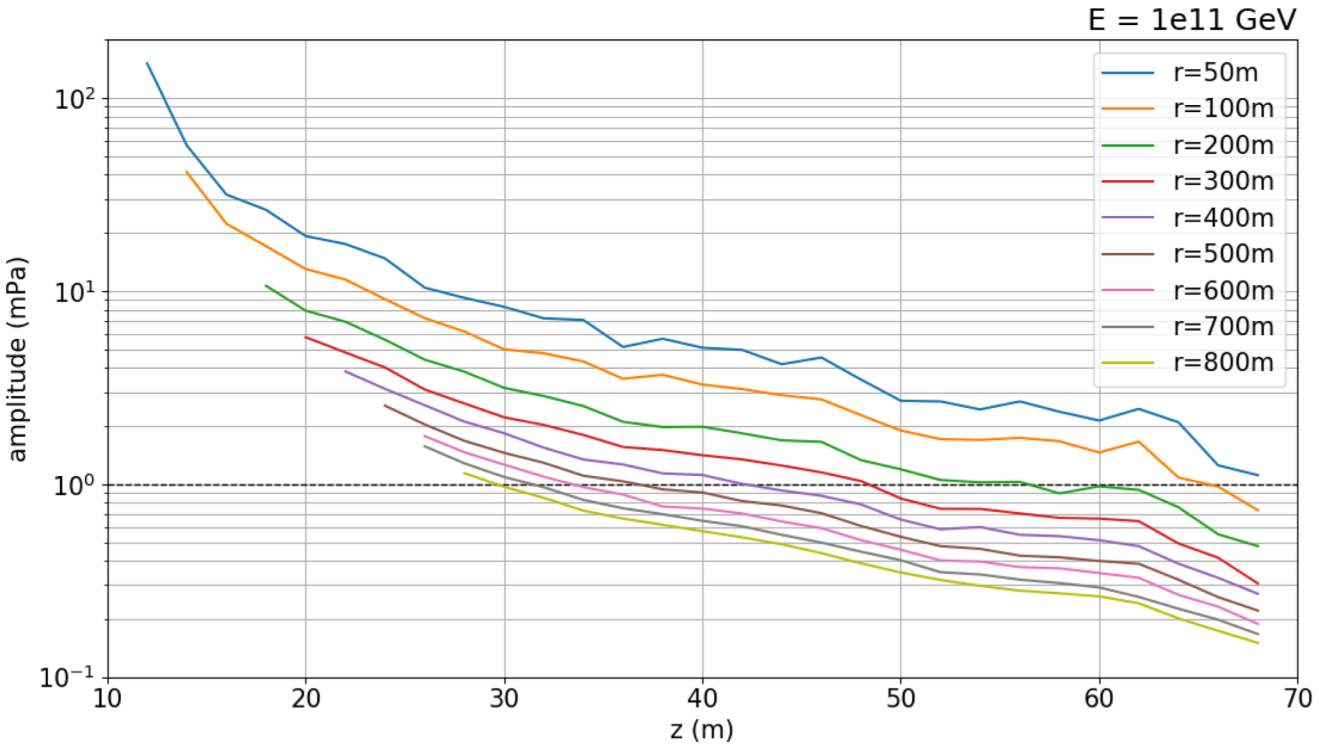






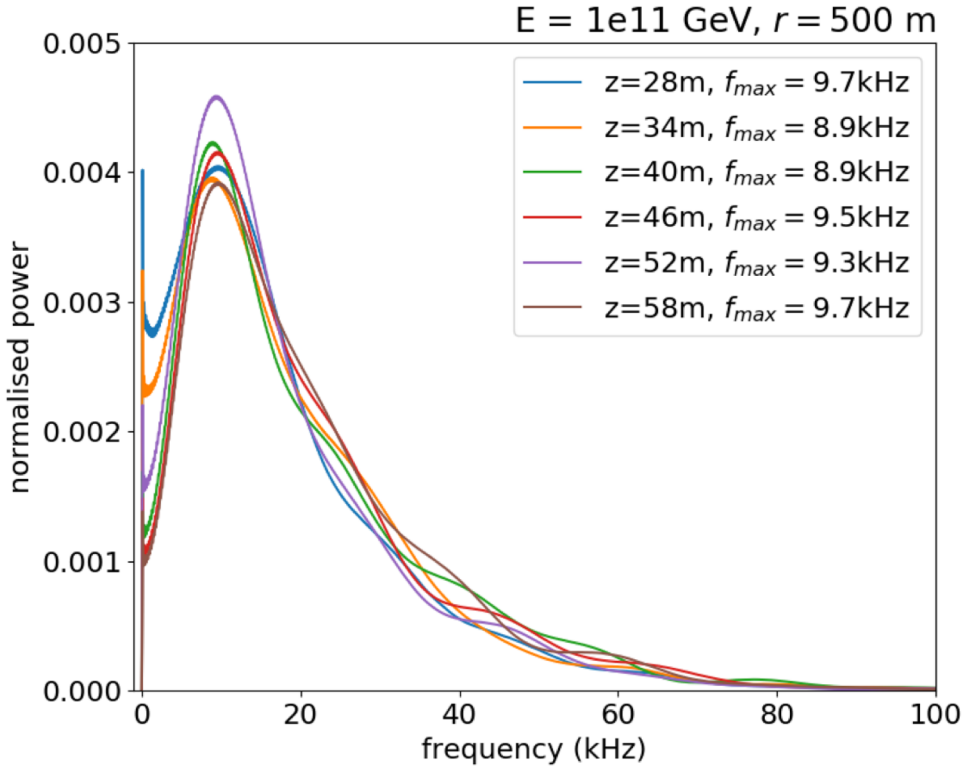
Characterisation early pulse for an average profile of a 10^{11} GeV shower

Amplitude



- Amplitude pulse decreases with observer depth
- Amplitude pulse decreases with radial distance (transition to far field)

Frequency



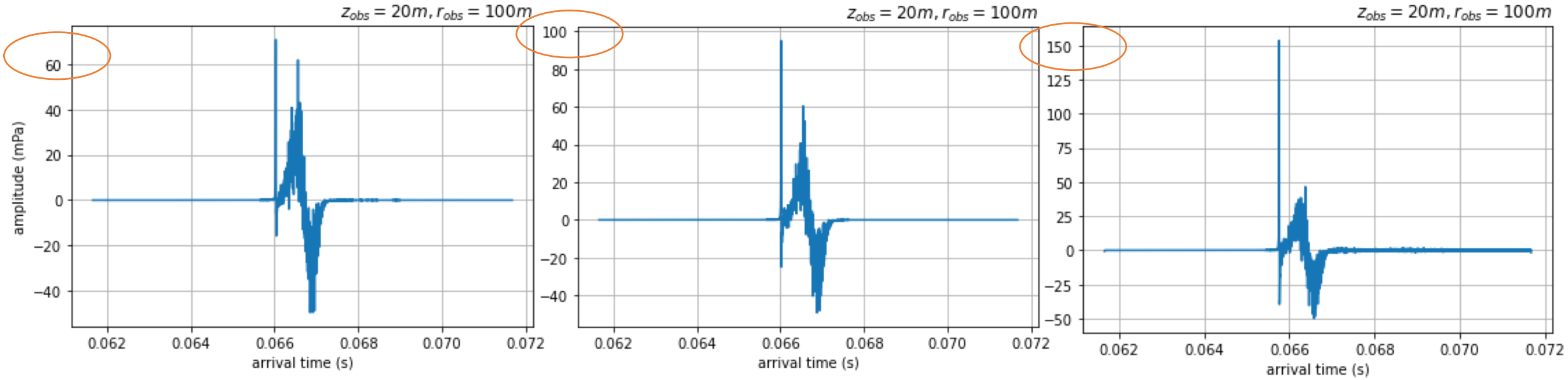
- Determined by the shower width

$$f \sim \frac{1}{2l_r/c_s}$$

6. SIMULATION OF NEUTRINO ACOUSTIC SIGNALS: Pulses hadronic showers

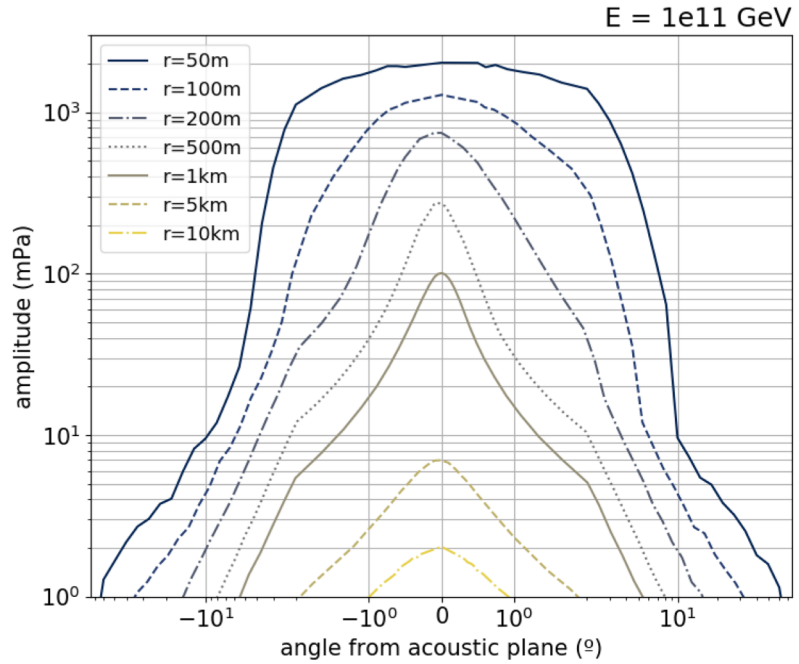
Characterisation early pulse: high variability from shower to shower

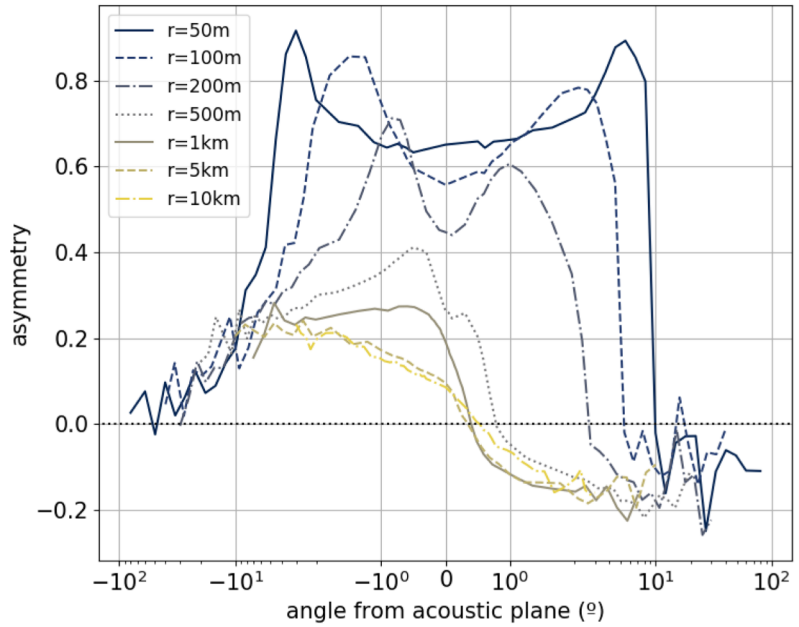
$5 \cdot 10^{11}$ GeV showers



6. SIMULATION OF NEUTRINO ACOUSTIC SIGNALS: Pulses **hadronic showers**

Characteristics main pulse

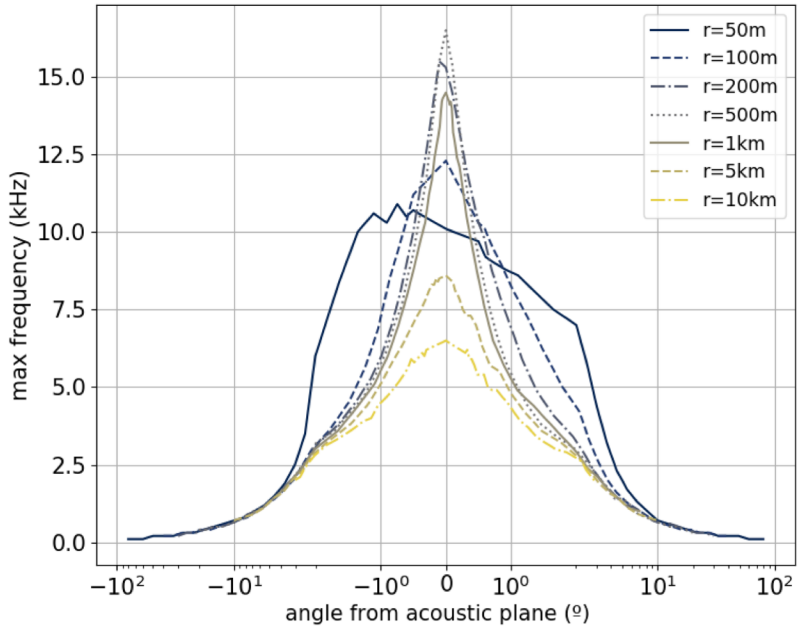


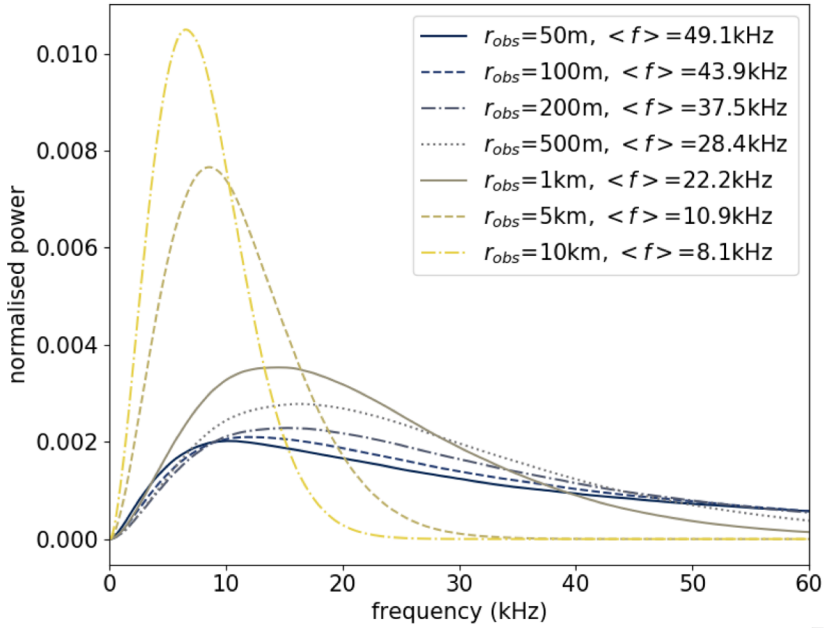


$$\frac{|P_{max} - P_{min}|}{|P_{max} + P_{min}|}$$

- Agreement with previous studies

[Bevan, S. *et al.* Study of the acoustic signature of UHE neutrino interactions in water and ice. *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.* 607, 398–411 (2009).]

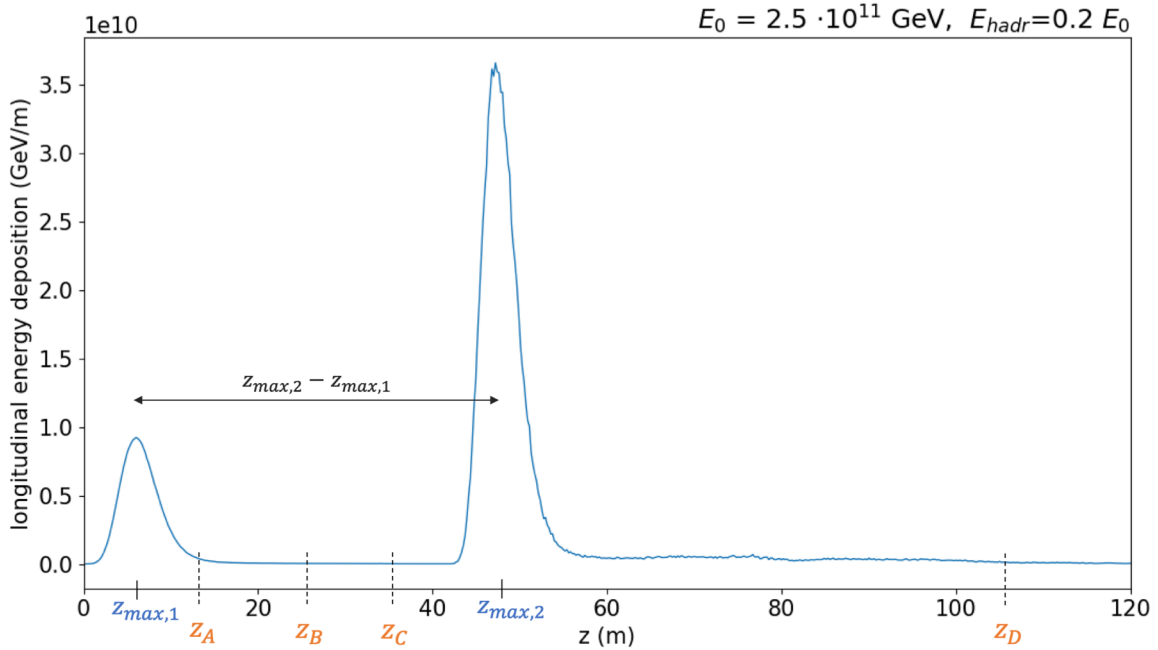


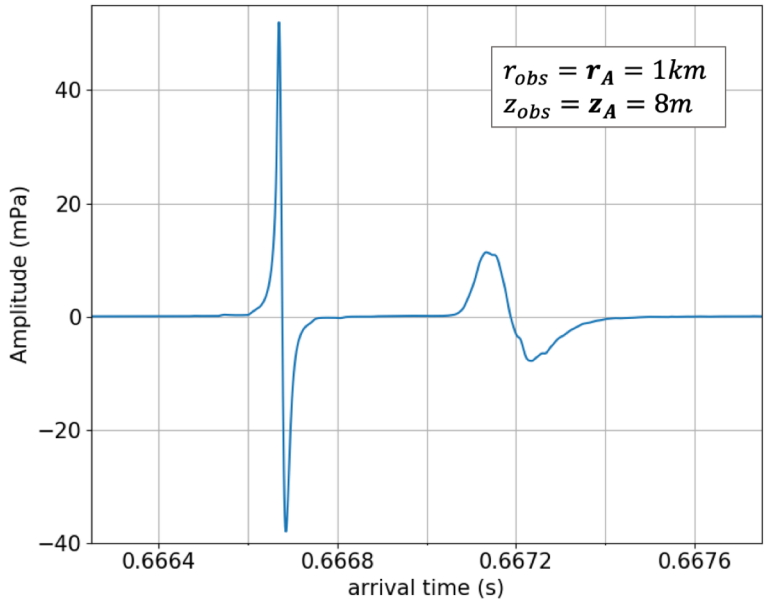


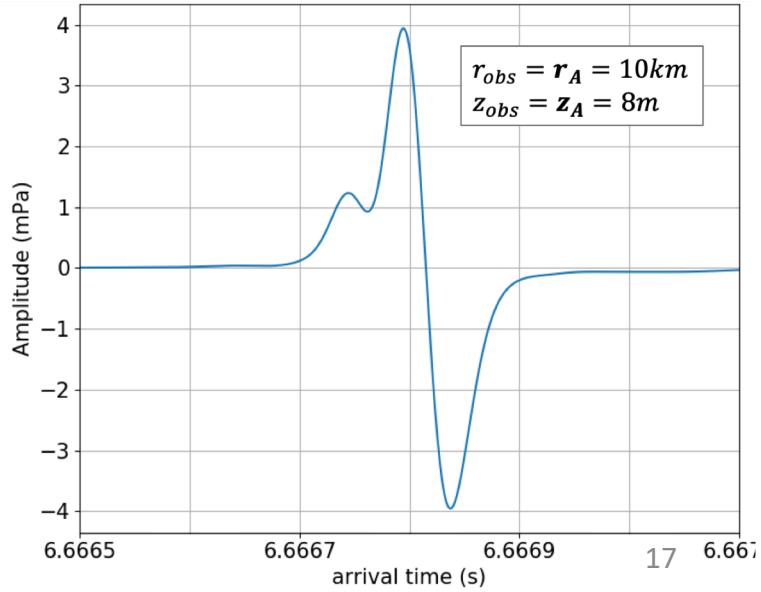
7. SIMULATION OF NEUTRINO INDUCED SHOWERS: Pulses ν_e charge current showers

What about ν_e charge current showers, (hadronic + electromagnetic)?

Possibility to observe more than one acoustic pulse due to the local energy maximums of the showers, **specially for E > 10^{11} GeV**







8. CONCLUSIONS AND NEXT STEPS

CONCLUSIONS

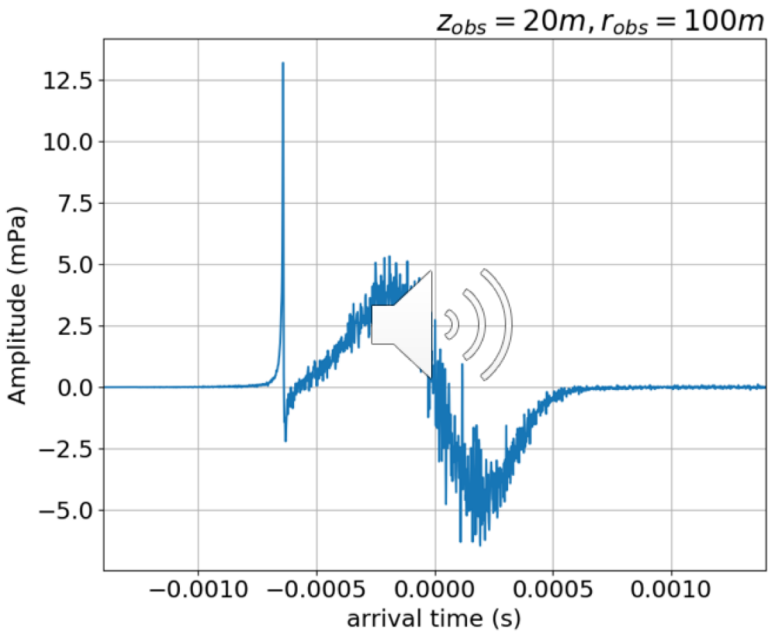
- **Hadronic showers** E > 10^{11} GeV have elongated tails characteristic of the LPM effect. → Creation of two pulses at near field
  - Early pulse: insight on the radial energy deposition profile of the showers
  - Extra information from a combined detection of an early and main pulse, e.g. distance from shower

- **Electromagnetic showers** are highly impacted by the LPM effect and photonuclear and electronuclear interactions become relevant, which seem to decrease multi-shower structure. → Possible observation of more than one pulse by electromagnetic showers
  - Possibility to differentiate ν_e CC interactions ?

NEXT AND FUTURE STEPS

- Project available at git
- Asses variance early pulse characteristics
- Asses uncertainties

- At some point… upgrade CORSIKA simulations to CORSIKA 8



Thanks for your attention!

CORSIKA-6600 vs CORSIKA-7700

	CORSIKA-6600	CORSIKA-7700
HE hadronic models	pre-LHC data	post-LHC data
Cross-sections e.m. interactions	*EGSDAT5*	*EGSDAT6* (updated)
3rd generation leptons	Not produced	Production, transport, decay
Charm particles	Not produced	Production, transport, decay

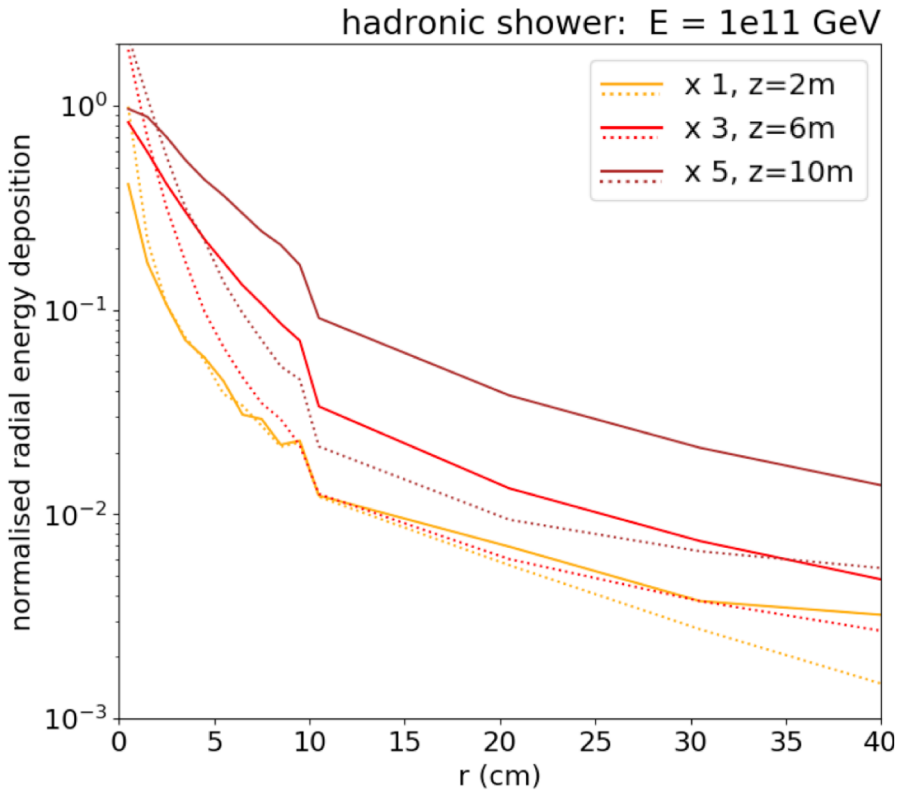
→ Largest impact

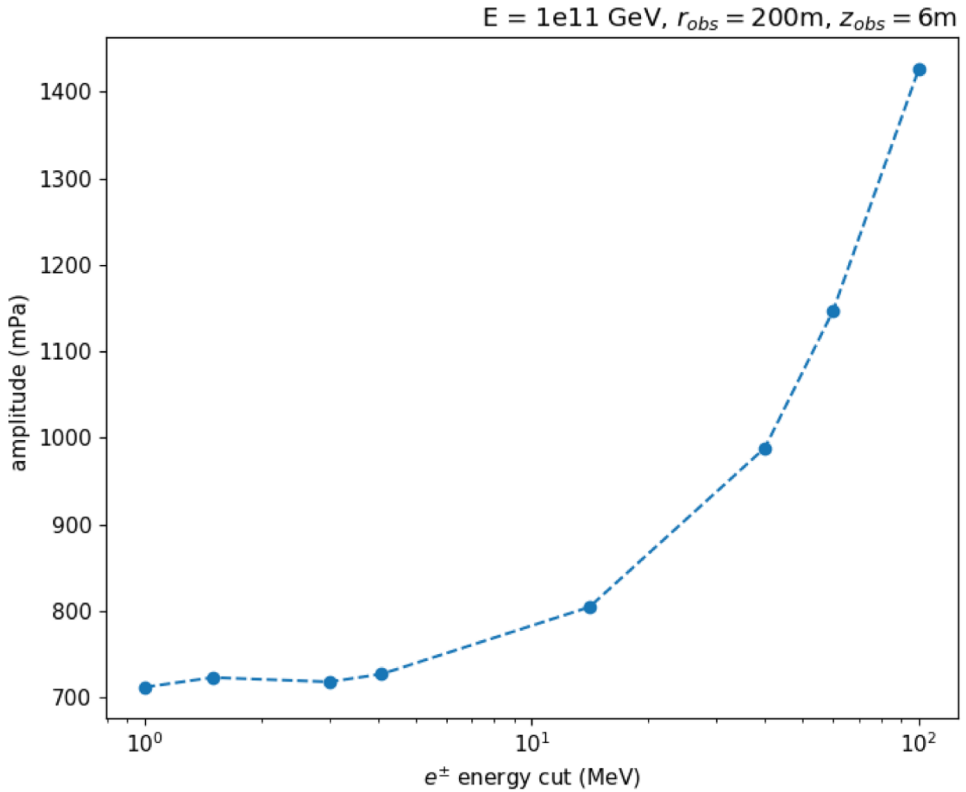
Effect energy cuts

E < 1e11 GeV E > 1e11 GeV

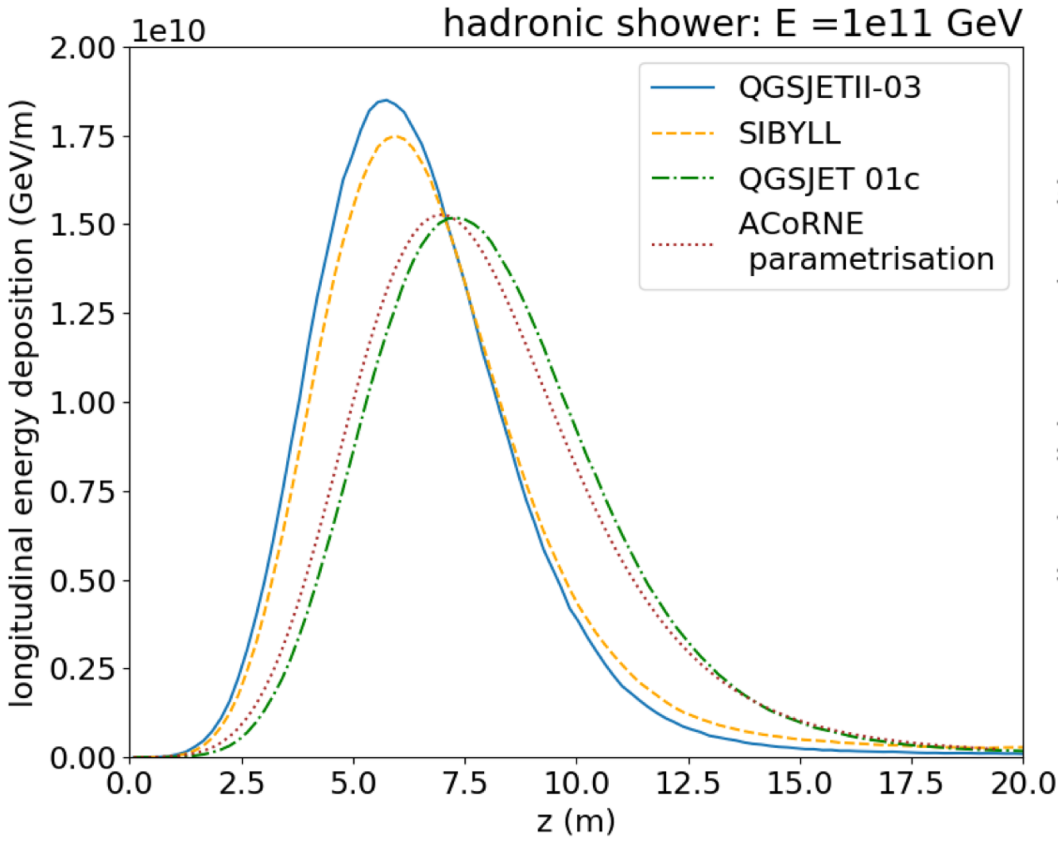
$E_{cut}^{e^\pm}$ (GeV)	E_{cut}^{γ} (GeV)
0.001	0.001
0.1	0.1

Increase cuts needed in order to simulate showers above 1e11 GeV.

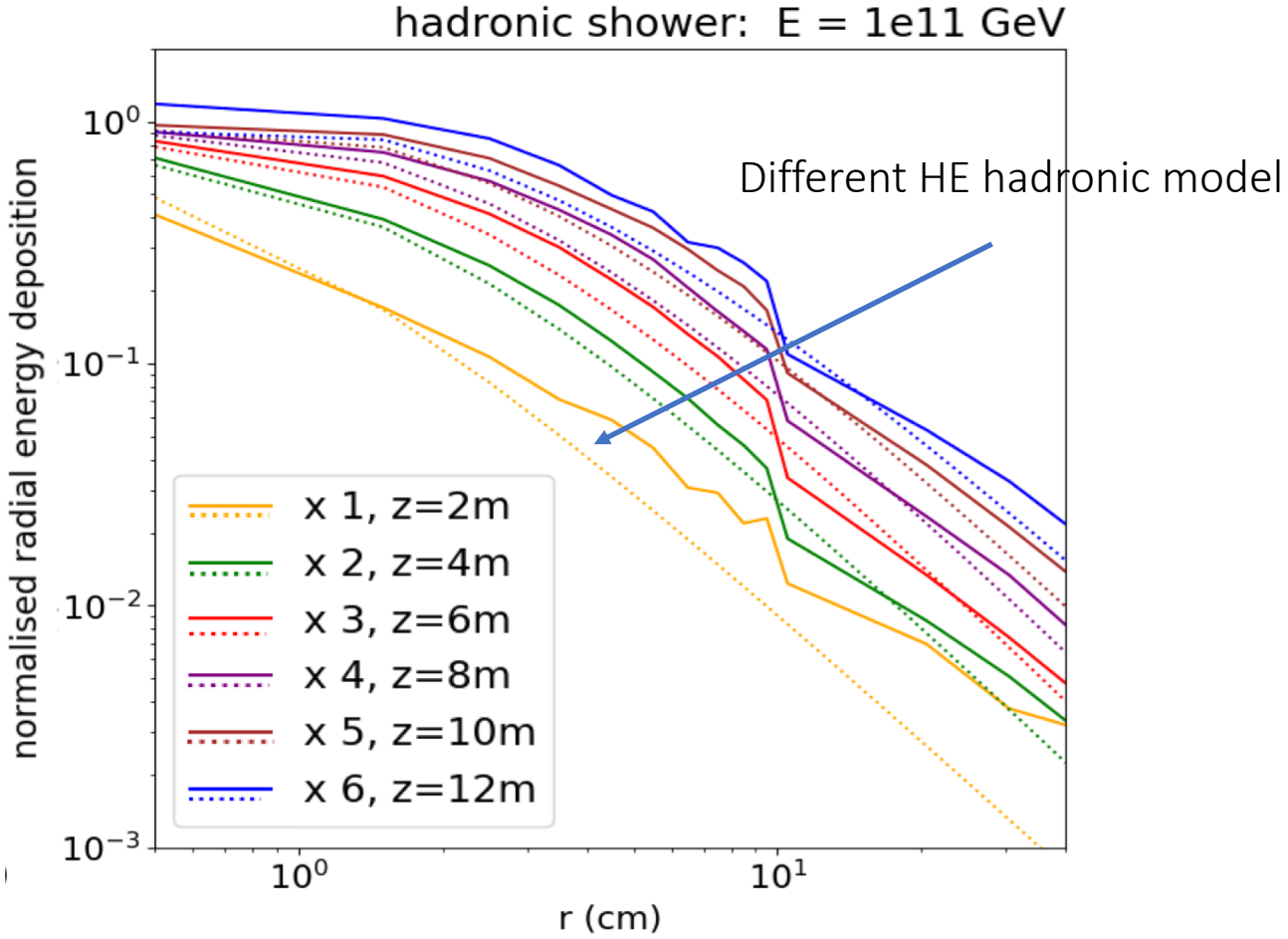




Energy deposition profiles: Impact high energy hadronic models



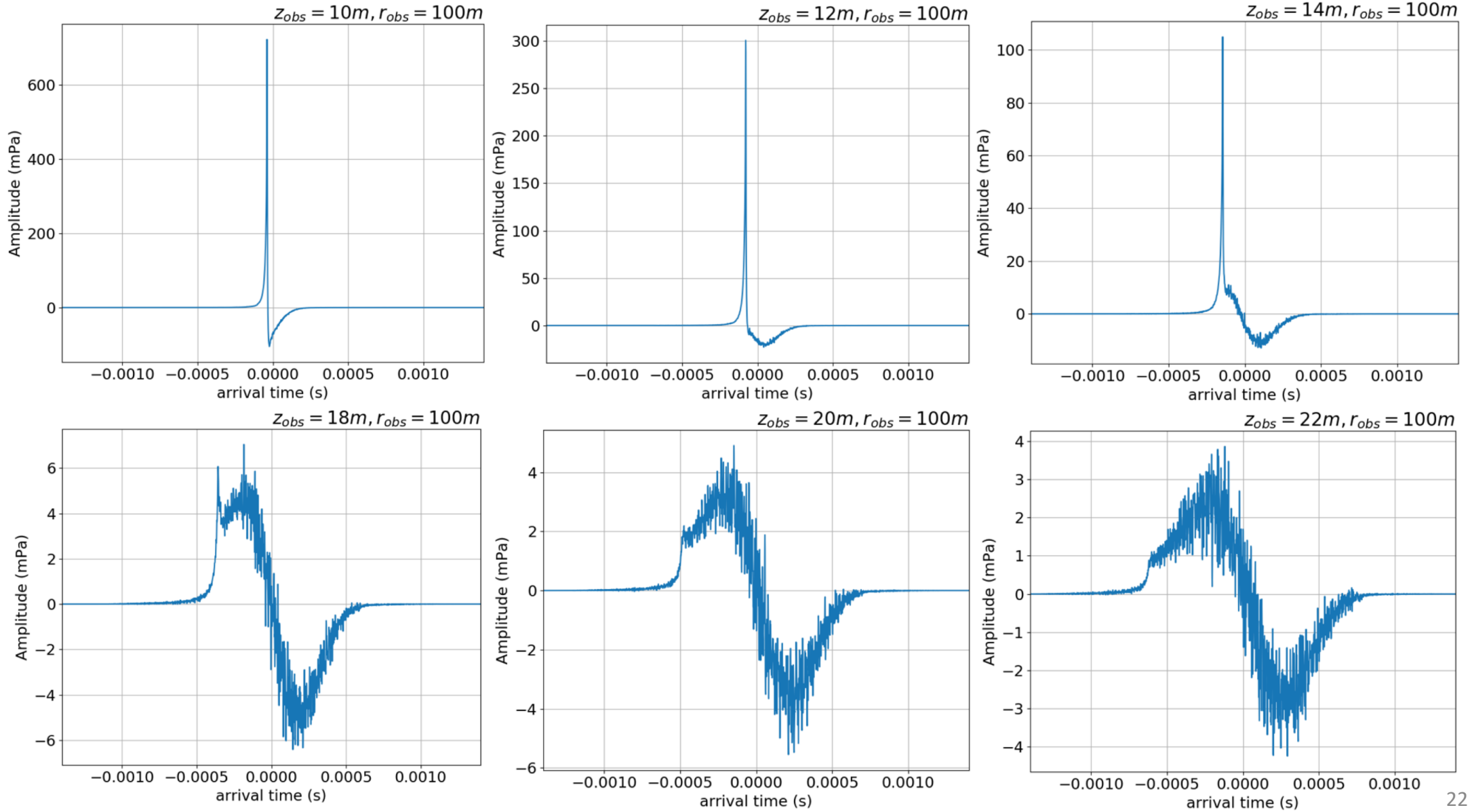
- Large impact HE hadronic model



- Smaller impact HE hadronic model

BACK UP SLIDES: Previous studies

Pulses using ACoRNE parametrisation (20 m long shower) → No early pulse



[Bevan, S. *et al.* Study of the acoustic signature of UHE neutrino interactions in water and ice. *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.* 607, 398–411 (2009).]

PARAMETERS:

f_s= 1 MHz (sampling frequency)
c = 1500 m/s

MC points	$5 \cdot 10^7$ ($r \leq 200$ m), 10^7 ($200 < r \leq 500$ m), 10^6 (500 m $< r \leq 1$ km), 10^4 (r = 5 km, 10 km)
Number rotations	100
Time window	4000 μs (main pulse), 10000 μs (with early pulse)

Table B.3: Relevant simulation parameters thermo-acoustic model.

Absorption
(model by ACoRNE collaboration):

- chemical coupling

Dominates from below a few kHz to 1kHz due to the B(OH3) and from 1 kHz to 100 kHz due to the MgSO4.

- viscous absorption

Dominates above 100 kHz.

[Bevan, S. *et al.* Study of the acoustic signature of UHE neutrino interactions in water and ice. *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.* 607, 398–411 (2009).]

→ **Input:** **2D array = energy deposition binned in volumes** $(\Delta z) \times (\Delta r) \times (\Delta \varphi = 2\pi)$ **+ Observer position =** (r_{obs}, z_{obs})

Generation of N **Monte Carlo** (MC) points → density proportional to energy deposition (Inverse transform method [1])

- MC points $\equiv (r_i, z_i)$
- Transformation to cartesian coordinates:
  $(r_i, z_i) \rightarrow (x_i, y_i, z_i)$
- Increase # MC points: N_r **rotations** around shower axis

Computation **flight time to observer** for each MC point

Histogram flight times to observer: $hist_times(t)$

Histogram flight times to observer: $hist_times(t)$

Computation **velocity potential** : $\Phi(t) = \frac{\alpha}{4\pi C_p \rho} \frac{1}{c_s(t-t_0)} hist_times(t)$

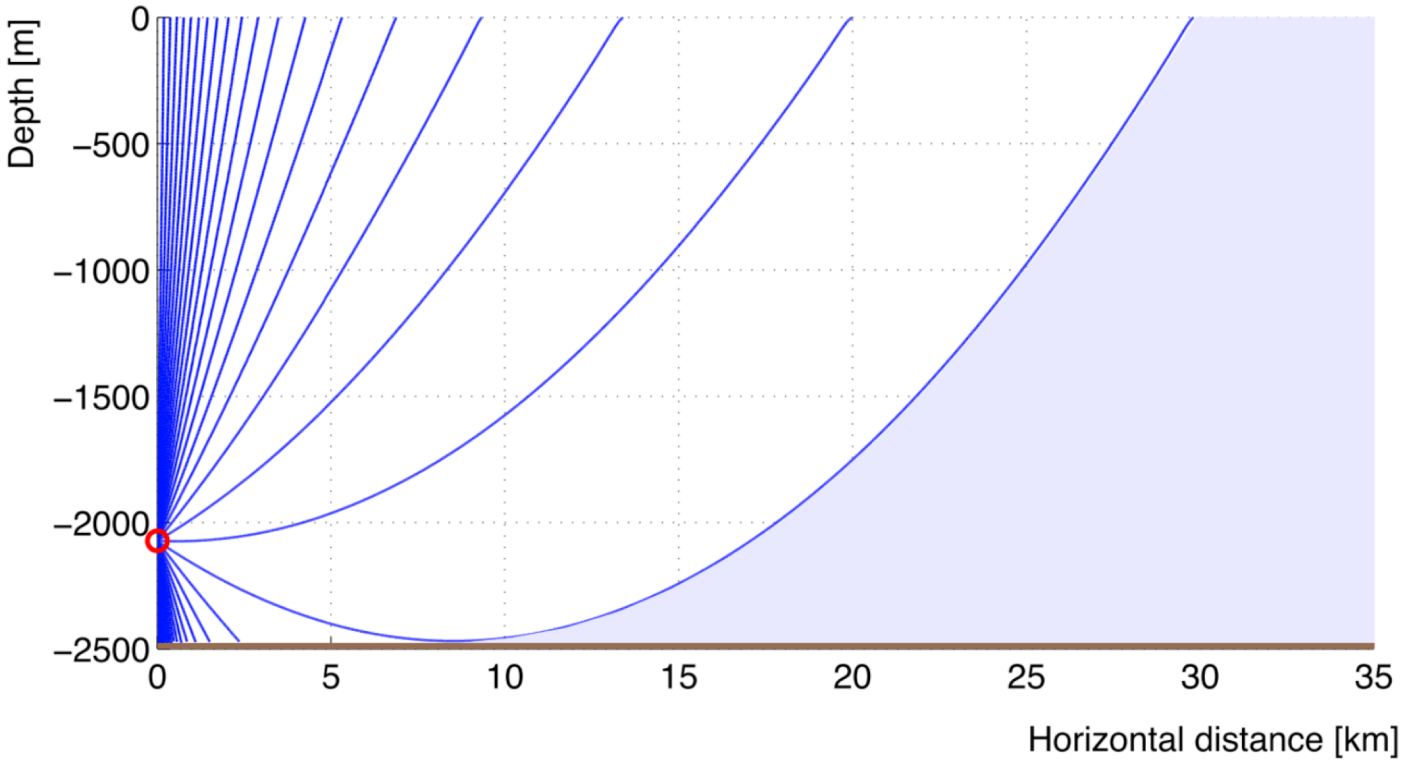
Fourier Transform $\Phi(t)$: $\boldsymbol{\Phi(f)}$

Computation $\boldsymbol{p(f)}$ with **attenuation** :

$$p(t) = -\rho \frac{\partial}{\partial t} \Phi(t) \quad \rightarrow \quad p(f) = -2\pi f \cdot \rho \cdot atten(f) \cdot \Phi(f)$$

→ Output: **Inverse Fourier Transform $\boldsymbol{p(f)}$: $\boldsymbol{p(t)}$**

- Constant speed of sound → refraction not taken into account

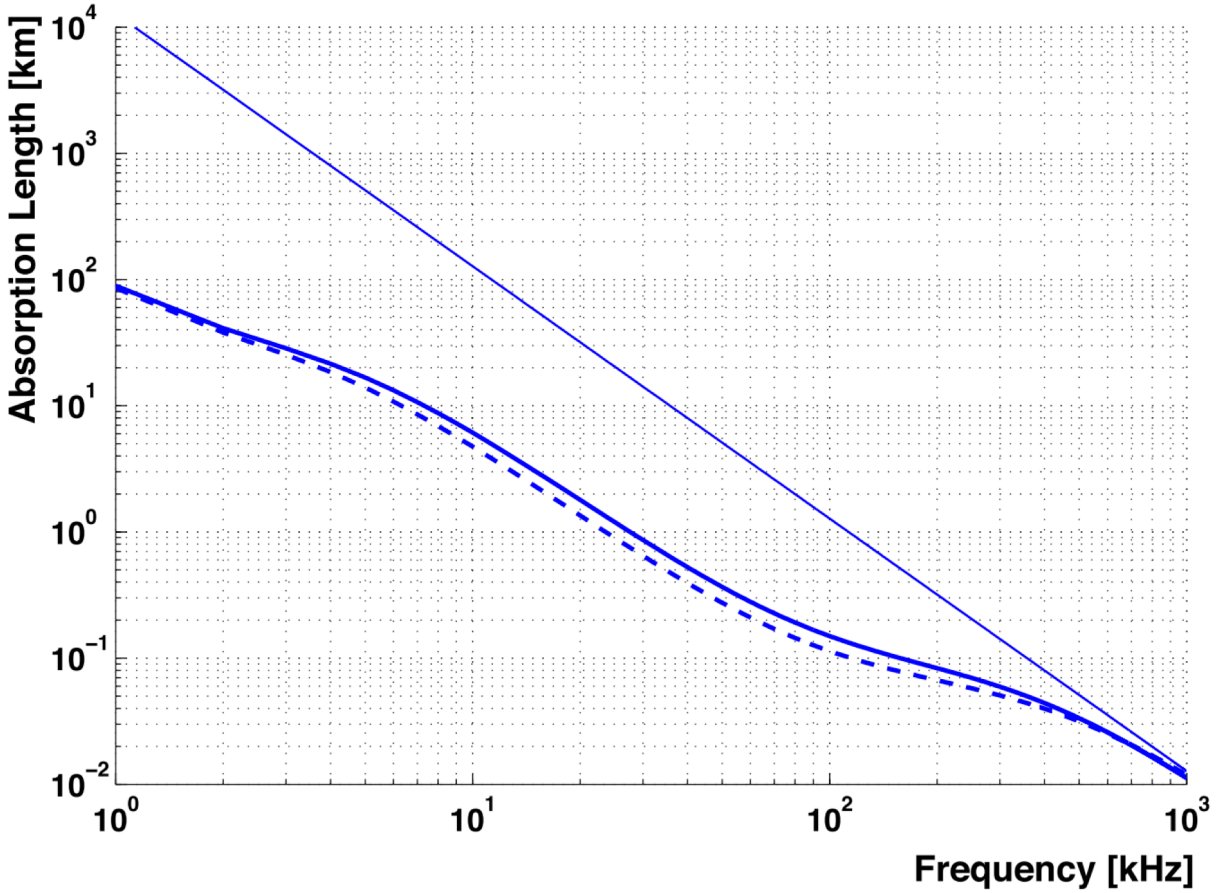


Not large impact in this study, since maximum observer distance used is 10 km

Figure 3.5: Acoustic ray trajectories at a depth of 2.5km, for the sea conditions in the KM3NeT and ANTARES site. The observer is indicated by a red dot, and the shaded region is the area from which acoustic rays can not reach the observer. From

[Lahmann, R. Ultra-High-Energy Neutrinos and Their Acoustic Detection in the Sea. (2011)]

BACK UP SLIDES: Absorption length in water



[Lahmann, R. Ultra-High-Energy Neutrinos and Their Acoustic Detection in the Sea. (2011)]