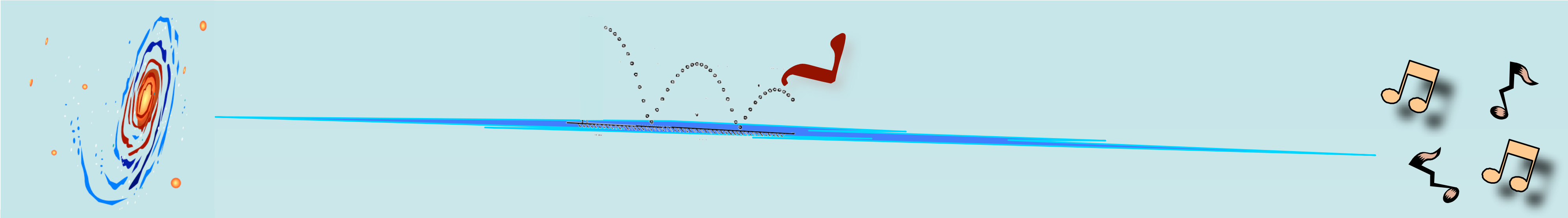

Acoustic Technique for Ultra-High-Energy Neutrino Detection in Underwater Telescopes

from Protons to Neutrinos

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PhD in Physics – XXI Cycle

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I.N.F.N. - Roma

Outlook

Introduction

- Neutrino Astronomy
- Submarine Observatories
  - Eth < 10^{16} eV ⇒ Cherenkov detection
  - UHEν ⇒ **Acoustic Detection**

The Thermo-Acoustic Mechanism and the Acoustic Signal

- Analytical Solution of the Wave Equation
- **Gruneisen Coefficient γ** and **Signal Amplitude as a function of Environmental Parameters** (Temperature, Salinity, Depth)

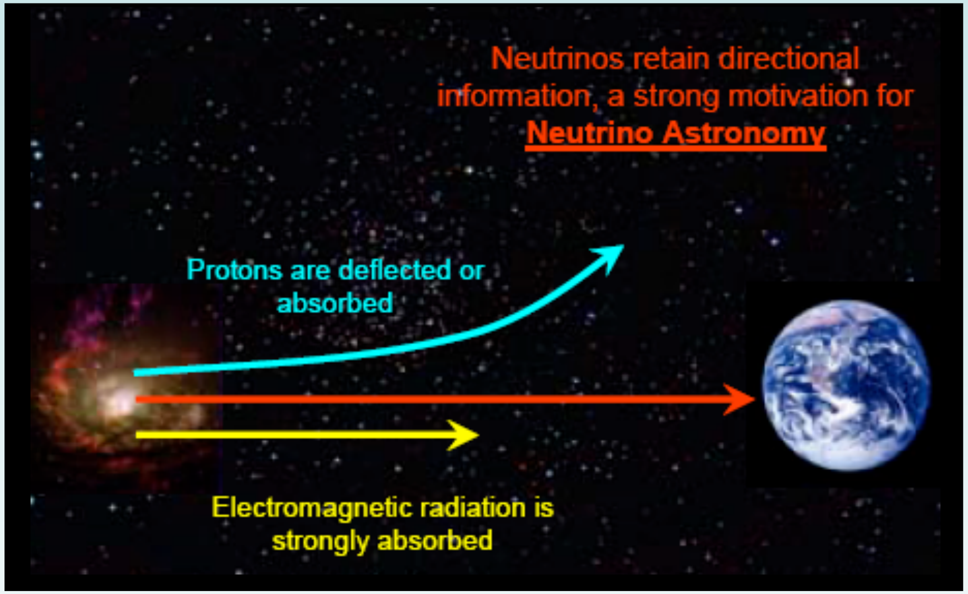
Test of the Thermo-Acoustic Mechanism at the ITEP Proton Beam

- Experimental set-up and Calibration Measurements
- **MonteCarlo**. AcSource = Geant4 Simulation of the proton interaction at the test beam
- **AcPulseComputation**
- **Investigating the performances of the MonteCarlo ➔ Data VS Sim**
- **Comparison with previous results** (Sulak *et al*. 1979)

Simulation of Neutrino-Induced Acoustic Pulse

- **MonteCarlo**. AcSource = CORSIKA Neutrino-induced Showers
- **AcPulseComputation**
- **Check of the model predictions** and **comparison with previous results**

Neutrino Astronomy



- **Astrophysics**

UHECν's as a diagnostic of astro-physical processes:

- astrophysical sources, accel. engines

  neutrino observations can discriminate between different acceleration mechanisms (hadronic/e.m.)

- cosmic rays propagation ■**GZK** cut-off

- **Particle Physics**

- $\sigma_{\nu N}$ at $E>E_{acc.}$
- physics beyond the SM

(strongly interacting ν's…)

UHEν's Production

■ *bottom-up* model : acceleration (AGNs, SNRs, GRBs…)

■ *top-down* model : decay (massive relic particles - CDM, primordial cosmological defects)

- **Cosmology**

- EHECν absorption on the CνB (■**Z-bursts**)
- top-down models

[1] T. K. Gaisser, F. Halzen, T. Stanev, Particle Astrophysics with High-Energy Neutrinos, *Phys. Rep.* 258 (1995) 173-236

[2] J. G. Learned, K. Mannheim, High-Energy Neutrino Astrophysics, *Annu. Rev. Nucl. Part. Sci.* 50, 679 (2000).

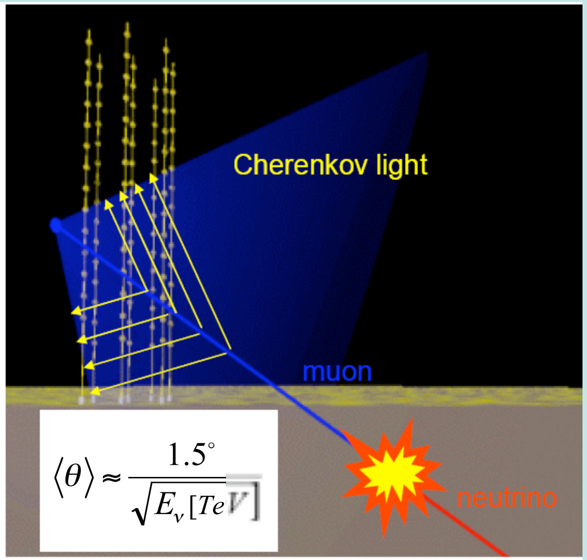
[3] D. V. Semikoz, G. Sigl, Ultra-High-Energy Neutrino Fluxes. New Constraints and Implications, J*CAP04*(2004)003

Event Rates & Detection Techniques

Predicted neutrino fluxes are very **LOW** → Cubic kilometer scale detectors required

→ Natural Target (ICE, WATER)

Optical Cherenkov neutrino detectors (up-going νs)



AMANDA/IceCube
Baikal
ANTARES, NEMO, NESTOR

– Light attenuation length (50-70m @440nm) limits **effective volume** at O(1km^3)

– $\mathbf{E_{th}<10^{16}eV}$ (Earth's opacity)

↓

search for **down-going** νs

To optimize signal-to-noise (atmospheric background) ratio

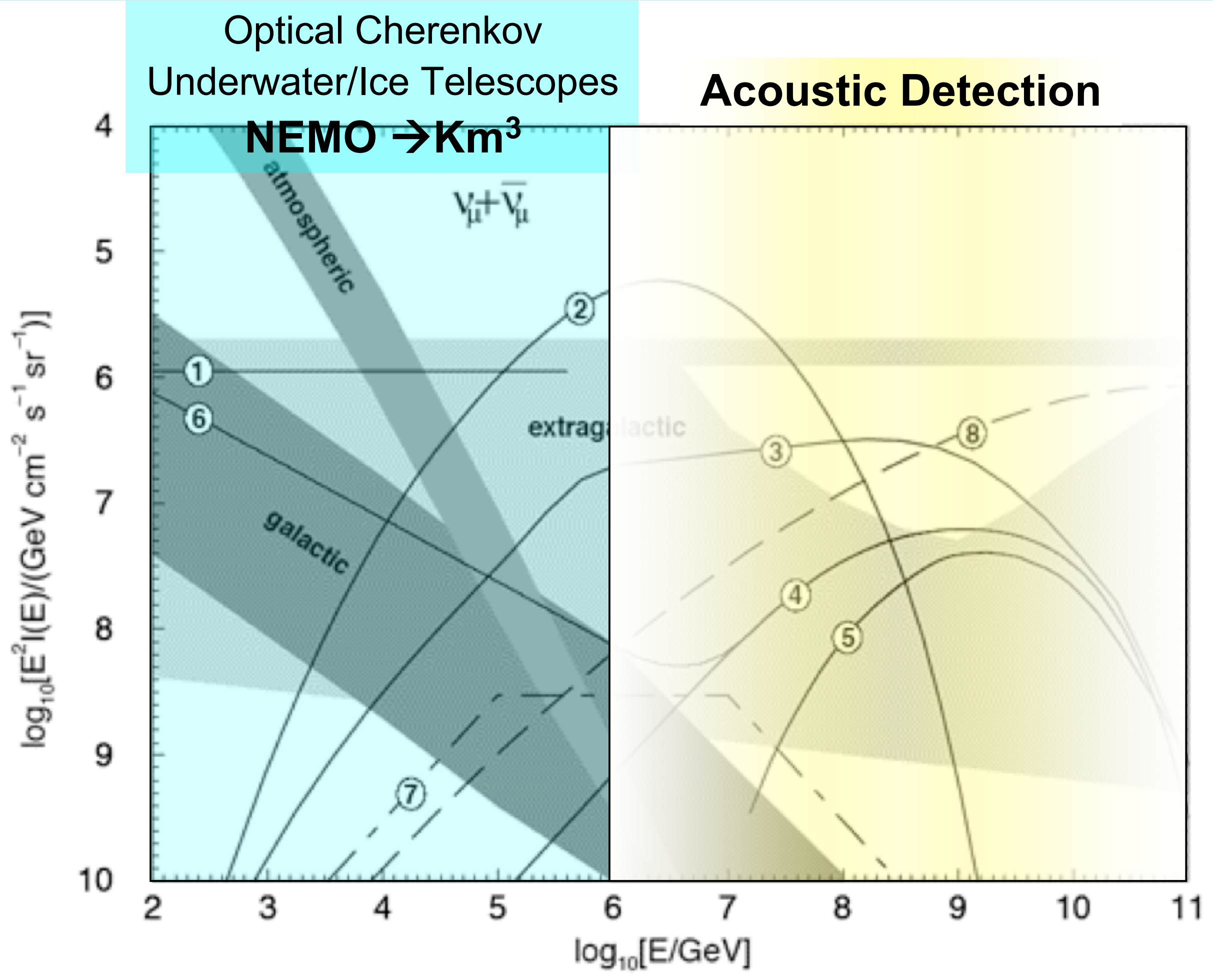
→ **increase $\mathbf{E_{th}}$**: at E_ν>10-100 TeV, astrophysical neutrino flux is more intense than atmospheric background

But at these energies, predicted neutrino fluxes are even lower…

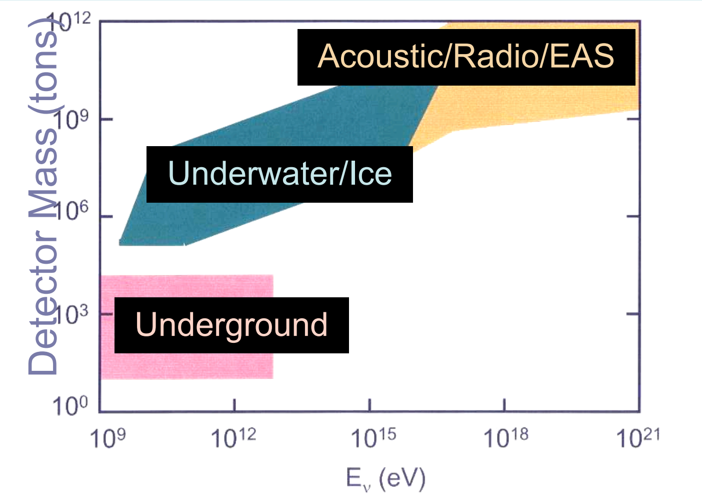
→ attenuation length O(1km) is required

- **Radio & Acoustic Detection Tecniques**

High Energy Neutrino Detection



(1-4 and 6) AGN models; *(5)* GZK; *(7)* GRB; *(8)* topological defects
[adapted from Learned and Mannheim, *Annu. Rev. Nucl. Part. Sci.* 50 (2000)]

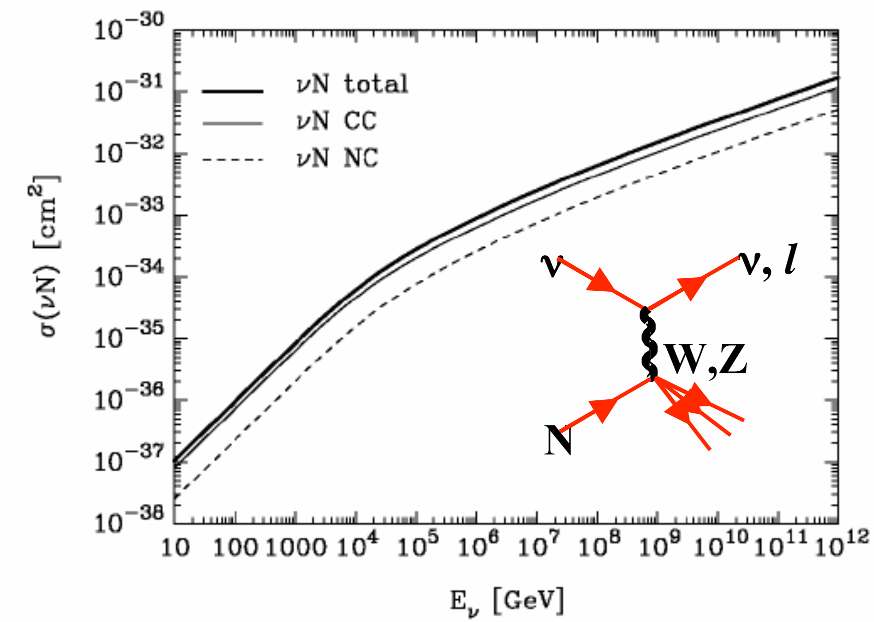


[adapted from Spiering, astro-ph/0012532]

Neutrino Interactions

The Thermo-Acoustic Mechanism and the Acoustic Signal

ν interaction → hadronic cascade / electro-magnetic cascade



[R. Gandhi *et al.* (1996), Astropart. Phys. 5, 81]

"instantaneous" & localized energy deposition

↓

local heating of the medium

↓

Local density variation

↓

PRESSURE WAVE

Thermo-Acoustic (Hydrodynamic) Mechanism of Energy Dissipation

G. A. Askaryan (1979), *Nucl. Inst. Meth.* 164, 267.

The Wave Equation

Wave Equation

$$\nabla^2 p(\vec{r},t) - \frac{1}{v^2}\frac{\partial^2 p(\vec{r},t)}{\partial t^2} = -\frac{\beta}{C_p}\frac{\partial^2 q(\vec{r},t)}{\partial t^2}$$

p(**r**, t)	Pressure
q(**r**, t)	Energy Density
v	Sound Speed
β	Thermal Expansion Coefficient
C_p	Heat Capacity

Solution (Kirchoff Integral)

$$p(\vec{r},t) = \frac{\beta}{4\pi \cdot C_p}\int \frac{dV'}{|\vec{r}-\vec{r}'|}\cdot\frac{\partial^2}{\partial t^2} q\left(\vec{r}', t - \frac{\vec{r}-\vec{r}'}{v}\right)$$

Introducing the hypothesis of

Instantaneous energy deposition

$$\dot{q}(\vec{r},t) = q(\vec{r})\cdot\delta(t) \qquad (\tau_{dep} \ll \tau_h)$$

the problem is reduced to the homogeneous case with the following initial condition:

$$p(\vec{r},t=0) = \frac{\beta}{C_p}\cdot q(\vec{r}) \qquad \dot{p}(\vec{r},t=0) = 0$$

Solution is given by the **Poisson Formula**

$$p(\vec{r},t) = \frac{1}{4\pi}\frac{\beta\cdot v^2}{C_p}\frac{\partial}{\partial R}\int_{S_{\vec{r}}^R}\frac{q(\vec{r}')}{R}d\sigma$$

The integral is performed over a spherical surface of radius *R*=*v*·*t*, centered at the detector position $\vec{r}$

The Poisson Formula

Energy Density
MonteCarlo Simulation
(Geant4, CORSIKA)

$$p(\vec{r},t) = \frac{1}{4\pi}\frac{\beta \cdot \mathrm{v}^2}{C_p}\frac{\partial}{\partial R}\int_{S_{\vec{r}}^{R}}\frac{q(\vec{r}\,')}{R}d\sigma$$

Gruneisen Coefficient γ

It is a dimensionless coefficient, depending on **environmental parameters**.
It determines the **signal amplitude**,
and thus it is a measure of the **thermo-acoustic mechanism efficiency**.

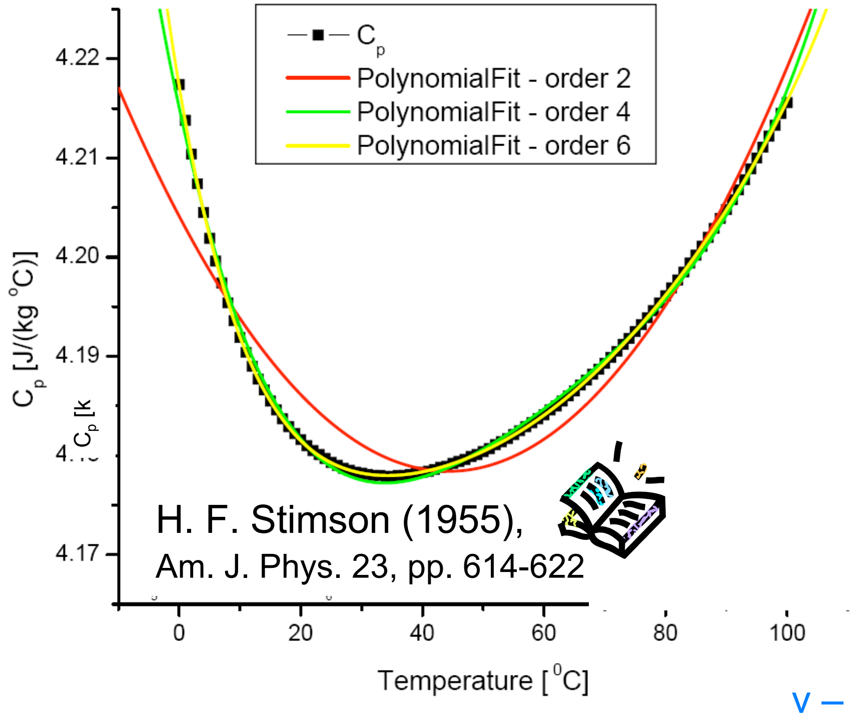
The Gruneisen Coefficient $\gamma = \frac{\beta \cdot v^2}{C_p}$

a parametrization with temperature

C_p – Thermal Expansion Coefficient [°C^{-1}]

Temperature dependence

6th order polinomial fit on Stimson data

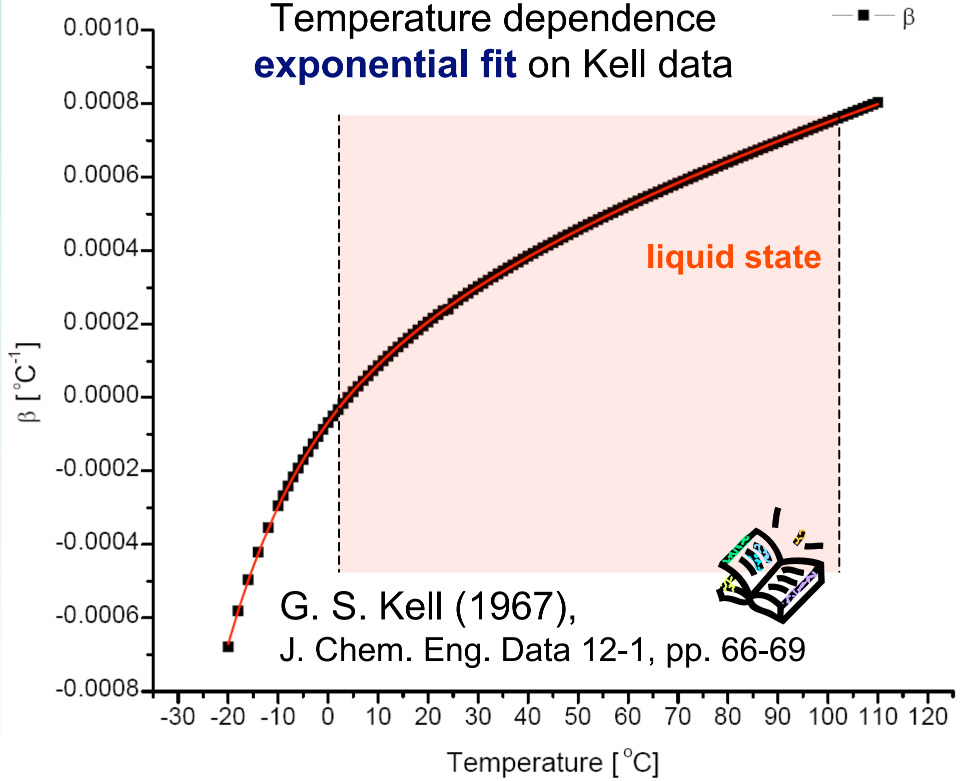


H. F. Stimson (1955),
Am. J. Phys. 23, pp. 614-622

β – Thermal Expansion Coefficient [°C^{-1}]

Temperature dependence

exponential fit on Kell data



G. S. Kell (1967),
J. Chem. Eng. Data 12-1, pp. 66-69

v – Sound Speed [m/s]

Sound speed dependence on environmental parameters (temperature, salinity, depth) has been investigated experimentally by several authors, resulting in many different empirical formulations. We consider an approximated and simplified version of the **Wilson Formula**:

$$v = 1449 + 4.6 \cdot T - 0.055 \cdot T^2 + 0.0003 \cdot T^3 + (1.39 - 0.012 \cdot T) \cdot (S - 35) + 0.017 \cdot Z$$

T = water temperature [°C];
S = salinity [psu];
Z = depth [dbar ~ m]

W. Wilson (1960),
Journ. Acoust. Soc. Amer.32:10, p.1357

Test of the Thermo-Acoustic Mechanism at the ITEP Proton Beam

Moscow, June 2004

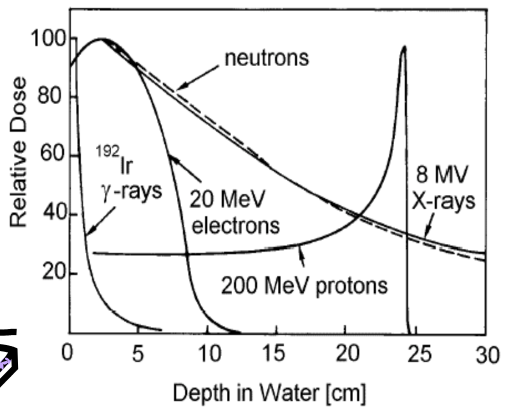
GDB, A. Capone, R. Masullo,
G. Riccobene, V.Lyashuk, A.Rostovstev

Protons Energy Deposition in Water

the Bragg Peak

If the primary proton energy is in the range 100-200 MeV, most of the energy is released at the end of the particle track, at the so-called **Bragg Peak.**

The Bragg Peak phenomenon fulfills the hypothesis of the thermo-acoustic model; it can thus work as **acoustic source** for calibration.

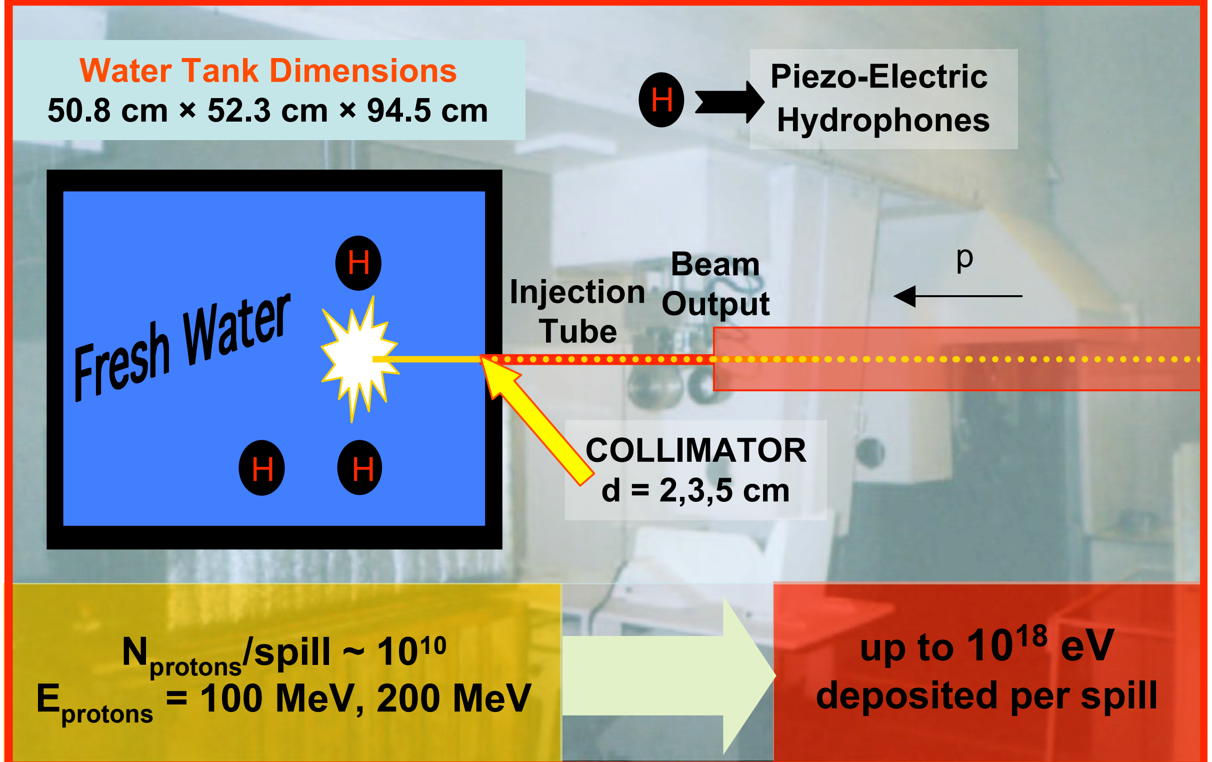


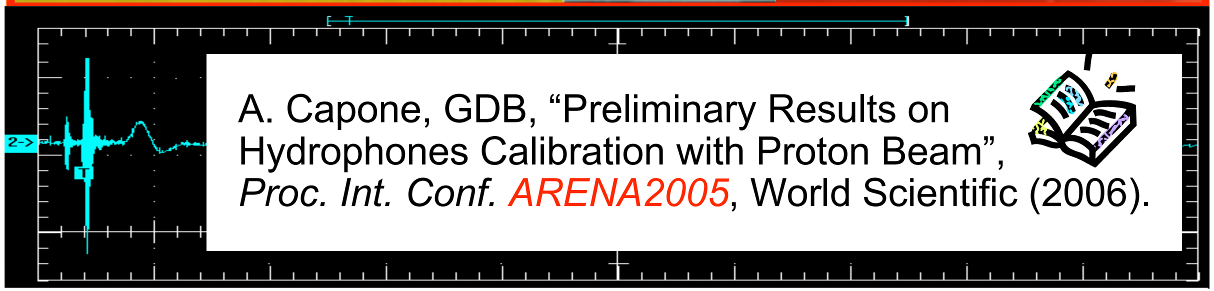
C. Grupen, arXiv:physics/0004015 (2000)

Uncertainties during the data taking
(beam profile, hydro. pos., temperature)

Monte Carlo can help

Experimental Set-Up





A. Capone, GDB, "Preliminary Results on Hydrophones Calibration with Proton Beam", *Proc. Int. Conf. ARENA2005*, World Scientific (2006).

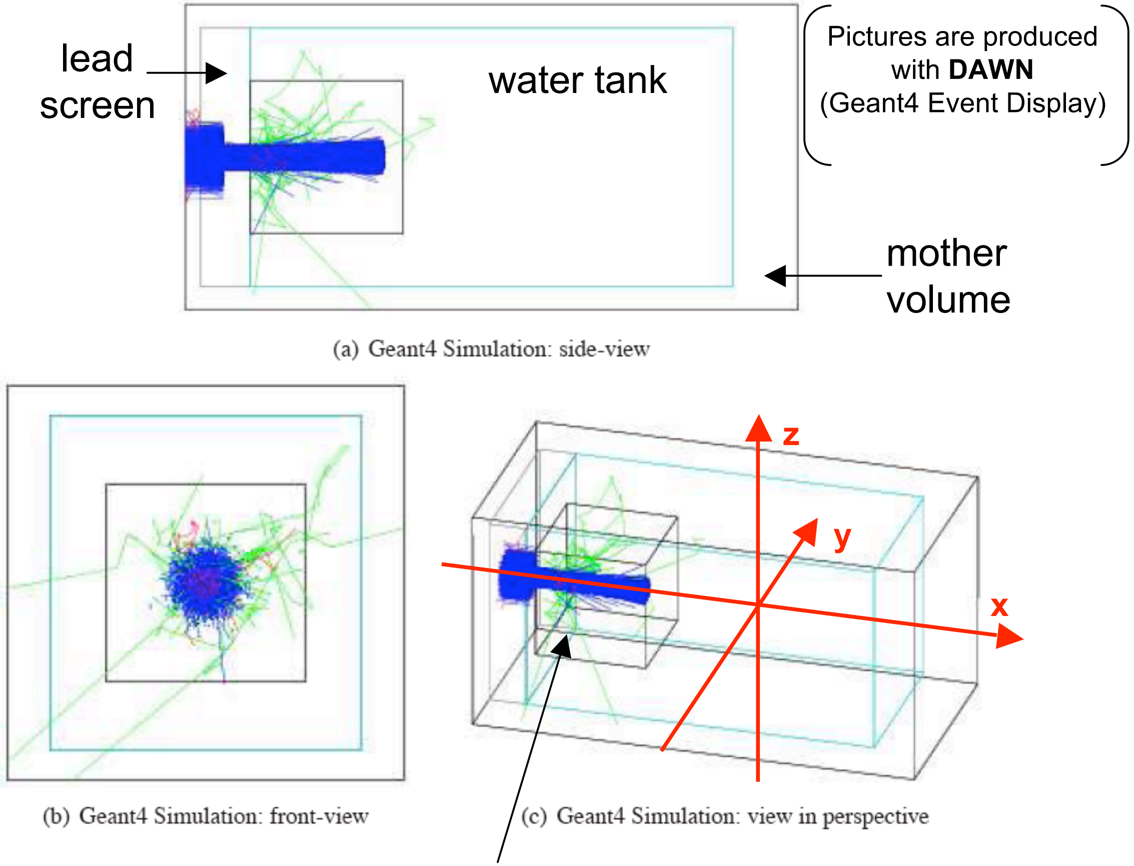
Monte Carlo

http://geant4.web.cern.ch/geant4/

AcSource = Geant4 simulation of ITEP test beam

Geant 4 Simulation Toolkit is used to reproduce the ITEP Test Beam experimental set-up

Pictures are produced with **DAWN** (Geant4 Event Display)



(a) Geant4 Simulation: side-view

(b) Geant4 Simulation: front-view

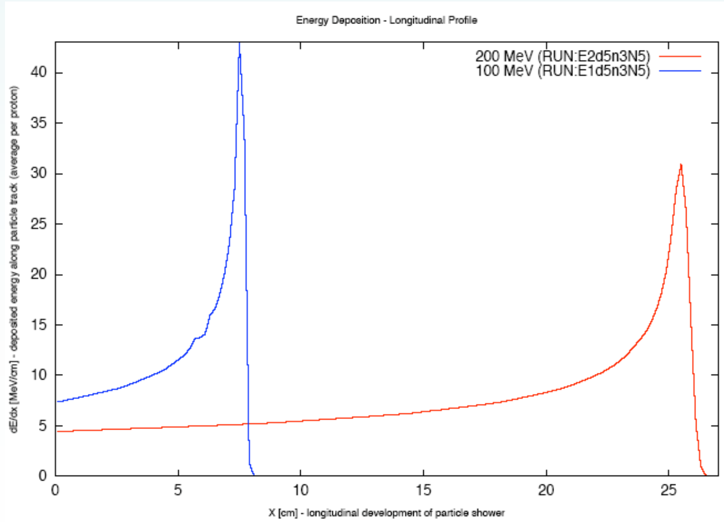
(c) Geant4 Simulation: view in perspective

sensitive volume

The sensitive volume is a cube with a side of 30 cm, divided in cubic cells (tri-dimensional grid), each one with a side of 0.2 cm and a volume of 0.008 cm^3

A detailed simulation of the **water tank** (class ItepDetectorConstruction) and of the **proton injector** (class ItepPrimaryGeneratorAction) has been performed.

The result is an output ASCII file with the "map" of the energy density deposition *rhoE(x,y,z)* over a tri-dimensional grid.



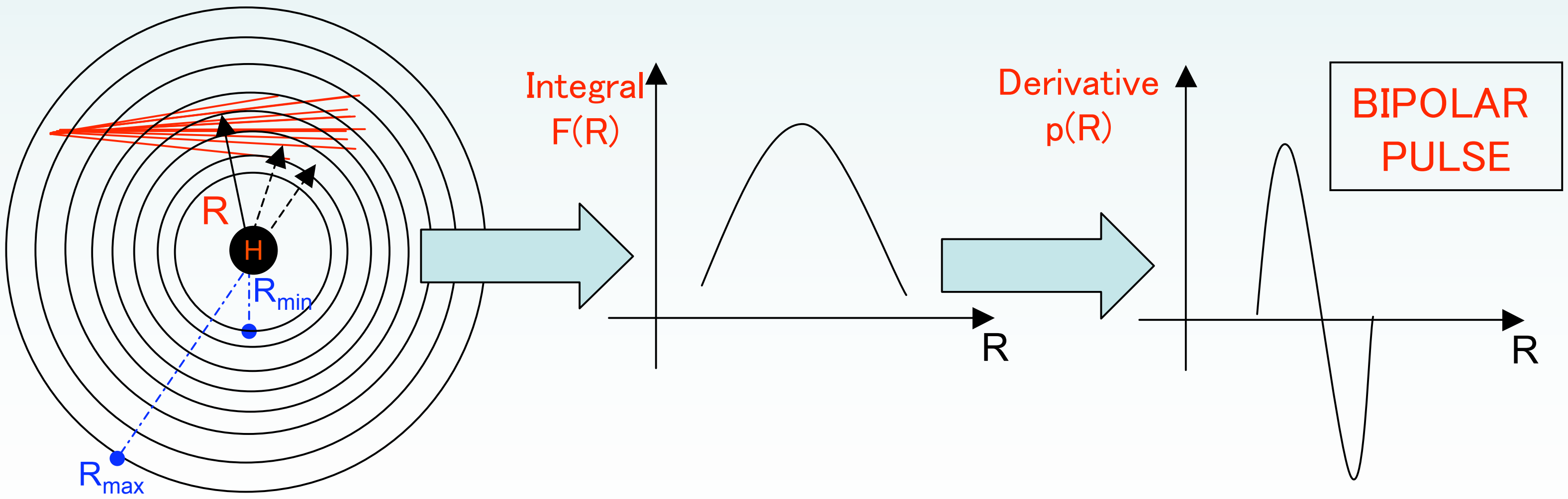
AcPulseComputation
the Bipolar Pulse

The main frame of reference is a set of Cartesian coordinates (O, x, y, z) centered at the middle of the water tank (target volume).
A set of spherical coordinates (H, R, θ, φ) is placed at the hydrophone position, with:

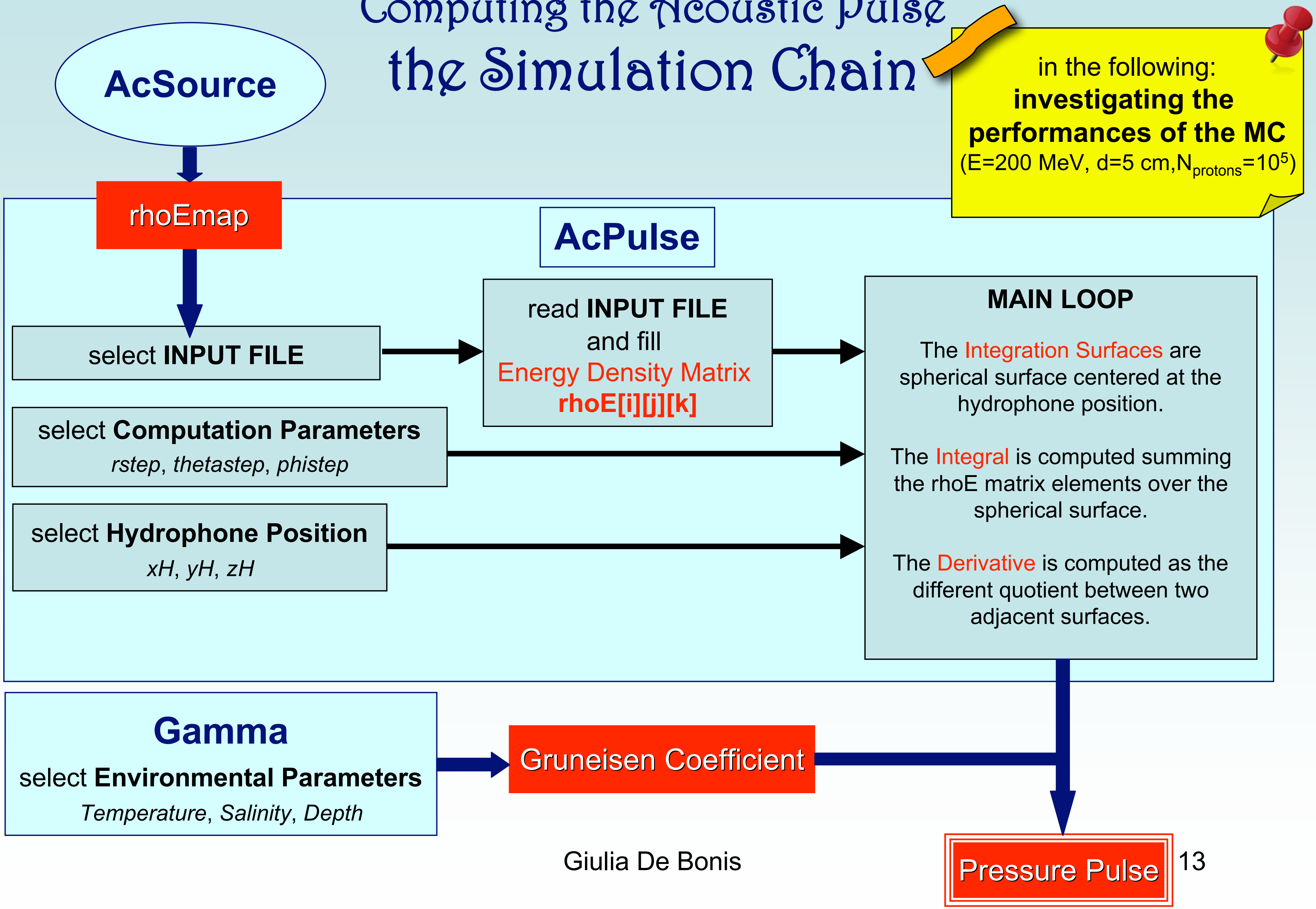
$R = (R_{min}, R_{max})$ (sorrounding the source)
$\theta = (0, \pi)$
$\varphi = (0, 2\pi)$

(In a discrete computation, the coordinates variation is defined by rstep, θstep, φstep)

The "pointer" moves all around, scanning the volume all around the hydrophone, and computing the integral F(R) over spherical surfaces.
Space derivative is computed between two adjacent spherical surface.

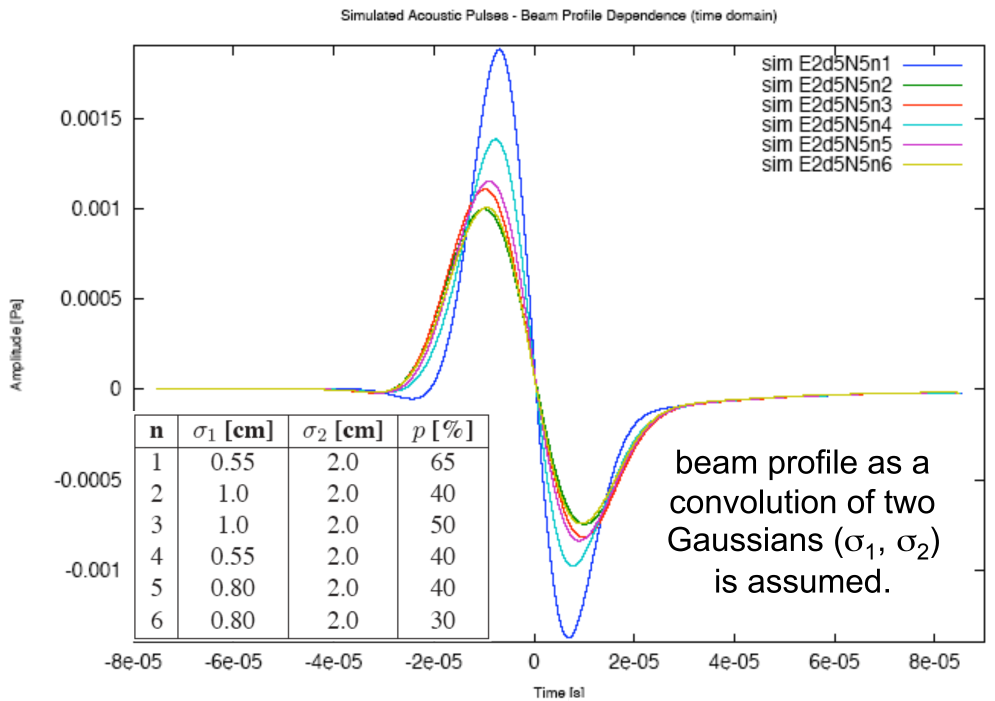


Computing the Acoustic Pulse
the Simulation Chain



Investigating the performances of the MonteCarlo

Beam Profile (Source Size) dependence



n	σ_1 [cm]	σ_2 [cm]	p [%]
1	0.55	2.0	65
2	1.0	2.0	40
3	1.0	2.0	50
4	0.55	2.0	40
5	0.80	2.0	40
6	0.80	2.0	30

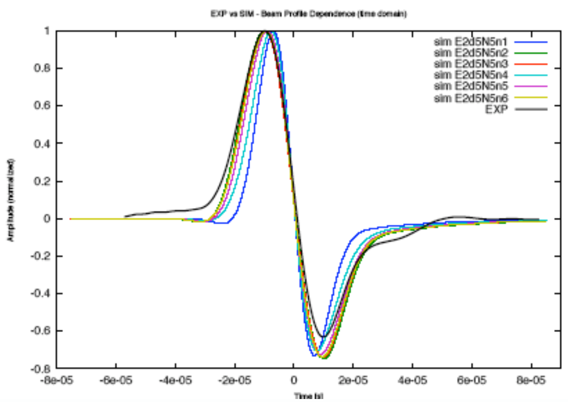
Beam profile settings determine the size and shape of the energy deposition.
Results are consistent with expectations from Askaryan (1979):

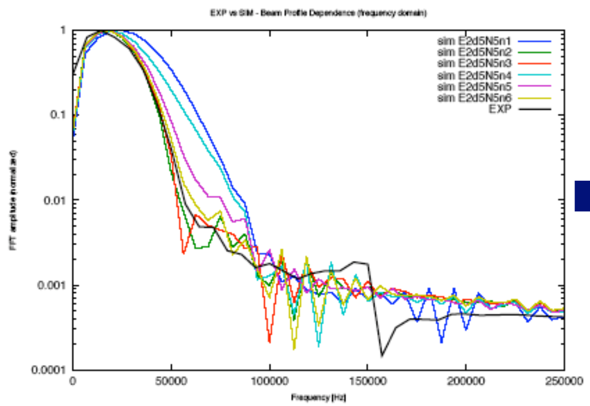
The frequency spectrum is centered at the value

$$f_{eff} = \frac{v}{2 \cdot \ell}$$

ℓ is the transverse size of the source
v is the sound speed.

narrow beam → smaller size → signal longer in freq. domain and shorter in time domain.
wide beam → larger size → signal shorter in freq. domain and longer in time domain.



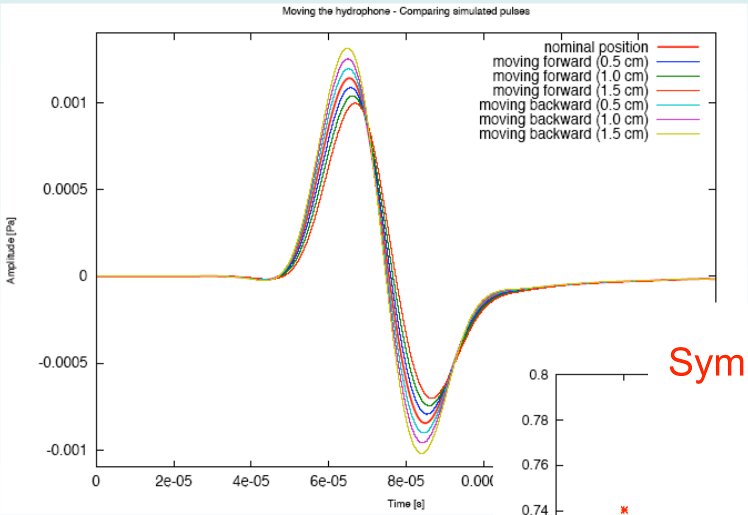


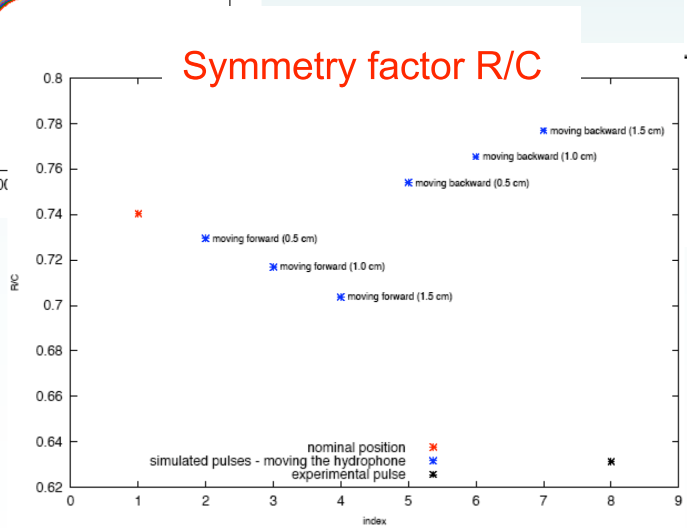
Comparing experimental data and simulation results, it is possible to have an indication on beam profile settings.

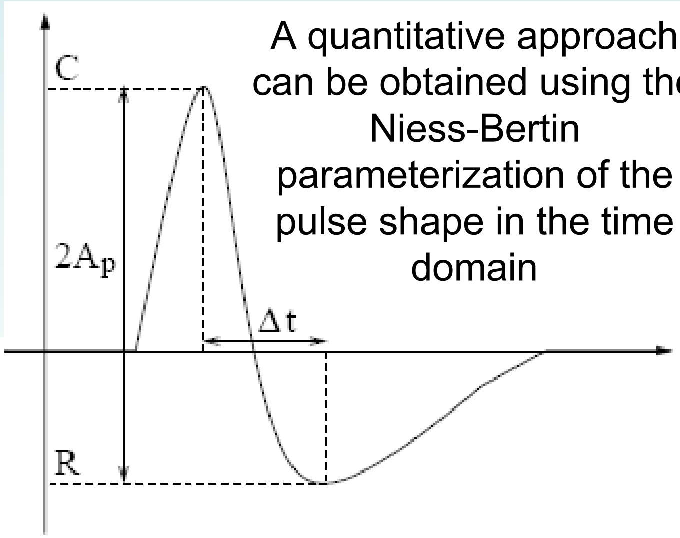
Investigating the performances of the MonteCarlo

Hydro pos dependence

- The amplitude of the pulse depends on the Gruneisen coefficient (next slide)
- The shape of the pulse depends on the shape of the source (beam profile settings) and on the geometry of the detection (hydrophone position)
- Once that the beam profile is selected, one can "**move the hydrophone**" in order to find the position of the detector that best reproduces the experimental data.







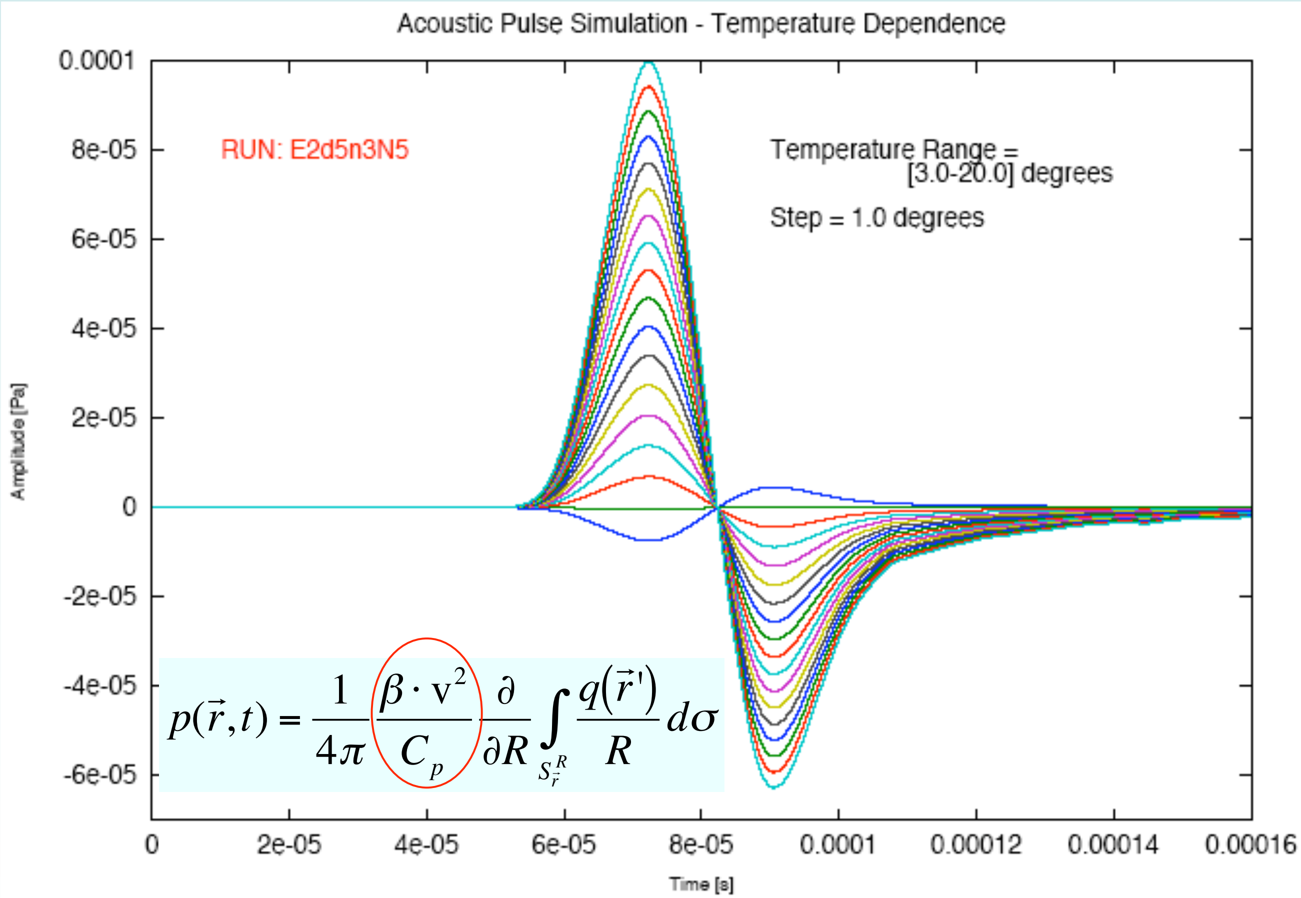
A quantitative approach can be obtained using the Niess-Bertin parameterization of the pulse shape in the time domain

V. Niess, V. Bertin, Astropart.Phys. Vol. 26, Issues 4-5, pp. 243-256 (2006), e-Print astro-ph/0511617.

Investigating the performance of the MonteCarlo

Temperature dependence

For a **fixed geometry** (hydrophone position and source shape), the amplitude of the signal depends only on the Gruneisen Coefficient, that is a **function of temperature**

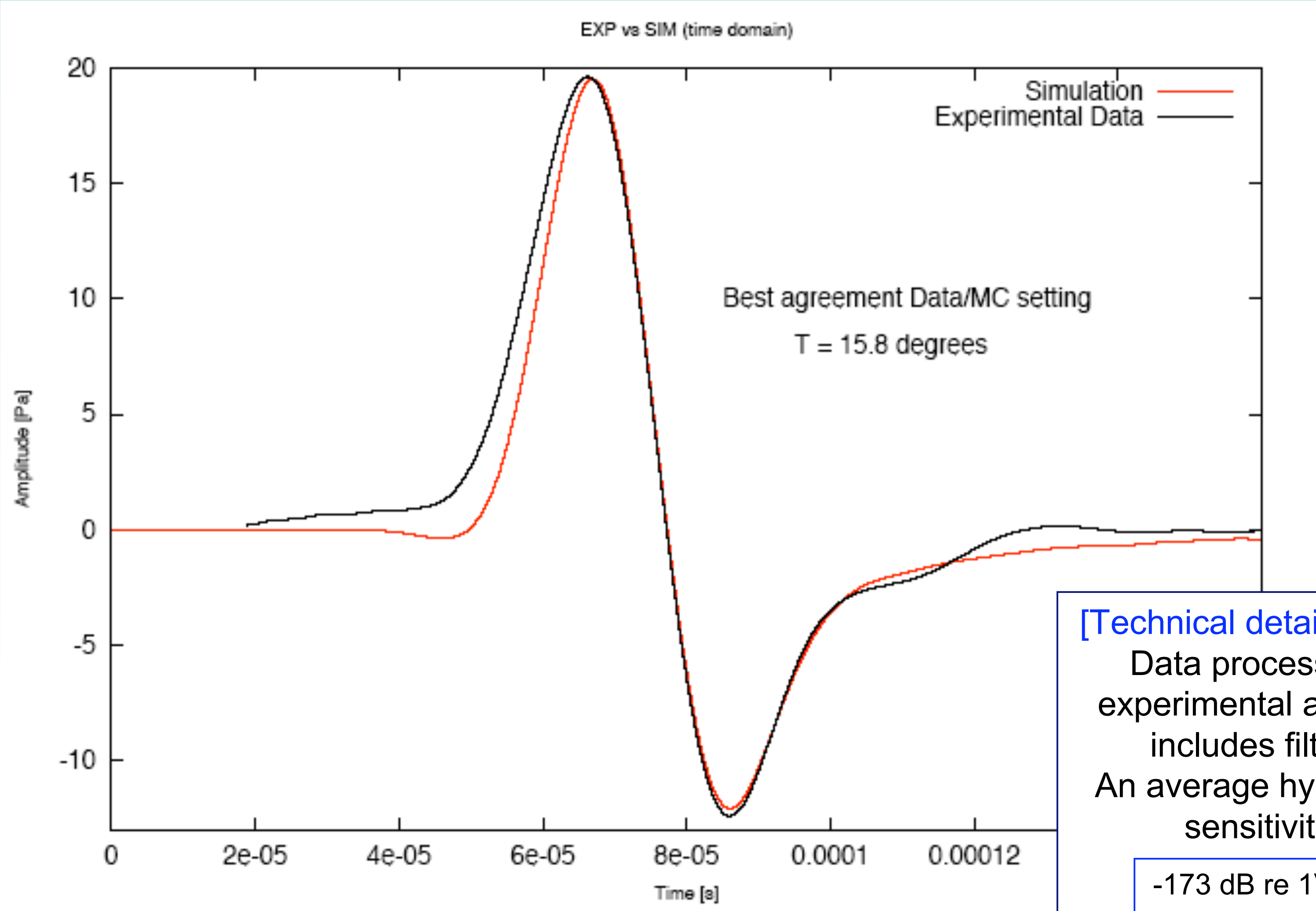


$$p(\vec{r},t) = \frac{1}{4\pi} \frac{\beta \cdot v^2}{C_p} \frac{\partial}{\partial R} \int_{S_{\vec{r}}^R} \frac{q(\vec{r}\,')}{R} d\sigma$$

The best agreement data/MC

[E=200 MeV, d=5 cm]

Selecting the "best" beam profile and the "best" hydrophone position, the best agreement data/MonteCarlo is obtained with **T=15.8°**



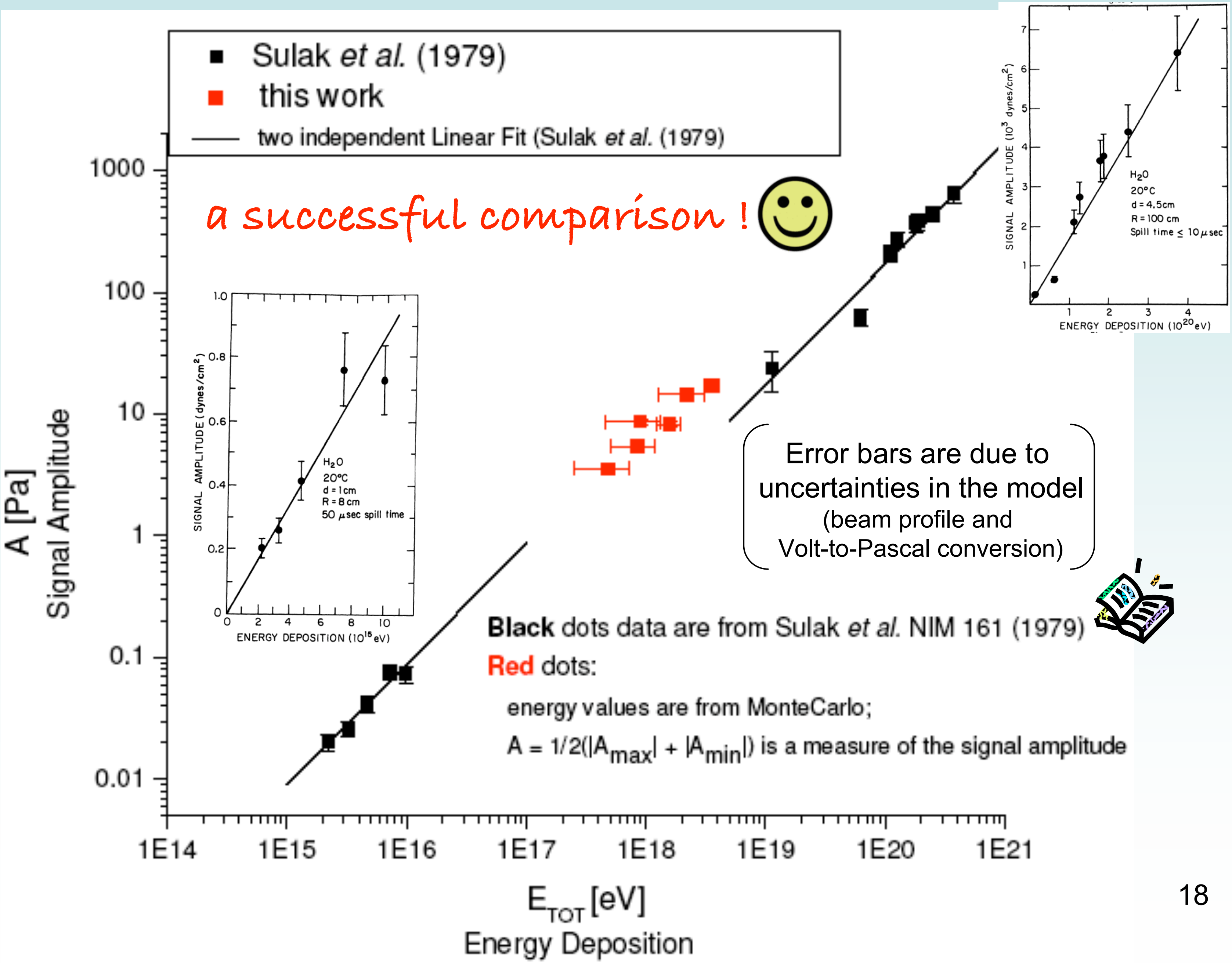
[Technical details in short]
Data processing on experimental acquistion includes filtering.
An average hydrophone sensitivity of

-173 dB re 1V/1μPa

is considered

Comparison with Sulak Data

Linearity of the **signal amplitude** with total deposited **energy**



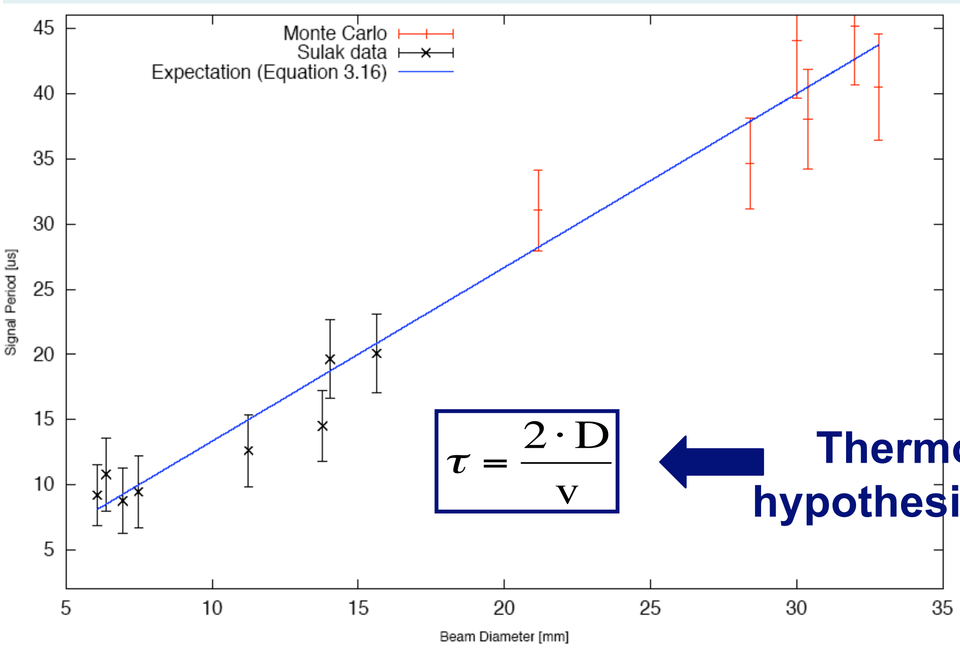
Comparison with Sulak Data: an additional test of the Simulation Chain

Validation of the thermo-acoustic model

• Sulak investigations aim to prove that thermo-acoustic mechanism of sound generation is dominant over alternative mechanisms.

• The ITEP simulation is based on the **thermo-acoustic hypothesis** (Poisson Formula) and it well describes the outcome of the ITEP experiment

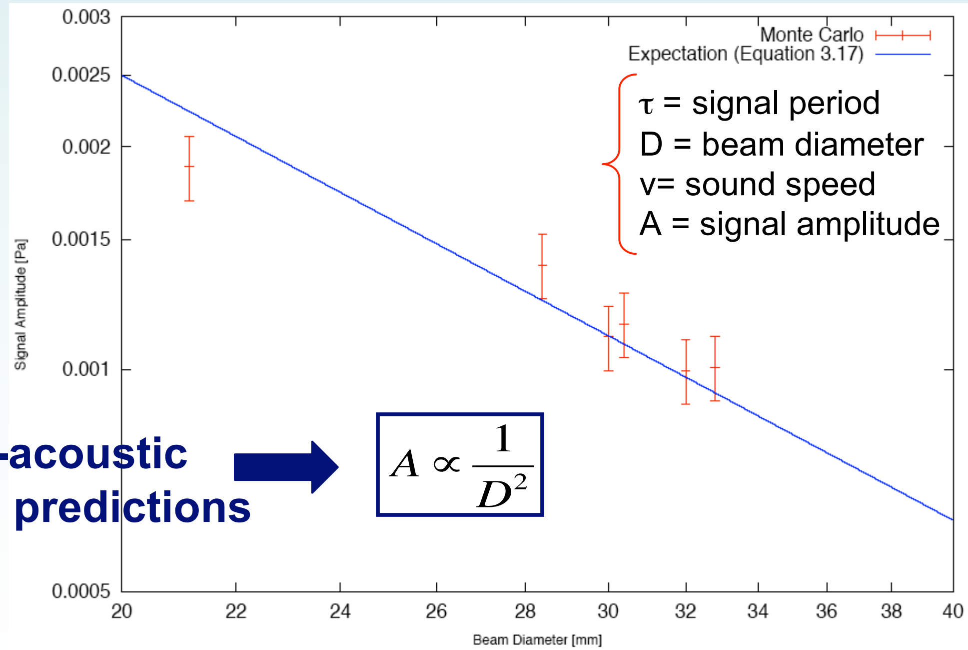
➔ Since the Monte Carlo shows agreement with Sulak results, this constitutes a further confirmation of the thermo-acoustic model at the ITEP test beam.



$$\tau = \frac{2 \cdot D}{v}$$

Thermo-acoustic hypothesis predictions

$$A \propto \frac{1}{D^2}$$



ITEP Test Beam - Conclusions

- After the preliminary results presented @ARENA2005 (Zeuthen), the ones presented today can be intended as **"conclusive" results** from the ITEP-2004 Test Beam.
- The development of the Monte Carlo has given the opportunity to **progress in the understanding of the thermo-acoustic mechanism**. Combining outcomes from data analysis and MC simulation, it is possible to have indications on some acquisition parameters that can **enrich the knowledge of the experimental setup**.

  ➔ Further test experiments can be planned to investigate the acoustic signal induced by particles interaction in water. A mandatory recommendation for the future is to include a strict control on environmental parameters and geometry.
- The ITEP test beam experiment produces confirmation of the thermo-acoustic mechanism of sound generation, as results in comparing MC and data. An additional validation comes from the good agreement with previous measurements (Sulak *et al*. - 1979), that, in addition, indicates that **the simulation chain**, developed for proton induced showers in the frame of the ITEP test beam experiment, **is well adequate to describe the thermo-acoustic phenomenon** of pressure pulse generation.

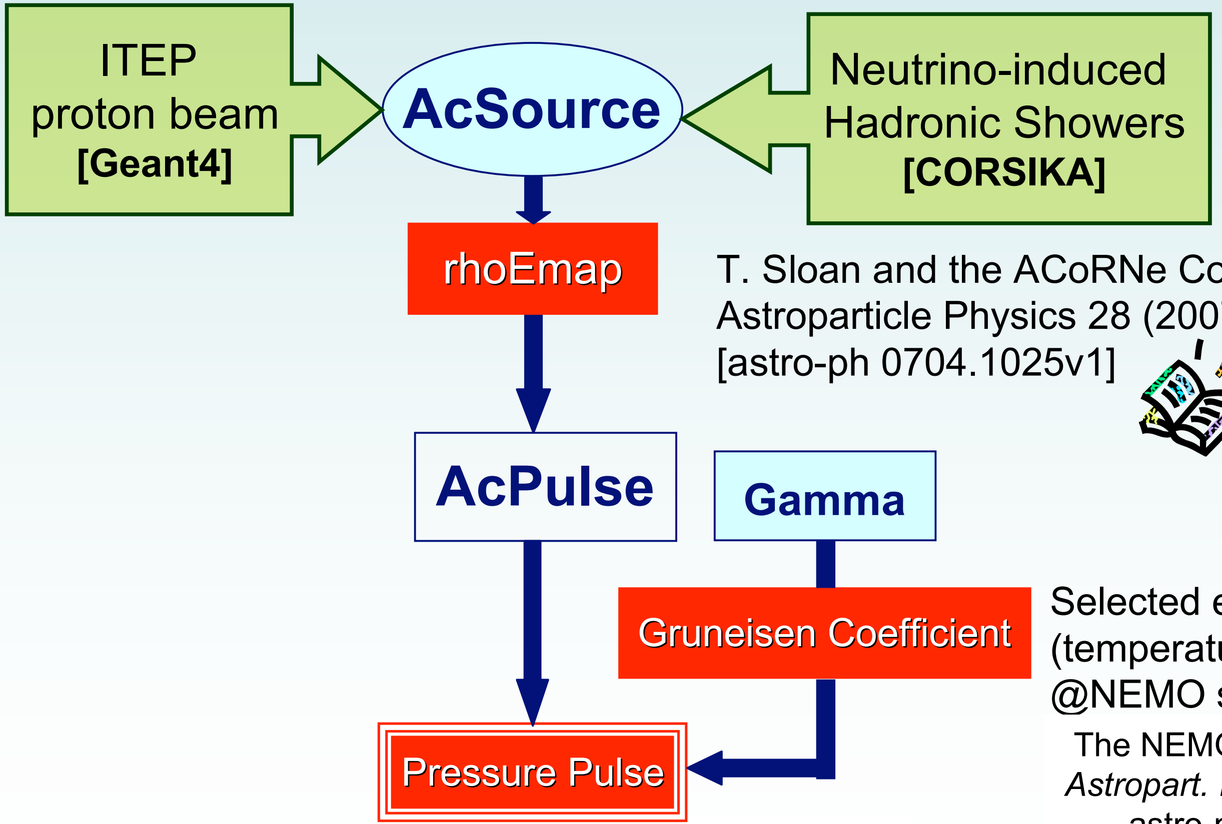
  ➔ The Monte Carlo can be applied as a valid tool to explore the neutrino case

from Protons... to Neutrinos

from Protons… to Neutrinos

Moving to the neutrino-case, AcPulse is fed with **neutrino-induced hadronic showers** propagating in water. The tracking of the particles in the shower and the evaluation of their energy losses is computed with a **modified** version of the CORSIKA code.

http://www-ik.fzk.de/corsika/



T. Sloan and the ACoRNe Collaboration
Astroparticle Physics 28 (2007)
[astro-ph 0704.1025v1]

Selected environmental parameters (temperature, salinity, depth) @NEMO site - Mediterranean Sea

The NEMO Collaboration
Astropart. Phys. 27 (2007)
astro-ph/0603701

AcSource = CORSIKA Showers

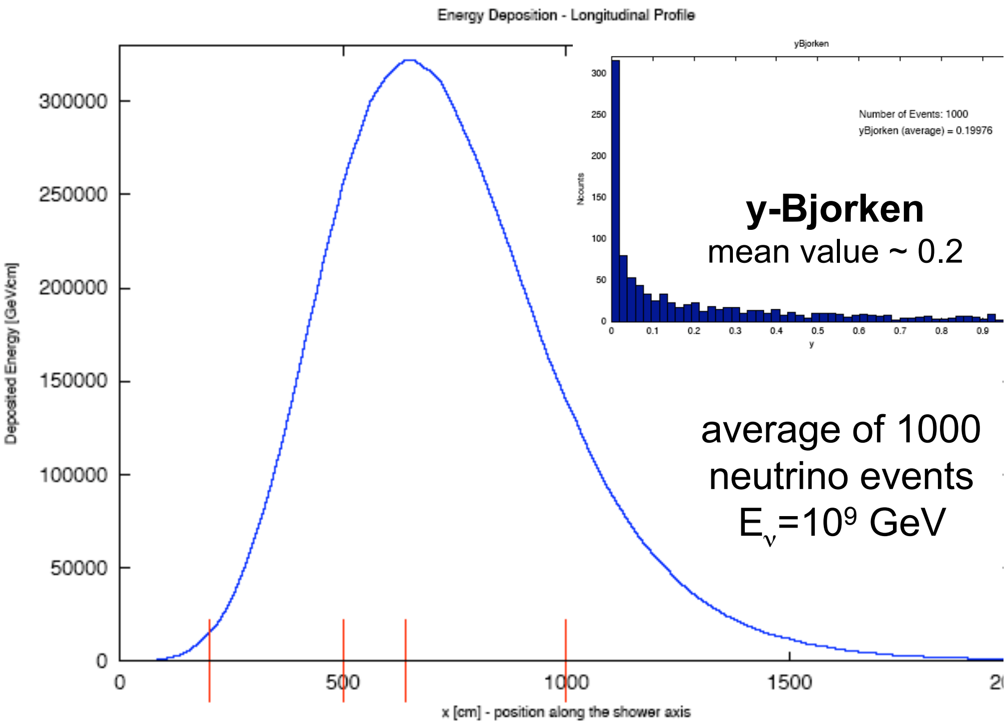
Neutrino-induced Hadronic Shower ($E_\nu=10^9$ GeV)

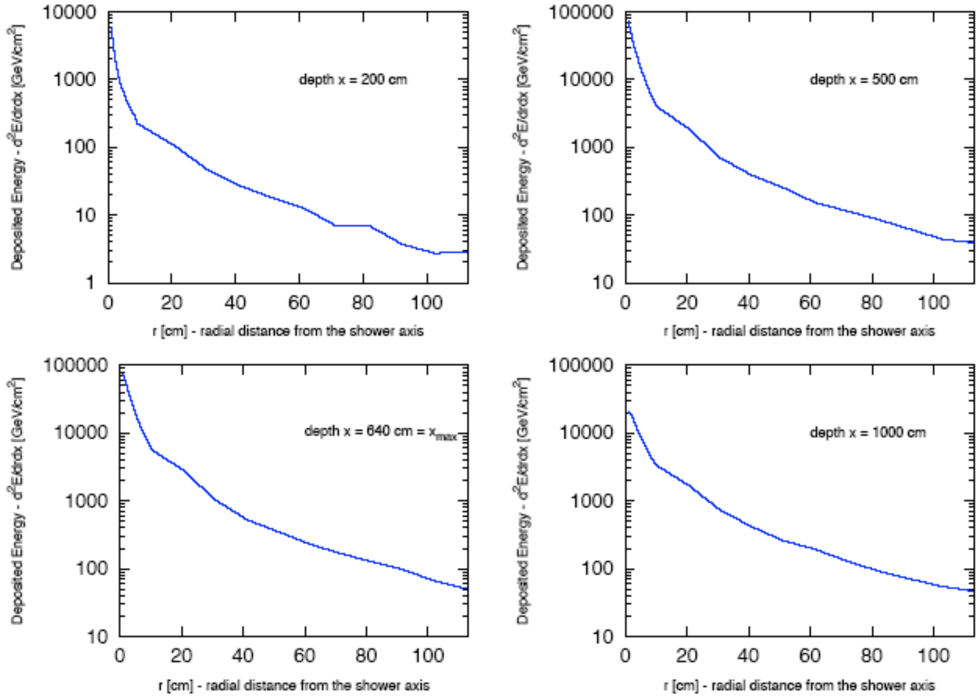
The CORSIKA AcSource Monte Carlo assumes that a CORSIKA proton induced shower is equivalent to a neutrino induced hadron shower at the same energy

↓

the CORSIKA shower collection reproduces the hadronic component of the particle cascade generated at the neutrino interaction point.

$$E_H = y_B E_\nu$$





Signal Amplitude A vs Distance R

($E_\nu = 10^9$ GeV and $X_H = X_{max}$)

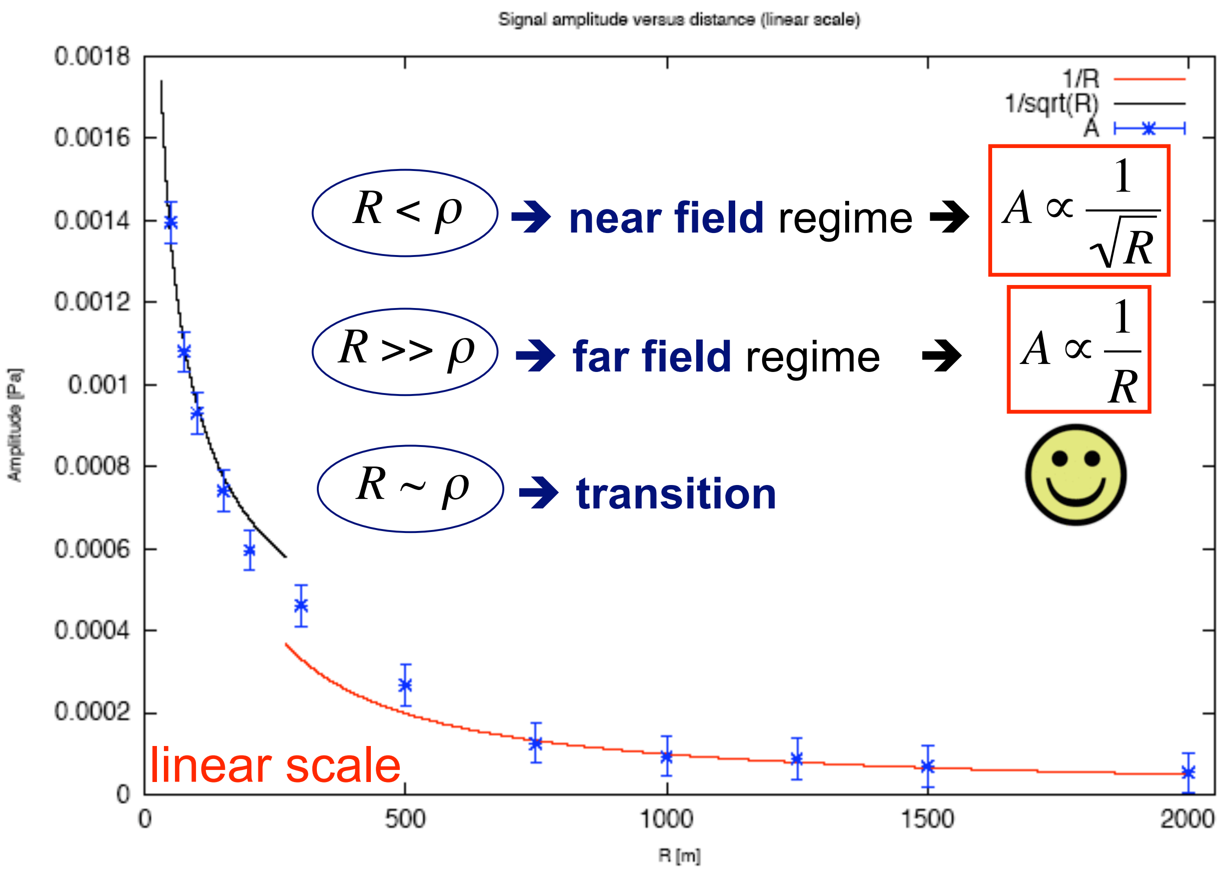
R is the distance between the shower axis and the receiver

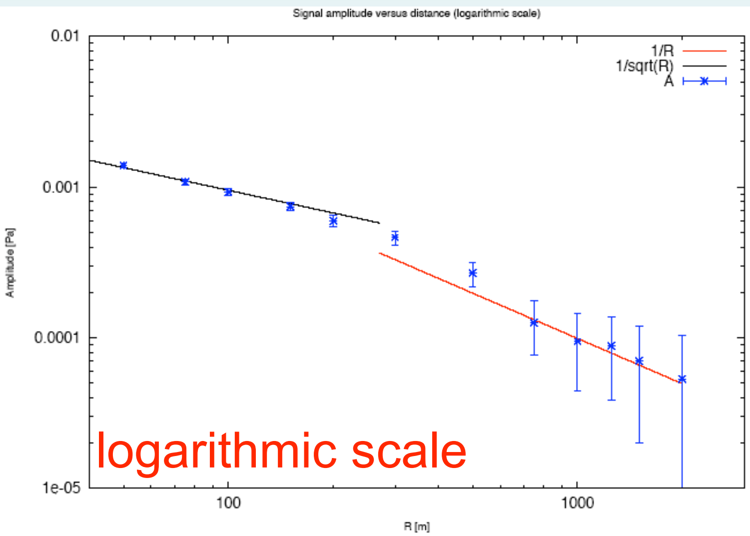
$$\rho = \frac{L^2}{\lambda}$$

- *L* is the length (longitudinal size) of the acoustic source
- λ is the wavelength of the acoustic pulse

λ is connected with source diameter (transverse size)

$$\lambda = 2 \cdot D$$

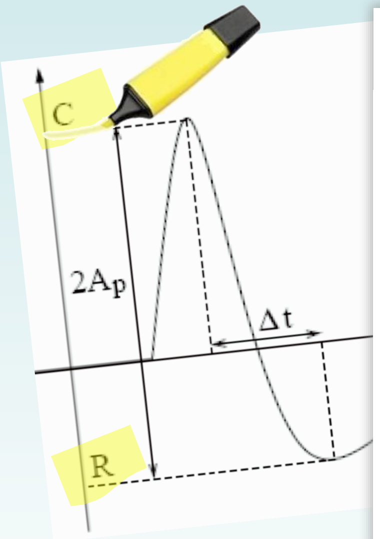




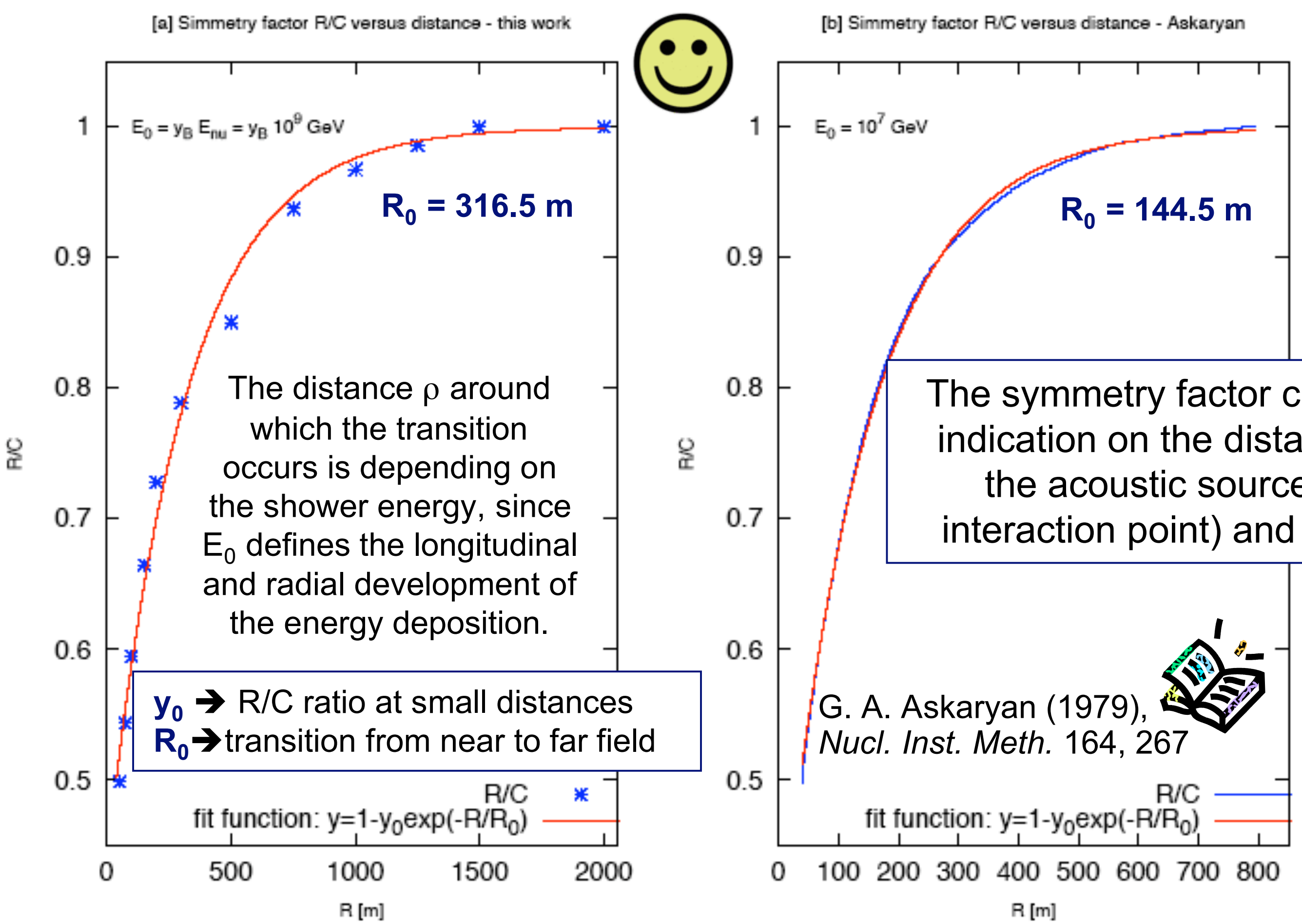
Symmetry Factor R/C vs Distance R

(E_ν=10^9 GeV and X_H=X_{max})

$R/C \rightarrow 1$ ➡ The further the hydrophone is, the more **point-like** the acoustic **source** appears, and therefore the more the pressure signal approaches a perfect **bipolar pulse**.



The outcome is consistent with Askaryan results (same fit function!)



The distance ρ around which the transition occurs is depending on the shower energy, since E_0 defines the longitudinal and radial development of the energy deposition.

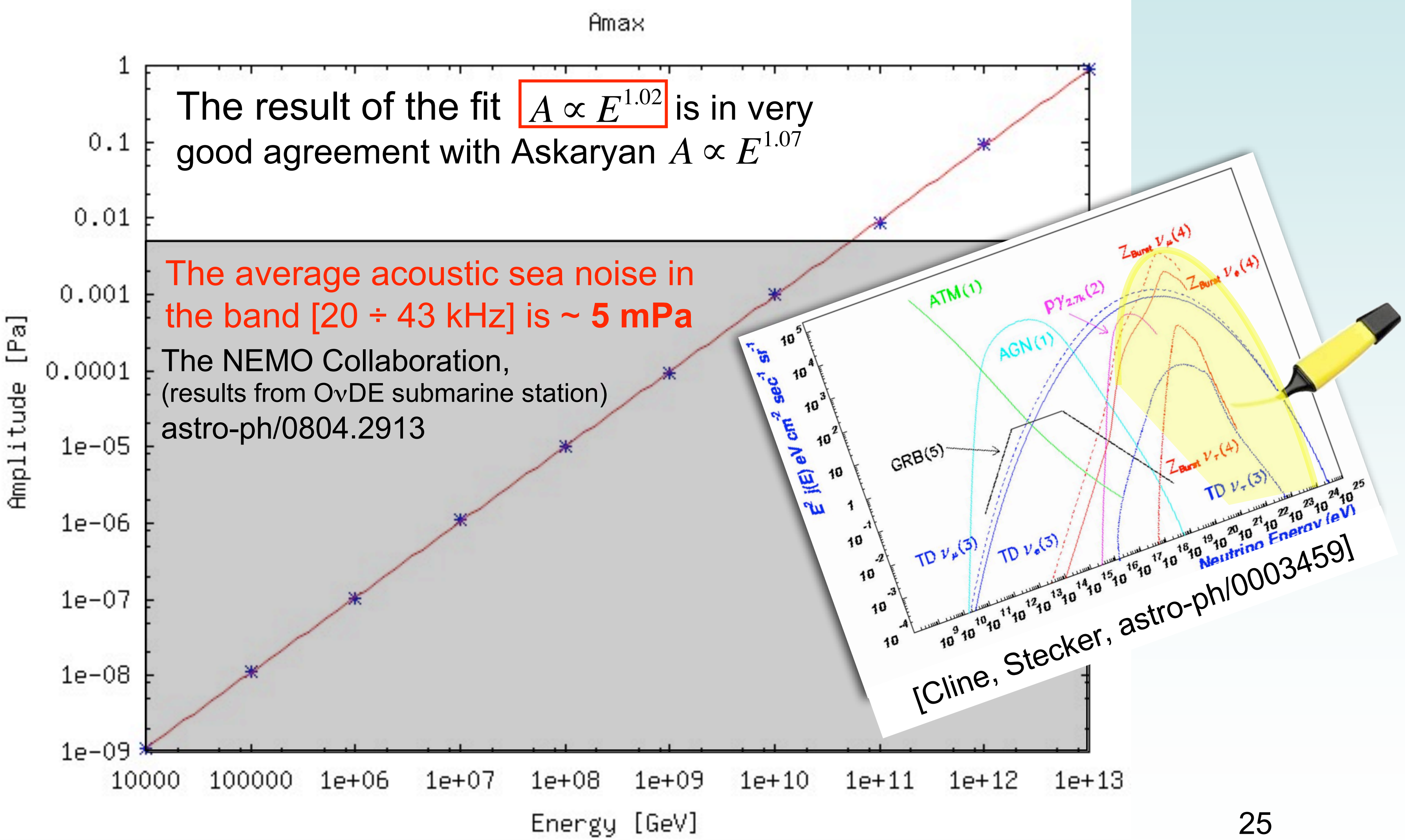
y_0 ➔ R/C ratio at small distances
R_0➔transition from near to far field

The symmetry factor can provide an indication on the distance between the acoustic source (neutrino interaction point) and the receiver.

G. A. Askaryan (1979), *Nucl. Inst. Meth.* 164, 267

Signal Amplitude **A** vs Energy E_ν

(**R**=1 km and $x_H = x_{max}$)



The result of the fit $A \propto E^{1.02}$ is in very good agreement with Askaryan $A \propto E^{1.07}$

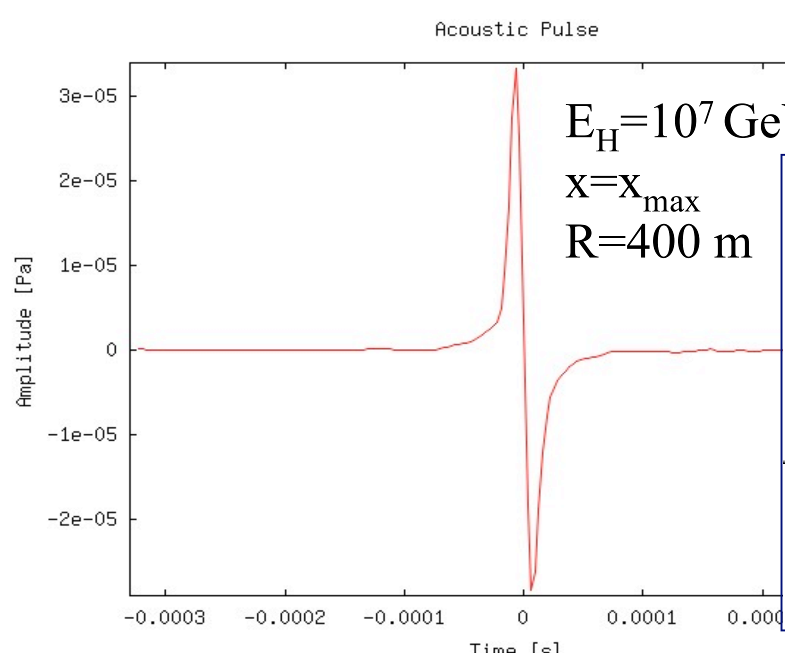
The average acoustic sea noise in the band [20 ÷ 43 kHz] is ~ **5 mPa**

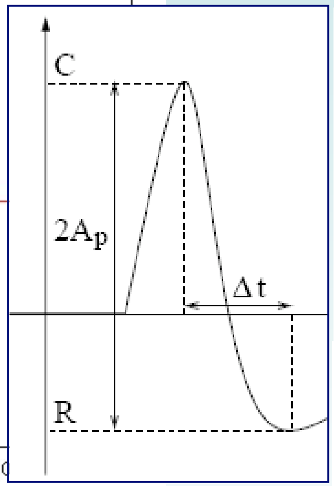
The NEMO Collaboration,
(results from OνDE submarine station)
astro-ph/0804.2913

[Cline, Stecker, astro-ph/0003459]

Acoustic Pulse
Comparison with previous results

preliminary



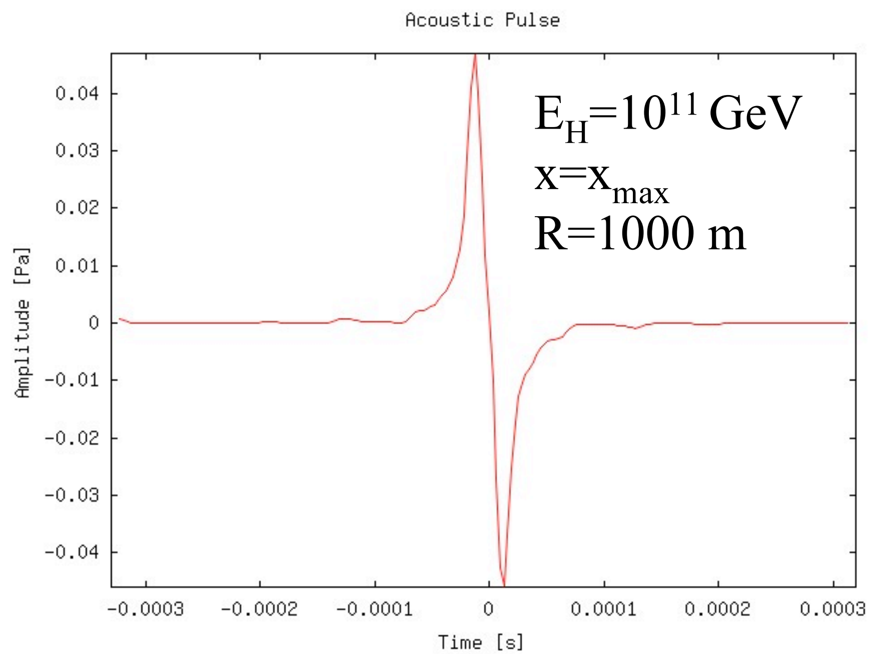


	$A_p[\mu Pa]$	$\Delta t[\mu s]$	R/C [%]
Askaryan	25	17	100
Learned	3	20	50
Dedenko	44	10	75
Niess	47	10	35
this work	31	13	84

[Results cited in: V. Niess, V. Bertin, Astropart.Phys. 26, Issues 4-5, pp. 243-256 (2006), e-Print astro-ph/0511617]

[Results cited in: The ACoRNe Collaboration, Astrop. Phys. 28 (2007), astro-ph 0704.1025v1]

	A_p[mPa]	$\Delta t[\mu s]$	R/C [%]
SAUND	47	19	67
ACoRNe	80	16	64
this work	46	26	97



Conclusions & Perspectives

- Results of the ITEP test beam experiment, supported by the Monte Carlo simulation, offer a **validation of the thermo-acoustic mechanism.**
- Simulation developed for the ITEP test beam experiment can be extended to the neutrino-case. **Results are consistent with predictions** of the thermo-acoustic model and **in agreement with previous results** (Askaryan)
- Still large uncertainties are present comparing computations from different authors. Further investigations are required.
- Preliminary studies show that signal amplitude @1km is **above the noise threshold** in the energy range where **top-down models and GZK neutrinos** are expected. Noise threshold can be lowered (***matched filters*** and ***beam forming*** techniques)➔ **F. Simeone**
- The work carried on up to now is intended to answer the key question:

How does a neutrino sound like?

Outcomes from the simulation of neutrino-induced acoustic pulses can provide hints to increase signal-to-noise ratio and to develop reconstruction algorithms, in order to include **acoustic neutrino detection in underwater telescopes** *à la* NEMO.

see F. Simeone's talk ☺

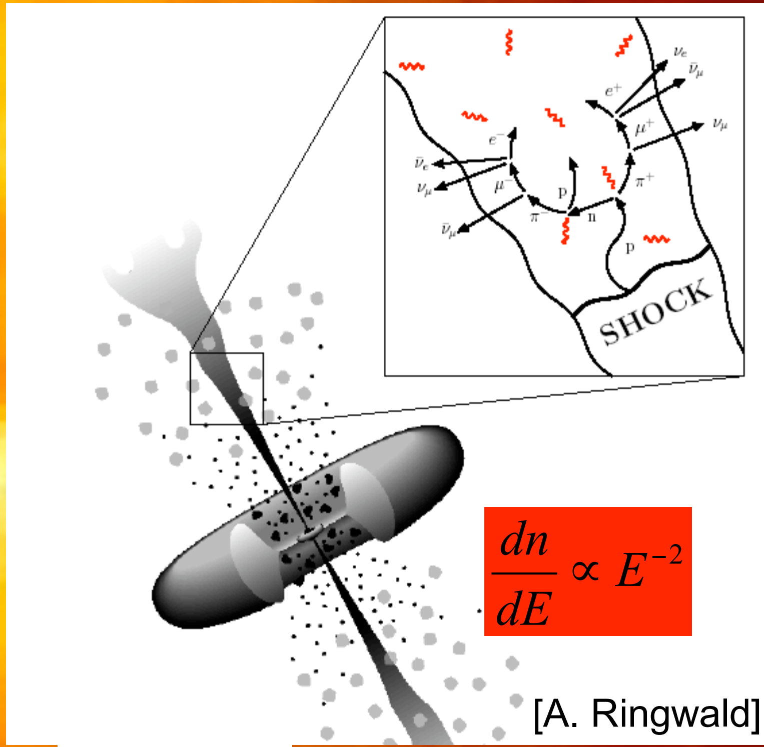
back-up slides

UHEν's Production: Acceleration
(*bottom-up* model)

Fermi engine (AGNs, SNRs)

- *protons*, confined by magnetic fields, are accelerated through repeated scattering by plasma shock fronts
- collisions of trapped protons with ambient plasma produce γs and νs:

$$p + N, \gamma \rightarrow X + \begin{matrix} \pi^{\pm} \rightarrow \text{neutrinos} \\ \pi^{o} \rightarrow \gamma - \text{rays} \end{matrix} \Bigg\} \quad E_{\nu} \sim 0.05\, E_{p}$$



$$\frac{dn}{dE} \propto E^{-2}$$

[A. Ringwald]

core of Galaxy NGC 4261
Hubble Space Telescope

CR Propagation → GZK cut-off

[Greisen – Zatsepin – Kuzmin]

The UHE CR horizon is limited by interactions with low energy background radiation

→ **Pion Photoproduction**

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ \quad \hookrightarrow \gamma\gamma \\ n + \pi^+ \\ \quad \hookrightarrow \mu^+ + \nu_\mu \\ \qquad \hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e \\ \hookrightarrow p + e^- + \bar{\nu}_e \end{cases}$$

$E\gamma \sim 10^{-4}$ eV (T~2.7 K) ⇒ $E_{th} \sim 3\times10^{19}$ eV

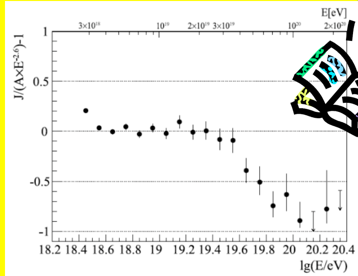
$n_{CMBR} \sim 400$ cm^{-3}, $\sigma_{p\gamma} \sim 100$ μbarn ⇒ $\lambda^{pCMBR}_{att} = \frac{1}{\sigma_{p\gamma} n_{CMBR}} < 50$ Mpc

! Pierre AUGER Observatory NEW RESULTS !

PIERRE AUGER OBSERVATORY

… towards a confirmation of the GZK cut-off

→ UHE neutrino source guaranteed by propagation processes



arXiv:0706.2096v1 [astro-ph]

GZK NEUTRINOS (diffuse flux)

Neutrinos at $10^{17\text{-}19}$ eV predicted by standard-model physics through the GZK process:

observing them is crucial to help understanding the GZK puzzle

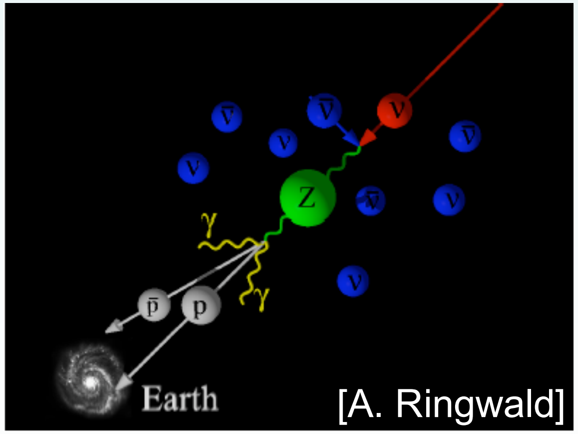
Z-bursts

[T. Weiler, D. Fargion]

$\nu + \underline{\nu}_{CB} \rightarrow Z_0$ $E_{th} \sim 10^{23}$ eV

Resonant annihilation produces a **dip** in a cosmic neutrino source spectrum *IF one has a source of 10^{23} eV neutrinos*

Z_0 decay into hadrons gives **10^{20+} eV protons** to explain any super-GZK particles, again *IF there is an appropriate source of neutrinos at super-mega-GZK energies*



[A. Ringwald]

The Z-burst proposal has the virtue of solving two completely unrelated (and very difficult) problems at once:

relic neutrino detection

AND

super-GZK cosmic rays

Radio Cherenkov Detection

Proposed by **Askaryan** (1962)

– UHEν interacts in a solid dielectric → e-γ shower

– Net charge excess develops in e-γ shower (interaction with atomic e^-)

– Charge excess moving at speed of light in vacuum

→ **Cherenkov radiation results**

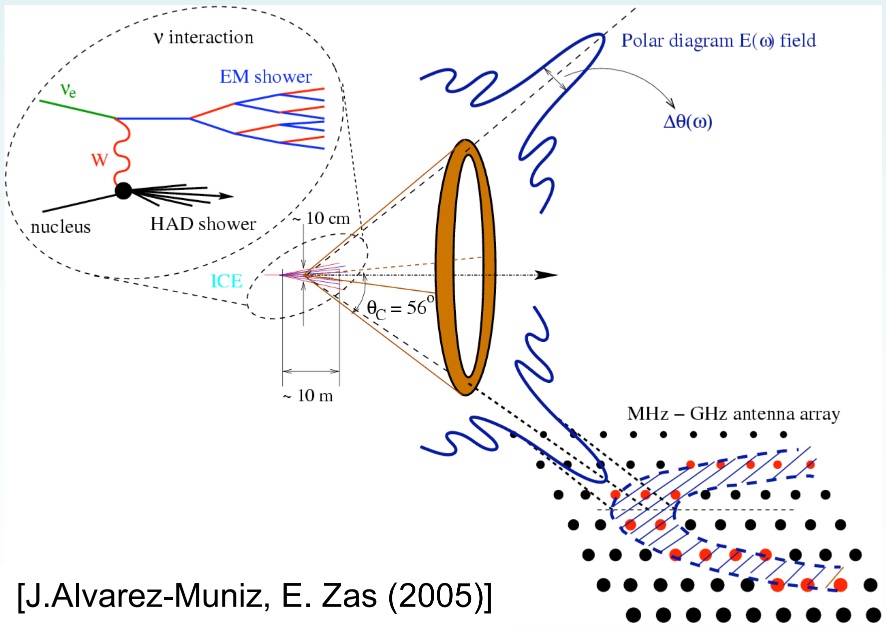
The key-point: Cherenkov radiation is **coherent** for wavelengths larger than the shower bunch size:

λ>> shower dimensions

For interactions in sand, salt and ice, radiation is coherent at frequency

f < 1-10 GHz

(coherent radio emission)



[J.Alvarez-Muniz, E. Zas (2005)]