Study of environmental thermal neutron fluxes: from EAS to Geophysics

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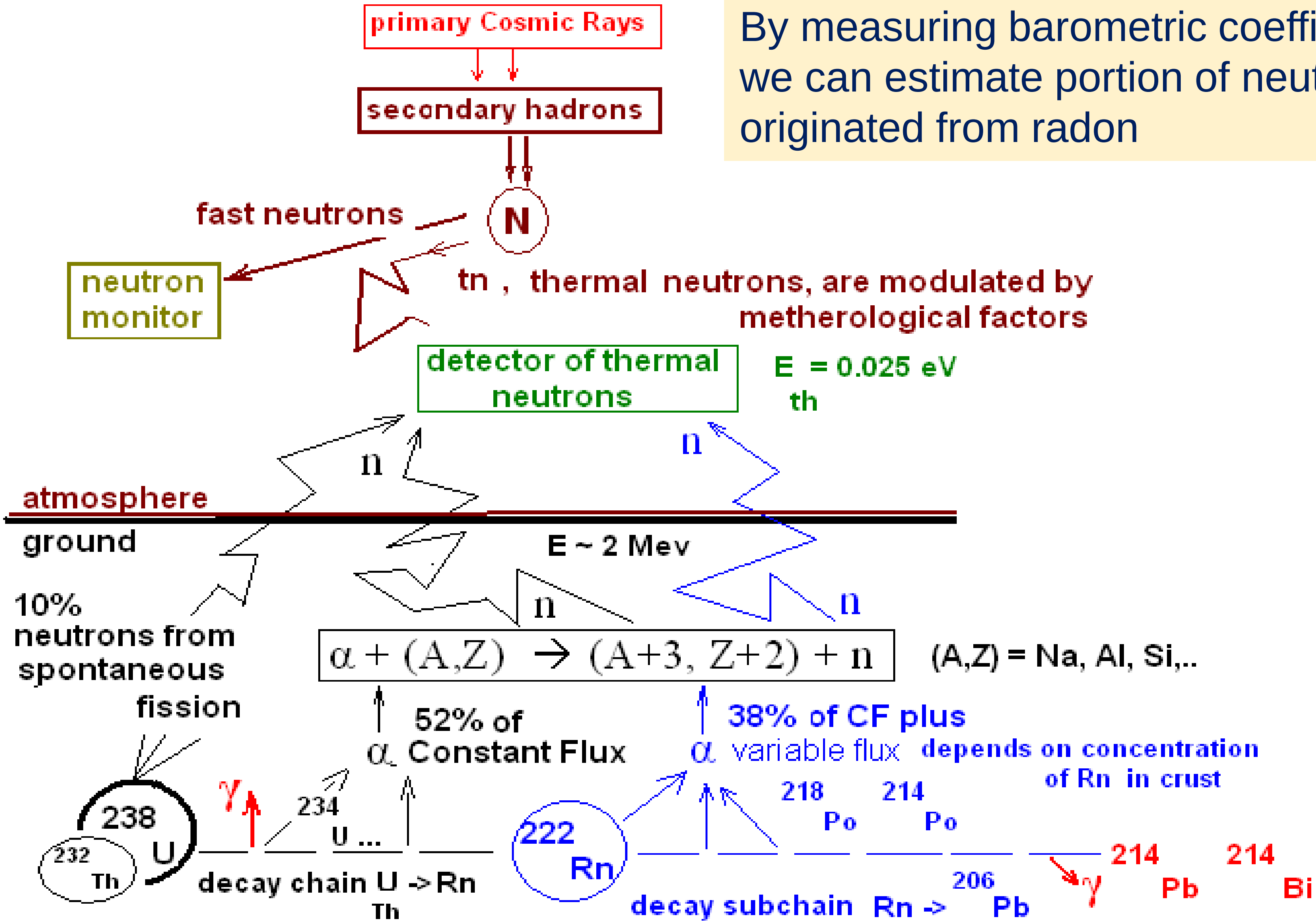
Outline

1. natural neutron sources
2. historical overview
3. neutrons in EAS
4. ENDA-LHAASO
5. environmental neutrons
6. global net of en-detectors and observed geophysical phenomena

Environmental neutron sources.
CR & Radon-due neutron production

By measuring barometric coefficient we can estimate portion of neutrons originated from radon



History

❖Neutrons in EAS

First measurements were in 1948-49 by Cocconi & Cocconi-Tongiorgi:

PHYSICAL REVIEW VOLUME 75, NUMBER 10 MAY 15, 194

Neutrons in the Extensive Air Showers of the Cosmic Radiation

VANNA COCCONI TONGIORGI
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

(Received February 7, 1949)

Neutrons associated with extensive air showers have been studied by recording delayed coincidences among Geiger-Müller counters and proportional BF_3 counters. The experiments have been performed at 260, 3260 and 4300 m above sea level. It has been shown that in the extensive showers both neutrons of moderate energies and radiations capable of producing such neutrons are present. The number of neutrons and neutron-producers in showers of different sizes is roughly proportional to the number of the electrons. The neutron-producers cannot be, at least in a large fraction, either electrons, or photons, or μ-mesons. Nuclear interactions induced by fast neutrons and protons are consequently thought to give the main contribution to the neutron production observed. The total neutron-producing-radiation is of the order of 2–3 percent of the electronic component of the showers at 3260 m. Its altitude variation is consistent with the assumption that nucleons constitute its main component.

The multiplicity of the neutron production in lead is very high: ~60 neutrons of energies between 2 and 15 Mev are produced at a time on the average.

Absolutely correct conclusion was made:

IX. CONCLUSIONS

The results obtained in the described experiments can be summarized as follows:

(a) In the extensive showers neutrons are present. The number of neutrons in the energy range between 2 and 15 Mev present in an extensive shower in the air is of the order of magnitude of 1 percent of the number of electrons belonging to the shower.

(b) Local production of neutrons in association with extensive showers has been observed in Pb, Fe and C and likely takes place in any material. In Pb a high number of neutrons (roughly 60) are produced simultaneously.

(c) Radiation capable of producing neutrons of moderate energy exists in the extensive showers. It

V. Tongiorgi. /On the Presence of Neutrons in the Extensive Cosmic-Ray Showers. // Phys. Rev. V. 73, No 8, (1948), p. 923-924.
3. V. Cocconi-Tongiorgi. / Neutrons in Extensive Air Showers of Cosmic Radiation.// Phys. Rev., v. 75, No 10, (1949), p. 1532-1540.

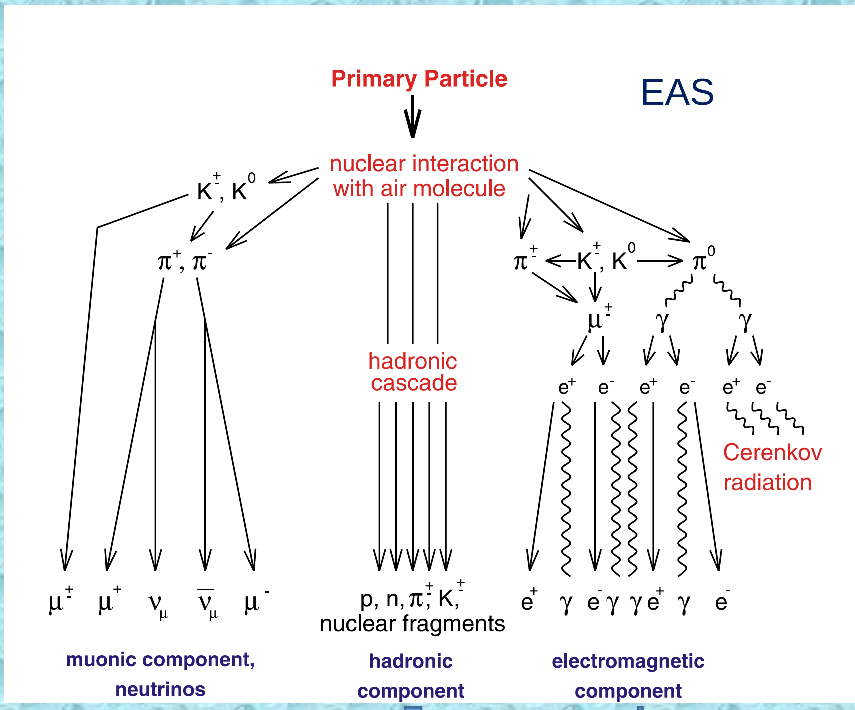
The above works led George Zatsepin to a conclusion that EAS is not e-m but hadronic (nuclear) cascade in air:

Up to 1949, EAS was considered as a pure e-m cascade in atmosphere.

Then George Zatsepin showed that this simplification was not true and EAS is a hadronic cascade while e-m component is produced by π^0 decays. This results in the two components are in equilibrium and all EAS features are defined by the hadronic component being a “skeleton” of the shower. (G.T. Zatsepin, DAN SSSR, 67, 993 (1949)).

The latter means one needs to study hadronic component first of all. Only hadrons existence at observation level indicates the equilibrium existence.

But up to date people use e-m theory of cascade development (NKG function, ages, etc.) and measure mostly electronic component, sometimes muonic and very rarely hadronic one.



many neutrons

few neutrons

K.Greisen. Cosmic Ray Showers. Annu. Rev. Nucl. Sci. 1960.10:63-108:

"The nuclear cascade which is the backbone of a shower is dominated by a very few high-energy particles, sometimes only one, in the core of the shower……, and showers of a given size are encountered at a single altitude in all stages of development."

"Since the interactions of the few nuclear active particles carrying most of the energy are governed by chance, both in location and in distribution of energy among the secondary particles, it is only natural that large fluctuations in the energy balance should occur from one shower to another, particularly among the smaller showers, in which there is often **only a single particle of very high energy in the core**."

"Slow neutrons, from thermal energies up to one Mev, must be very abundant in the showers, but have not yet been measured."

Therefore, 2 counclusion can be made:

1. The number of high energy hadrons Nh is small – this results in high fluctuations;
2. Evaporation neutrons must be measured and could serve as an energy estimator.

Later it was forgotten for ~30 years…

New interest appeared when in 90-s FIAN group claimed about anomalies in EAS neutron distributions as measured by Tien Shan NM.

The latter stimulated us to repeat their measurements. As a result, we found that all “anomalies” can by explained by methodical reasons. On the other hand, the phenomenon which we called as “Neutron bursts” does exist.

Then we proposed to use EAS thermal neutrons as a calorimetric parameter and energy estimator.

Later we developed electron-neutron detector (en-detector) and have proposed Multi-component EAS array and later the PRISMA (PRImary Spectrum Measurement Array) – a novel type of EAS arrays measuring hadronic component over full array area.

1999- experiment in Mexico using NM

ELSEVIER

Astroparticle Physics

Astroparticle Physics 16 (2001) 157–168

www.elsevier.com/locate/astropart

Study of "neutron bursts" with Mexico City neutron monitor

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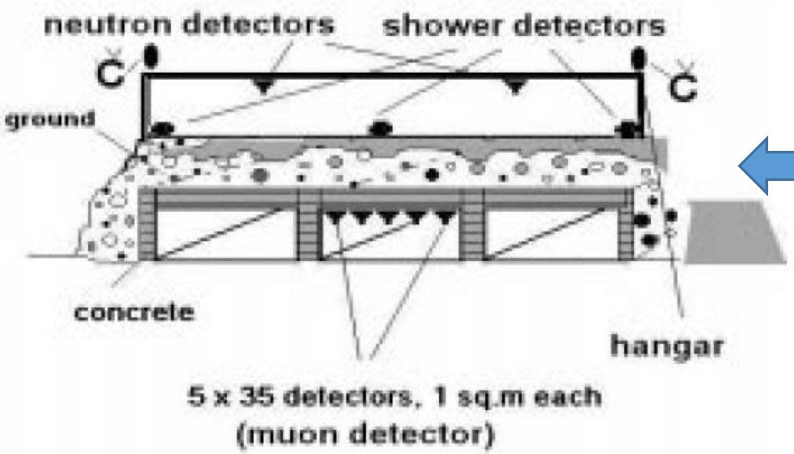
1. Our experiment has confirmed the existence of *neutron bursts*, i.e. events in the neutron monitor with very high multiplicity of recorded neutrons both in the boron counters and in the outer scintillator detectors.

2. Neutron gas counters do not work properly at high counting rate during the burst events. To measure correct time distribution, fast neutron detectors must be used. At present, the full oscilloscope screen control allows us to estimate the actual number of neutrons in the registered bursts.

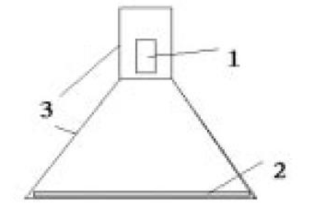
3. We observed several interesting effects in *neutron bursts* that known neutron physics processes can explain satisfactorily. In particular, the apparent "delayed component" of the showers may well be explained by the albedo neutrons from the ground and surrounding media.



MULTICOM cross section

2001

Baksan:
First Prototype of Multicomponent array –“Multicom”



Thermal neutron detector
1 - PM tube
2 - scintillator (ZnS + B10)
3 - iron housing (light shield)

[D. D. Djappuev, A. S. Lidvansky, V. B. Petkov, and Yu. V. Stenkin. Compact multicomponent array for EAS study (MULTICOM) [Proceedings of ICRC 2001: 822]

2009

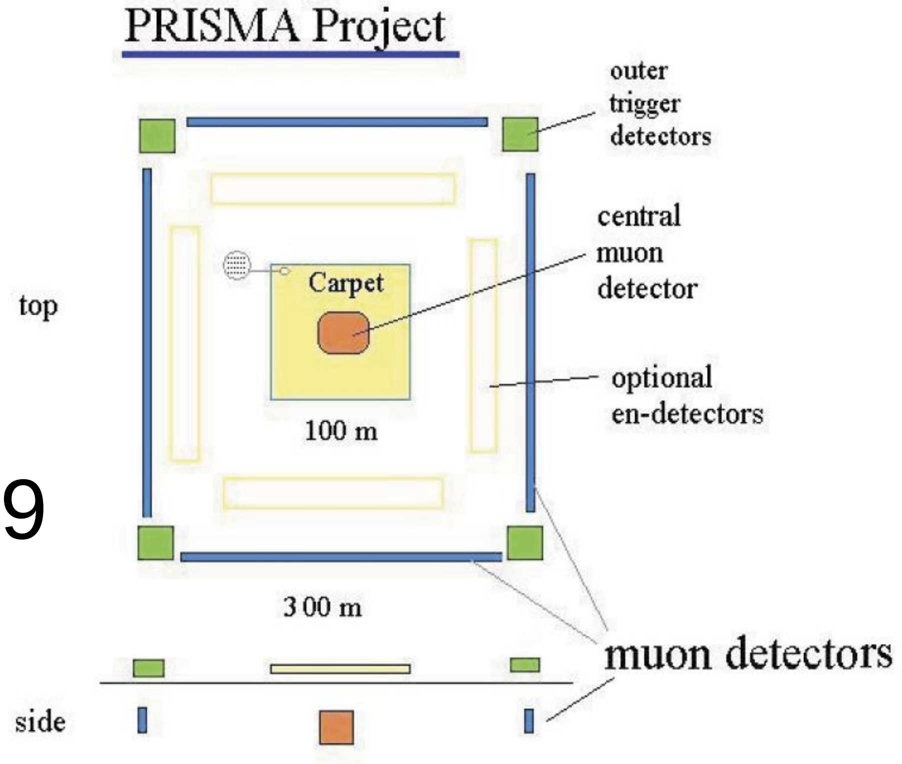
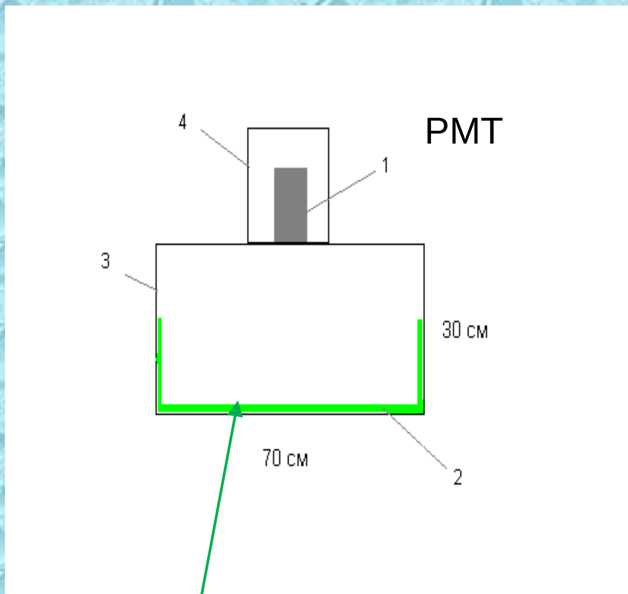


Figure 2. The PRISMA lay-out (top and side view).

[Yu.V. Stenkin. On the PRISMA project. // Nucl. Phys. B (Proc. Suppl.), v. 196, 2009, p. 293-296]

First EN-Detector of thermal neutrons and electrons:



Scintillator compound
$^{6}LiF+ZnS(Ag)$
30 mg/cm^2
Enriched with ^{6}Li up to 90%

Relativistic charged particles give ~50 КэВ
This is below our threshold (~3 mip).

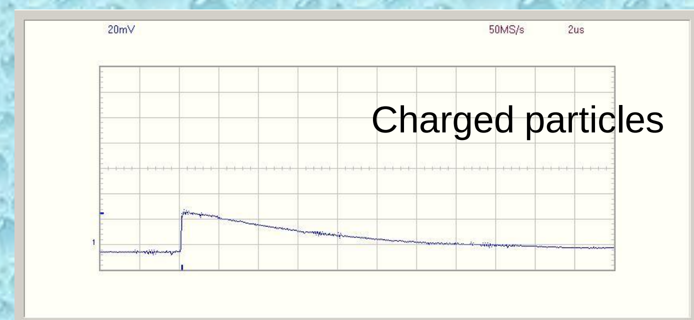
en-detector is not sensitive to beta and gamma background

Nuclear reaction in use:
$^{6}Li + n \Rightarrow {}^{3}H + \alpha + 4.78$ Mev.

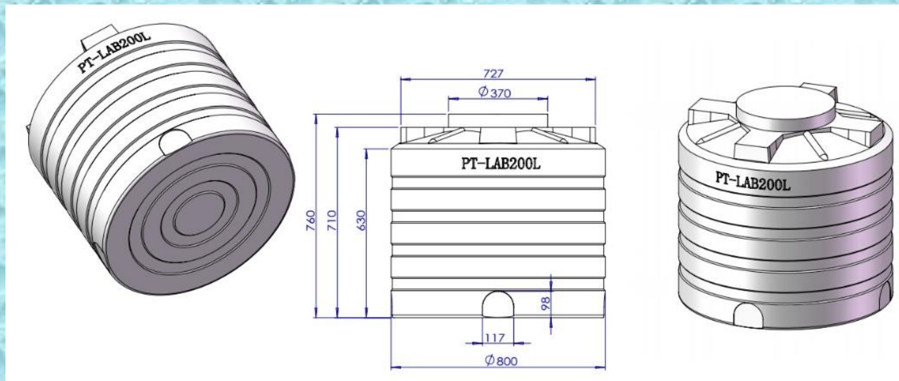
Resulting particles produce in ZnS(Ag), scintillations which are recorded by PMT “FEU-200”, of 6” diameter.

Detector counting rate ~0.5 / sec at surface

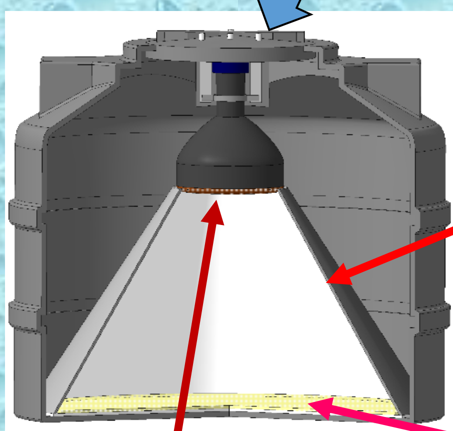
Pulse shape selection in en-detectors



Modern en-detector



ENDA-LHAASO en-detector



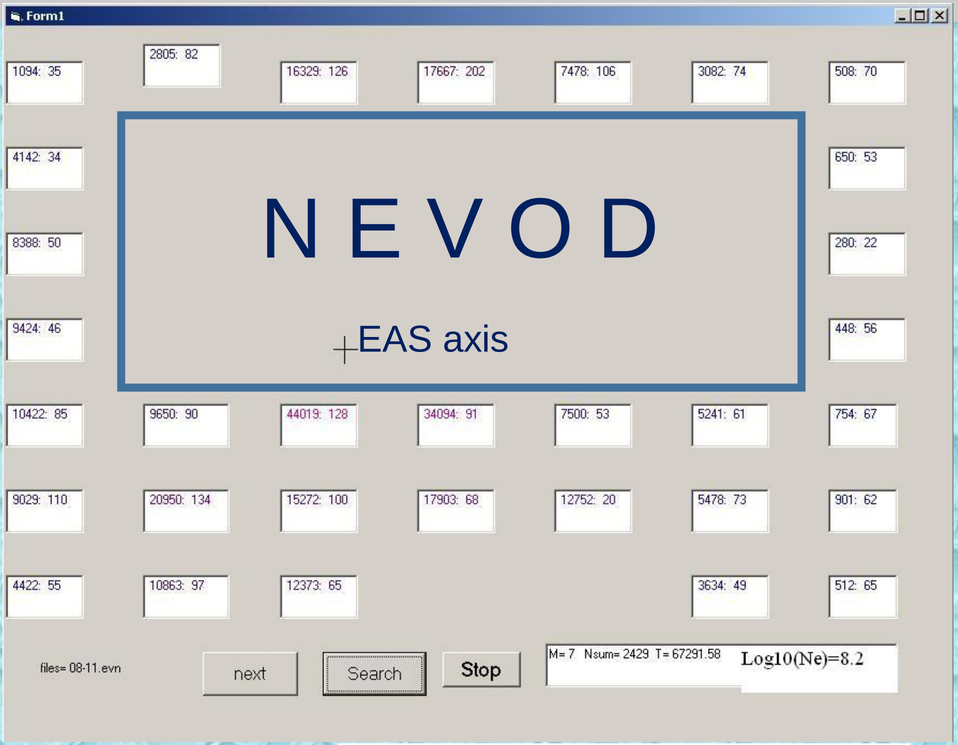
Light collecting cone

Boron scintillator compound (~20% efficiency at 50 mg/cm^2)
ZnS(Ag)+B_2O_3

4” PMT CR165 (Beijing Hamamtsu)

PRISMA prototypes (Prisma-32 in MEPhI, sea level)

(D.M. Gromushkin, V.V. Alekseenko, A.A. Petrukhin, et al. The ProtoPRISMA array for EAS study: first results. Journal of Physics:ConferenceSeries **409** (2013) 012044)



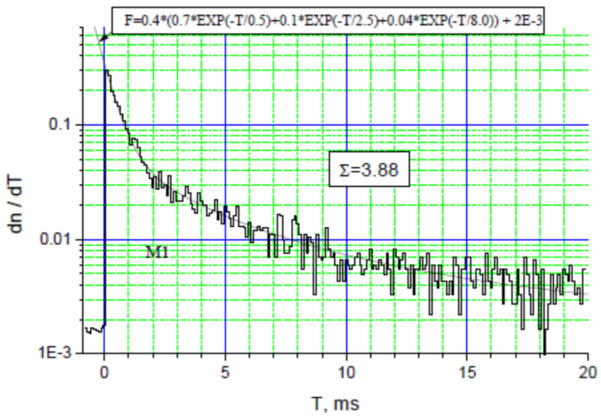


Figure 3. Recorded neutron time distribution for all events selected by M1 trigger.

Measured EAS neutrons time distribution

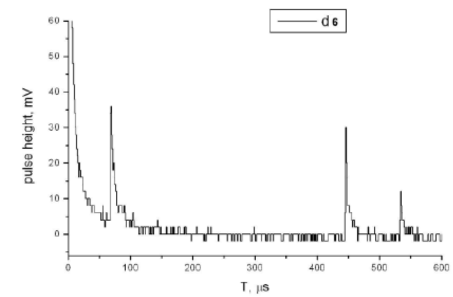


Figure 4. An example of the expanded oscillogram for one detector #6 in time interval 0 – 600 μs.

O. B. Shchegolev, et al. Primary Cosmic Ray Energy Spectrum Above the "Knee" Measured with PRISMA-32 Array. *Physics of Atomic Nuclei, 2020, Vol. 83, No. 2, pp. 290–293.*

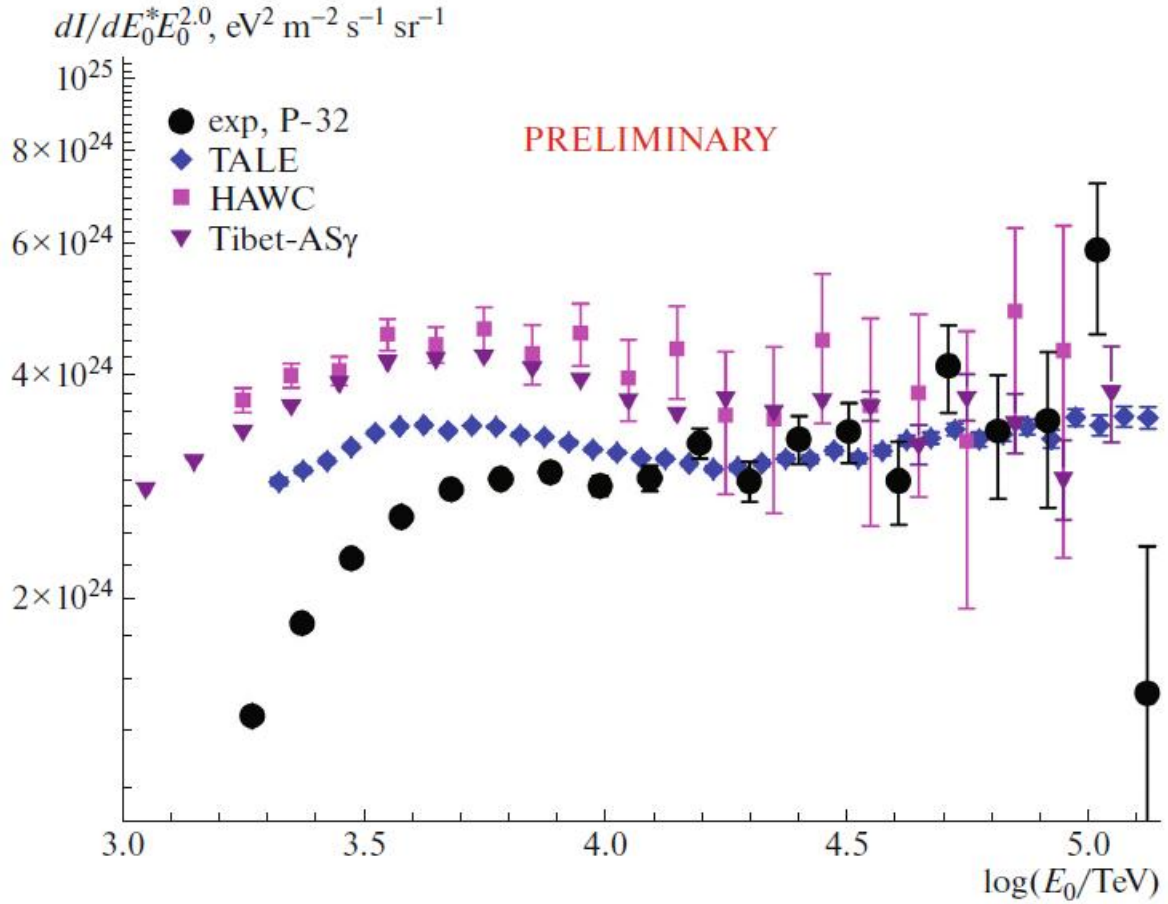


Fig. 2. Primary energy spectrum recalculated with linear fit shown in Fig. 1 from neutron multiplicity spectrum measured by the PRISMA-32 array (circles). For comparison energy spectra obtained by some other experiments are shown [2, 3, 12].

PRISMA4-YBJ prototype (Tibet, 4300 m a.s.l.)

Astroparticle Physics 81 (2016) 49–60

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journal homepage: www.elsevier.com/locate/astropartphys

Detection of thermal neutrons with the PRISMA-YBJ array in extensive air showers selected by the ARGO-YBJ experiment

Cross-calibration has been made with ARGO-YBJ detectors

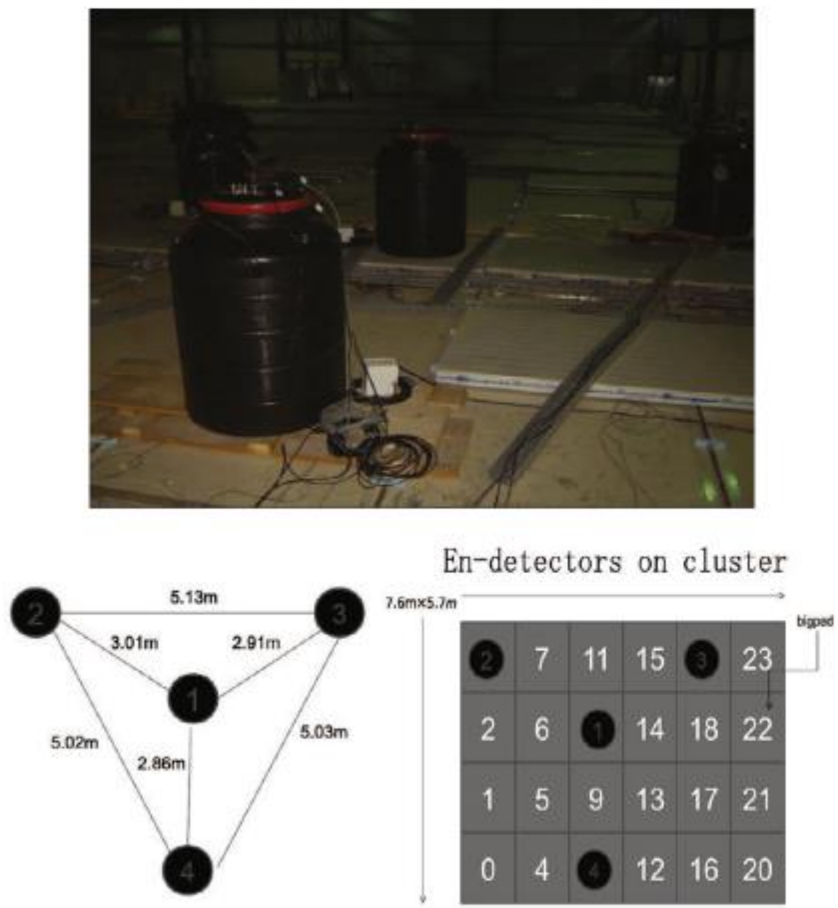


Fig. 5. Upper plot: photo of PRISMA-YBJ above the ARGO-YBJ RPC carpet. Lower left: layout of PRISMA-YBJ. Lower right: PRISMA-YBJ on the ARGO-YBJ cluster 78.

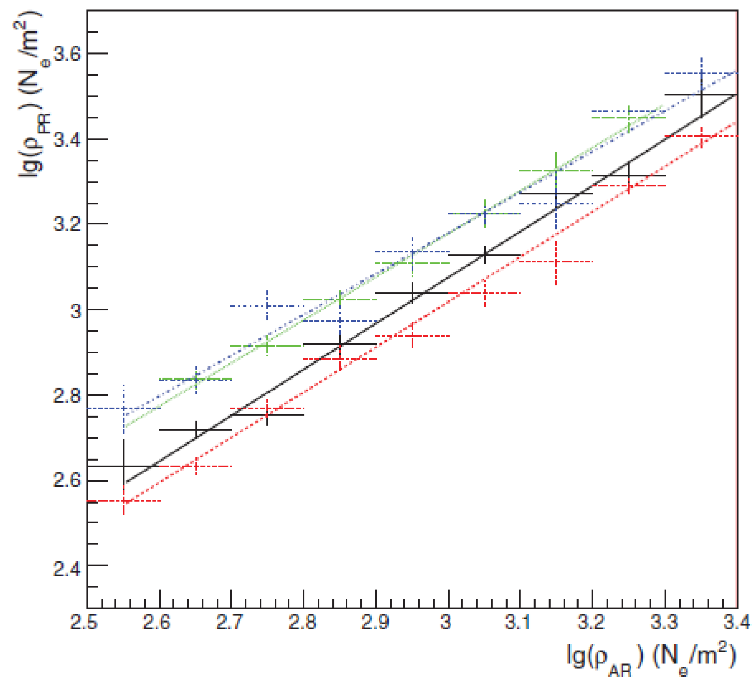


Fig. 11. Correlation between the electron densities measured by the four EN-detectors of PRISMA-YBJ via the fast signals (ρ_{PR}) and those measured by the corresponding RPCs of ARGO-YBJ (ρ_{AR}): D1 (black solid line), D2 (red dashed line), D3 (green dotted line) and D4 (blue dot-dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Preliminary results were obtained

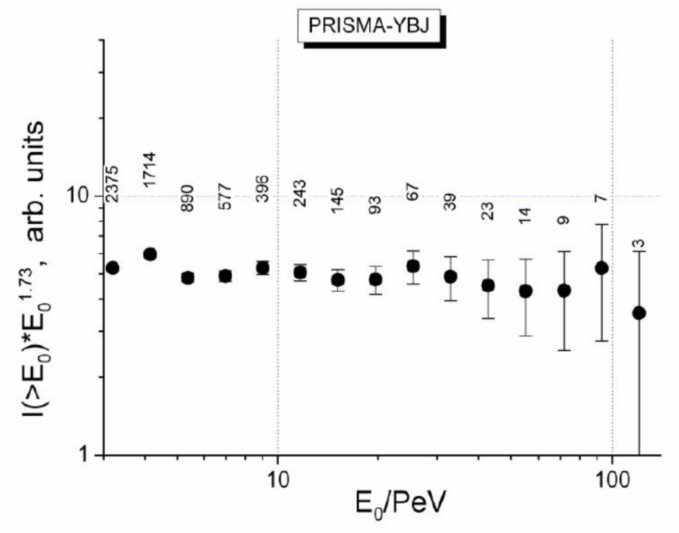


Figure 4: Primary spectrum recovered from EAS size spectrum in thermal neutrons.

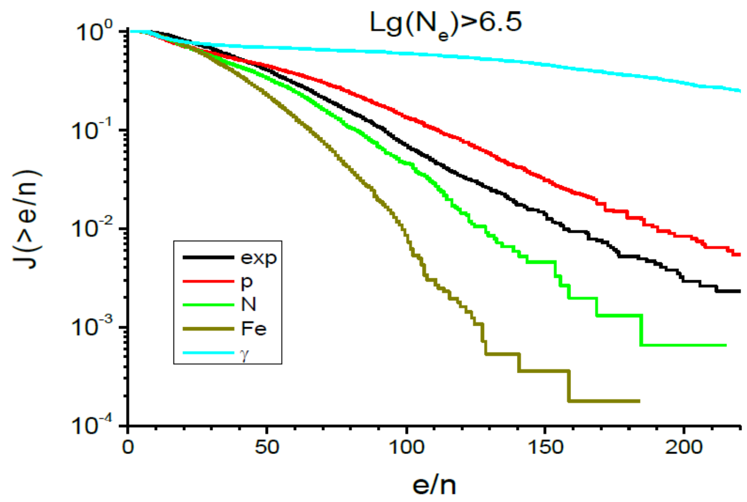


Figure 1: Simulated function $F(>R, A)$ for different primary particles at an altitude of 4300 m in comparison with observation.

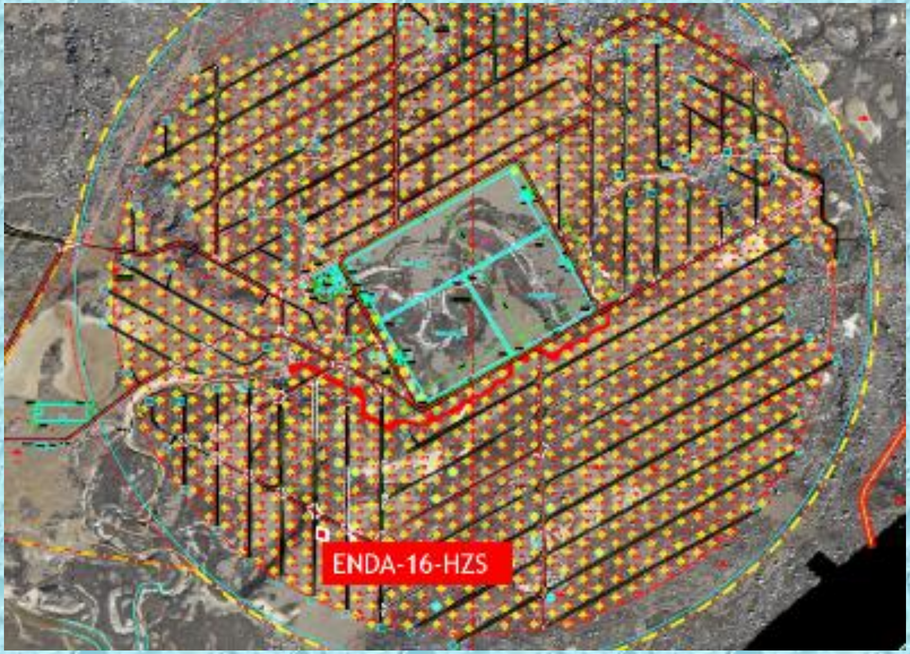
Primary spectrum recovered from neutron EAS size.

Stenkin Yu. et al.
PoS(ICRC2017)488

Stenkin Yu. et al.
PoS(ICRC2017)485

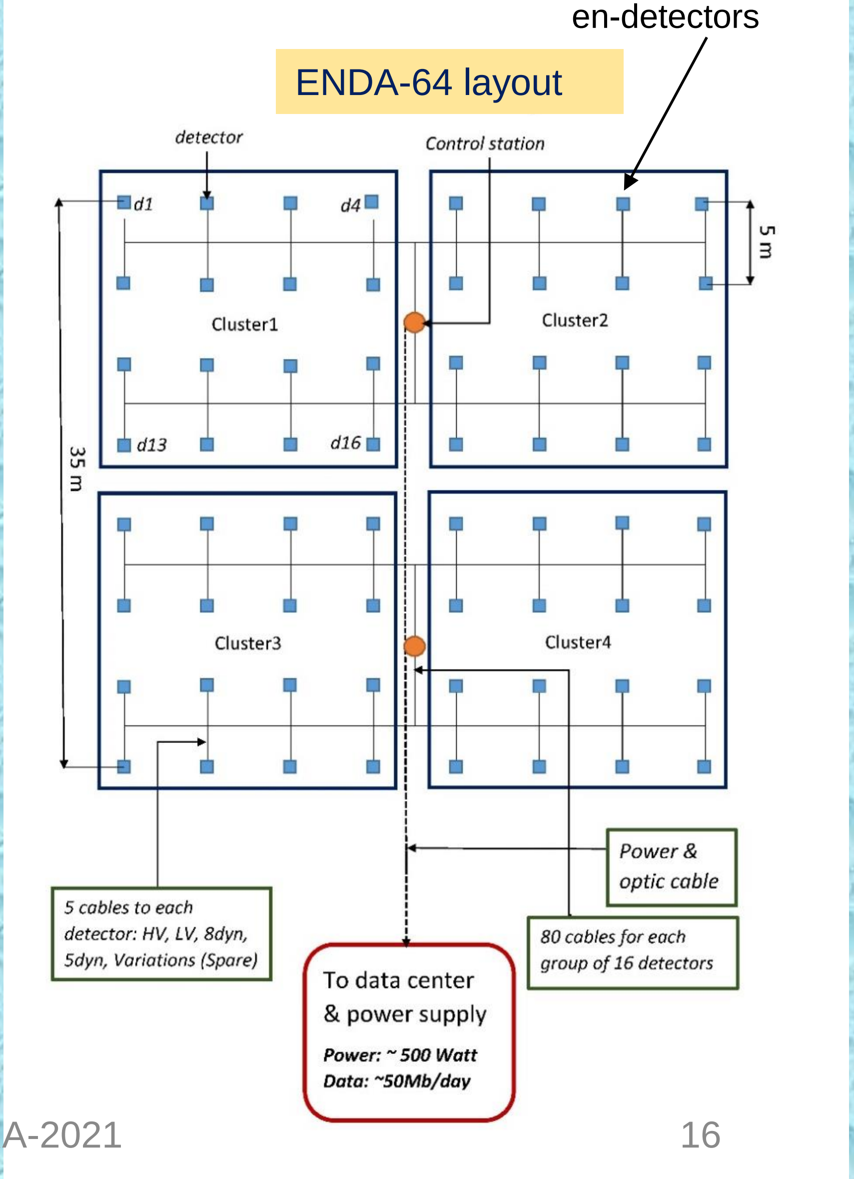
A novel method for CR mass composition measurements has been developed and Implemented.
Result of P4-YBJ:
light composition up to ~100 PeV.

ENDA -LHAASO
(Electron-Neutron Detector Array)



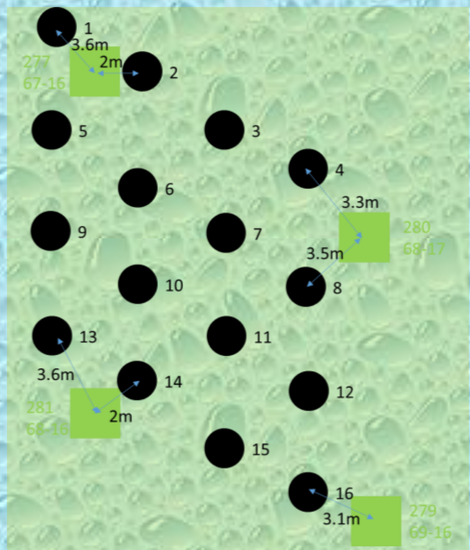
1 working cluster – 16-en-detectors

Future expansion: ENDA-64 -> ENDA-400

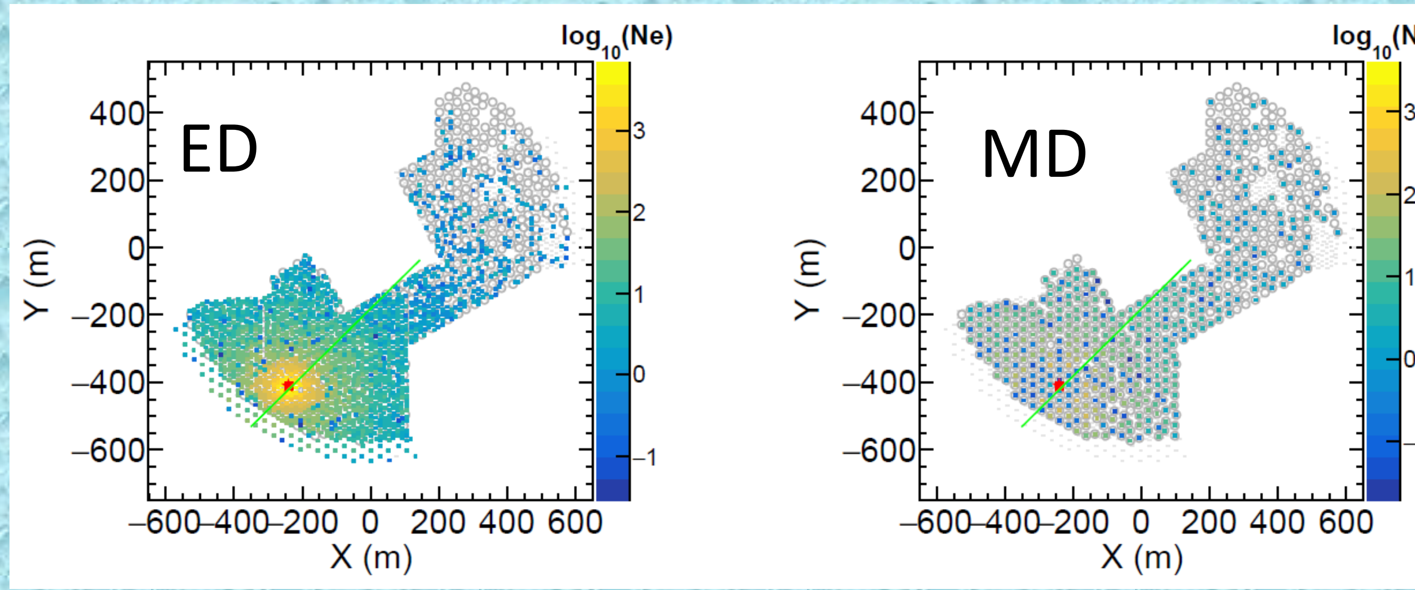


ENDA-LHAASO: One Coincident event 1

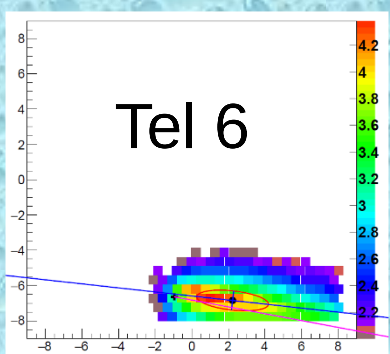
20210205_event4531

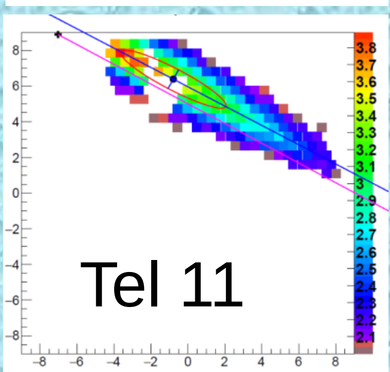


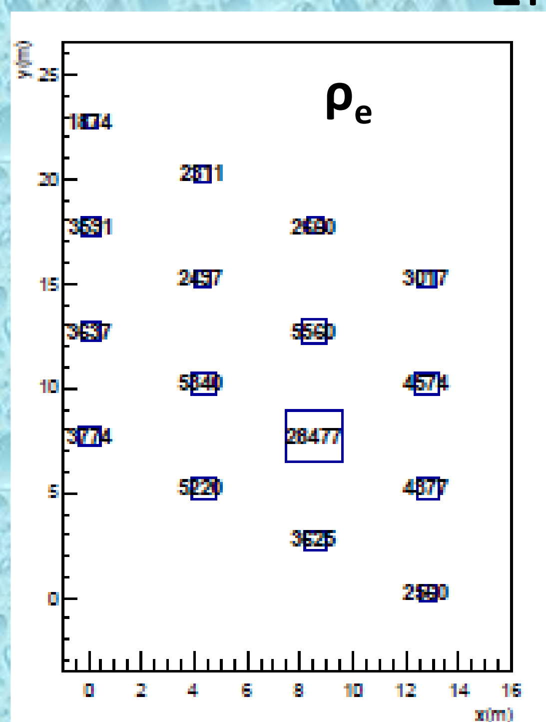
WFCTA

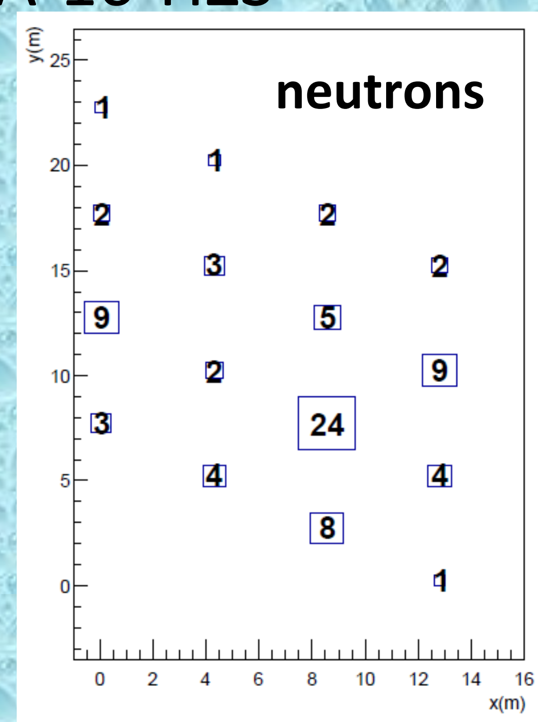


ENDA-16-HZS





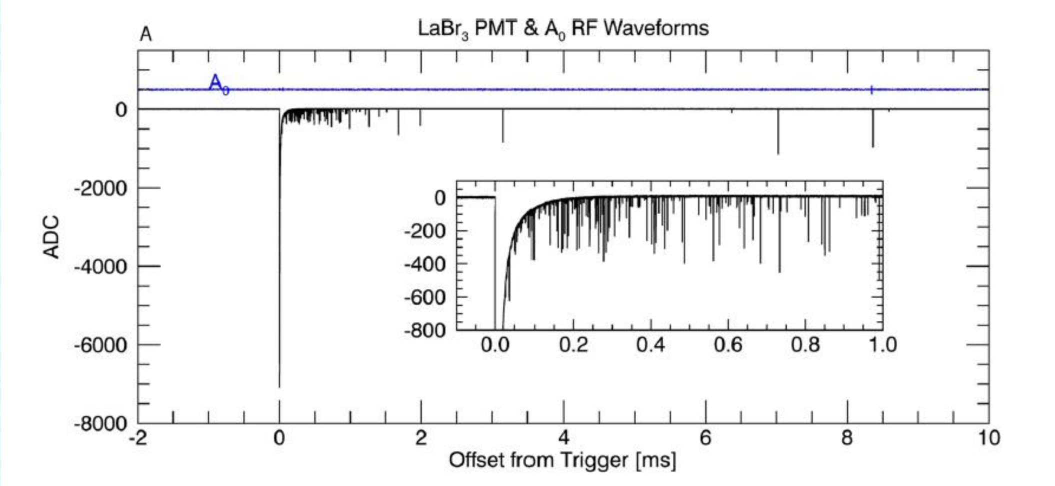


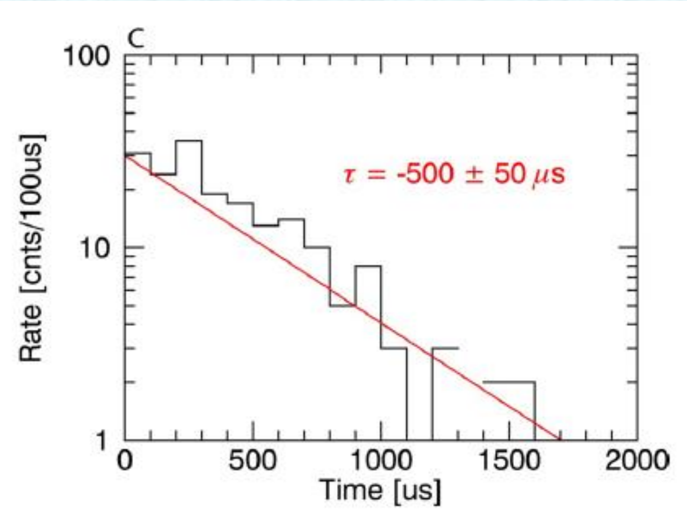


Recently HAWC published a paper confirming our measurements of neutrons in EAS:

Gregory S. Bowers, et al. **Fair Weather Neutron Bursts From Photonuclear Reactions by Extensive Air Shower Core Interactions in the Ground and Implications for Terrestrial Gamma-ray Flash Signatures.//Geophysical Research Letter. (2021), Doi:** 0.1029/2020GL090033

The only difference is that they recorded not neutrons but secondary delayed gammas produced by neutron captures in surrounding matter.





<u>Their conclusion:</u>

"This means that the signature of neutron bursts should be expected from any large cosmic ray shower that has a sufficiently large electromagnetic component, even "coreless" showers (Stenkin, 2003) at lower altitudes."

is not correct! The most part of neutrons is produced by hadron interactions

❖Environmental neutron variations

Environmental thermal neutron fluxes are in equilibrium with the media and the media changes can affect the neutron flux in it.

Moreover, neutrons originated from natural radioactivity are connected with radon concentration in soil and surrounding matter. This allows one “to look” underground up to several meters and to noninvasively monitor radon concentration there.

Measuring environmental neutron flux variations makes it possible to study various geophysical phenomena.

First measurements of environmental neutron background were made in the middle on 20th century (see for example C.J. Hatton. /The neutron monitor. // Progress in Elementary Particle and Cosmic Rays Physics, vol. X, North-Holland, Amsterdam, (1971), p. 3-100. and references there).

Some early results can be found in:

Gorshkov, G. V., et al.: Natural neutron background of the atmosphere and the Earth's crust, M., Atomizdat, 1966.

B.M.Kuzhevskij's group from MSU published a lot of papers on the subject (for example ***Б.М. Кужевский.*** **Нейтронное поле Земли.** *Геофизические процессы и биосфера*. 2005. Т. 4, № 1/2. С. 18-26).

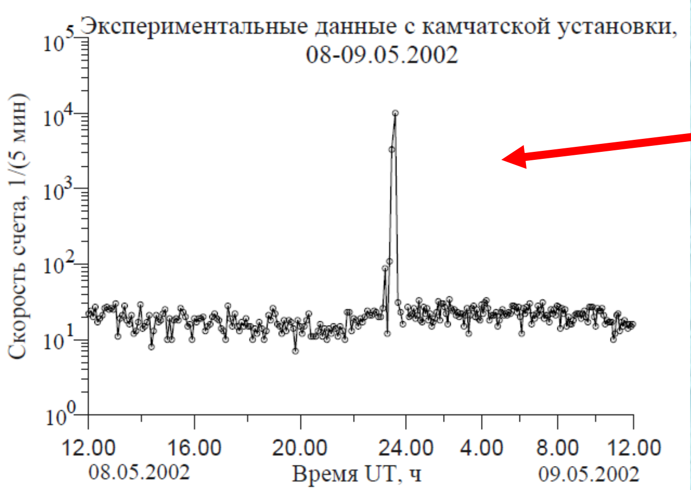


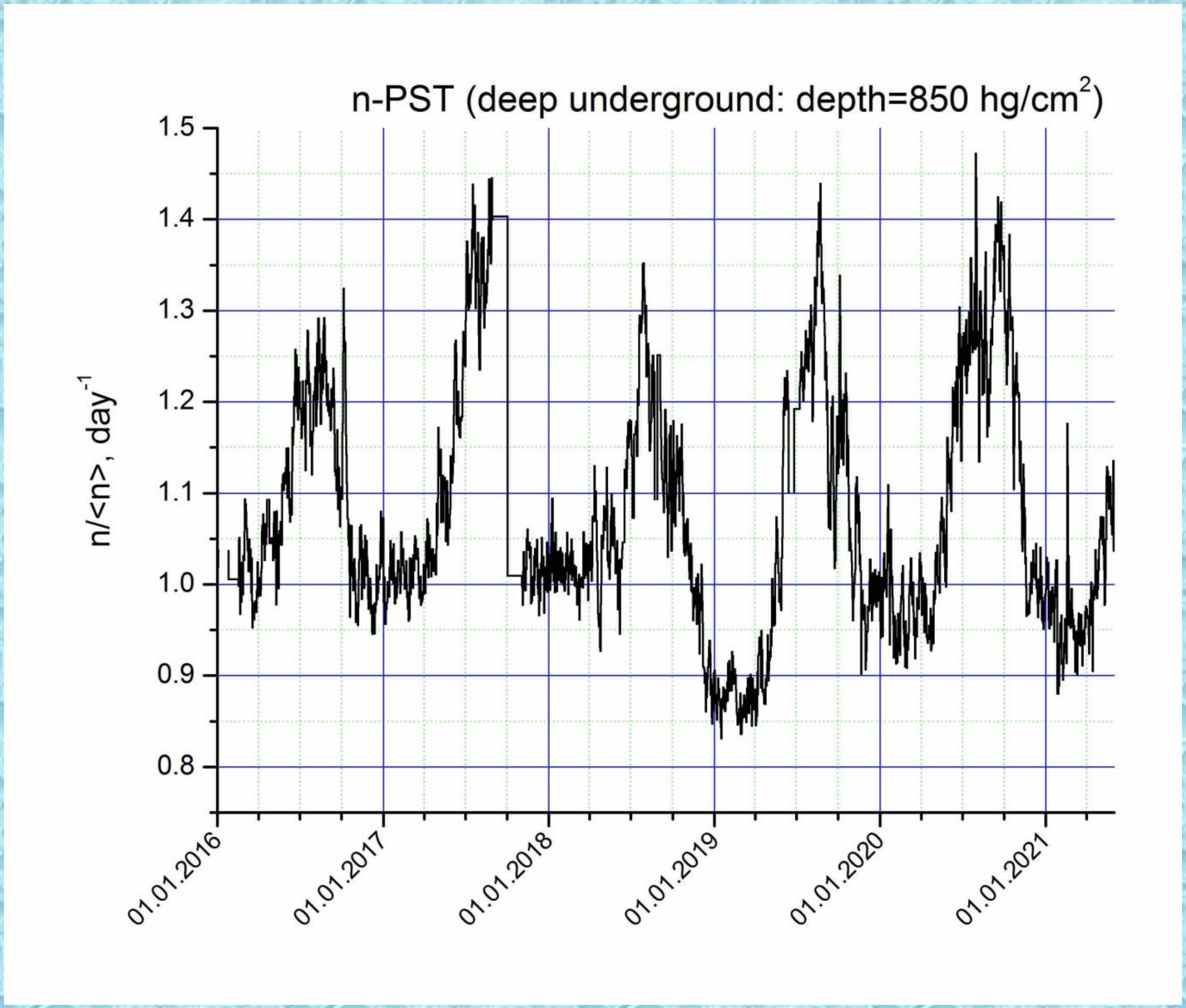
Рис. 3. Возмущение нейтронного поля Земли, зарегистрированное на Камчатке, в точке с координатами: 52^0 49΄ с.ш. и 158^0 07΄ в.д.(по оси абсцисс – мировое время, по оси ординат – количество зарегистрированных нейтронов за пять минут). Через сутки на Камчатке произошло землетрясение с магнитудой 4,7 балла. Координаты эпицентра: 52,27° с.ш. и 160,50° в.д.

Very strange behavior of neutron background which could not be explained by physical reasons.
The most probable explanation is an e-m noise.
Detector's pulse shape was not analyzed.

Unfortunately such abnormal increases are seen in other their papers as well.

But, these works stimulated us to repeat them

For comparison: how our en-detector works for a long period of 5 years



Only seasonal wave with amplitude of ~20% is seen in neutrons deep underground

Unfortunately, many “anomalies” were also published in other works dealing with environmental neutron measurements:

- “High increase” of neutrons during thunderstorms
- “Increase” of neutrons during Sun eclipses
- “Increase” of neutrons during earthquakes
- Abnormal tidal waves in neutrons

The problem is that people did not analyze pulse shape in these works. As a result instead of neutrons bursts they highly likely recorded “busts of pulses” produced by e-m noise. The latter especially possible during thunderstorms.

For example, Armenian group first also published “increase of neutron flux during thunderstorms but later, after starting of pulse digitizing and applying of Pulse Shape Selection they claimed that before it was e-m noise, not particles. (*Chilingarian A.* **DO RELATIVISTIC ELEMENTARY PARTICLES ORIGINATE IN THE LIGHTNING DISCHARGES?** //Bulletin of the Russian Academy of Sciences: Physics. 2017. T. 81. № 2. C. 238-240.).

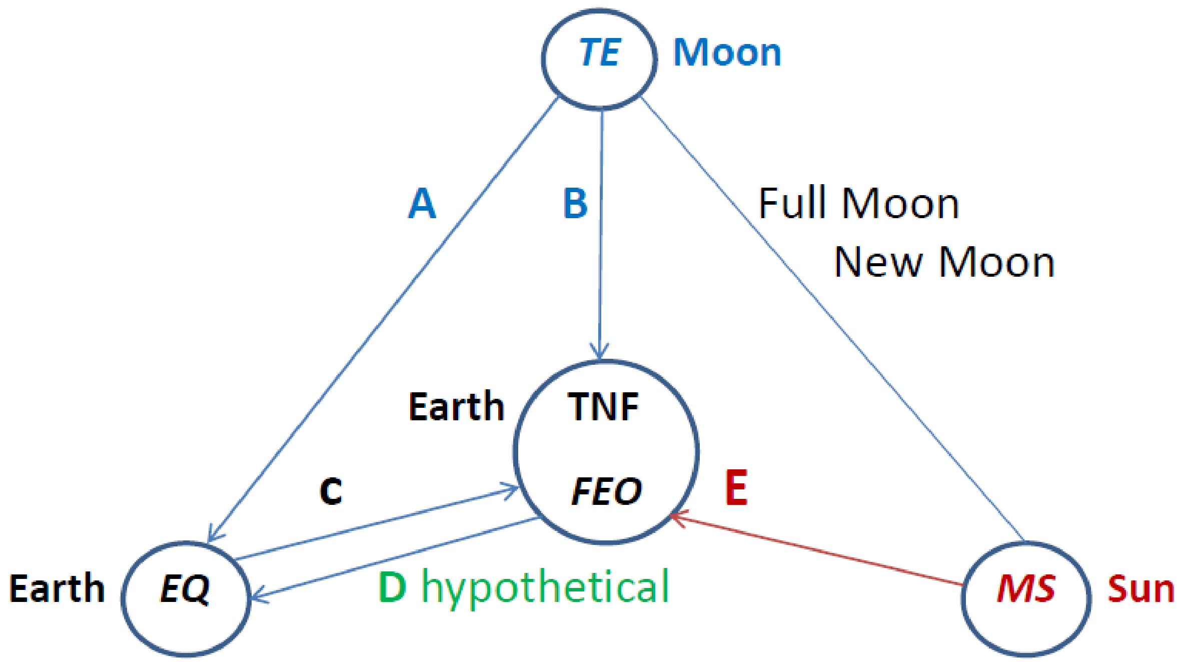
Geophysical researches with thermal neutrons

- Seasonal variations
- Moon tidal waves
- Neutrons in thunderstorms
- Forbush effect and environmental neutrons
- Barometric pumping effect for neutrons
- Earth free oscillations in neutrons
- Earthquakes
- Strong magnetic storms

Slide shown by Victor Alekseenko at WASDHA-2018

Moon Earth and Sun as the actors in the Nature △ play

A, B, C, D, E := ties between actors and phenomena



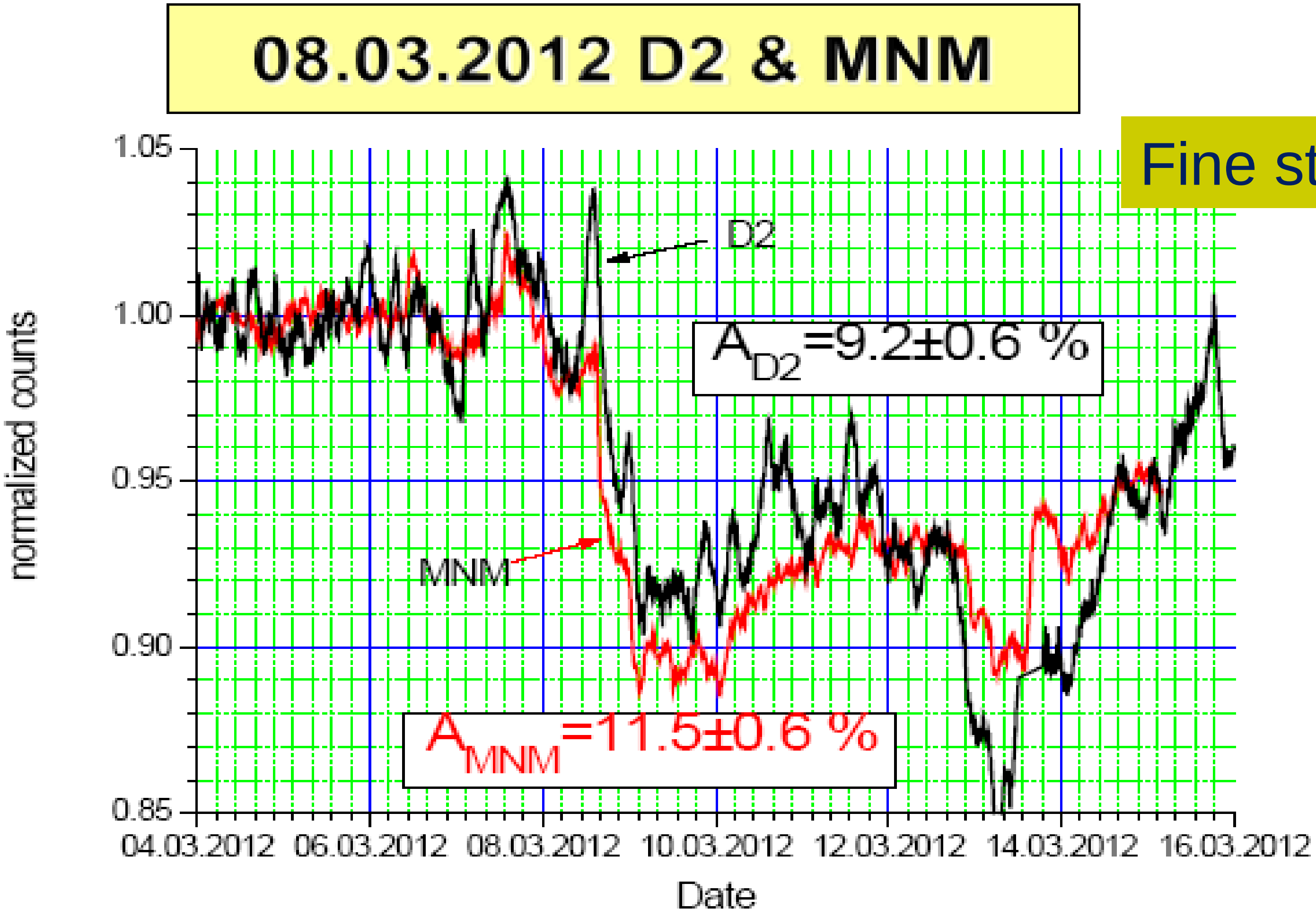
TNF-thermal neutron flux

<u>Phenomena :</u>

TE - gravitational Tidal Effect ***FEO*** -Free Earth Oscillations ***EQ***-earthquake

MS - magnetic storms

Forbush decreases



Fine structure is seen

V. Alekseenko, F Arneodo, et al. Registration of Forbush decrease 2012/03/08 with a global net of the thermal neutron scintillation *en*-detectors. Journal of Physics:Conference Series **409** (2013) 012190

Decrease of Atmospheric Neutron Counts Observed during Thunderstorms

V. Alekseenko,[1] F. Arneodo,[2] G. Bruno,[3,*] A. Di Giovanni,[2] W. Fulgione,[3,4] D. Gromushkin,[5] O. Shchegolev,[6] Yu. Stenkin,[5,6] V. Stepanov,[6] V. Sulakov,[7] and I. Yashin[5]

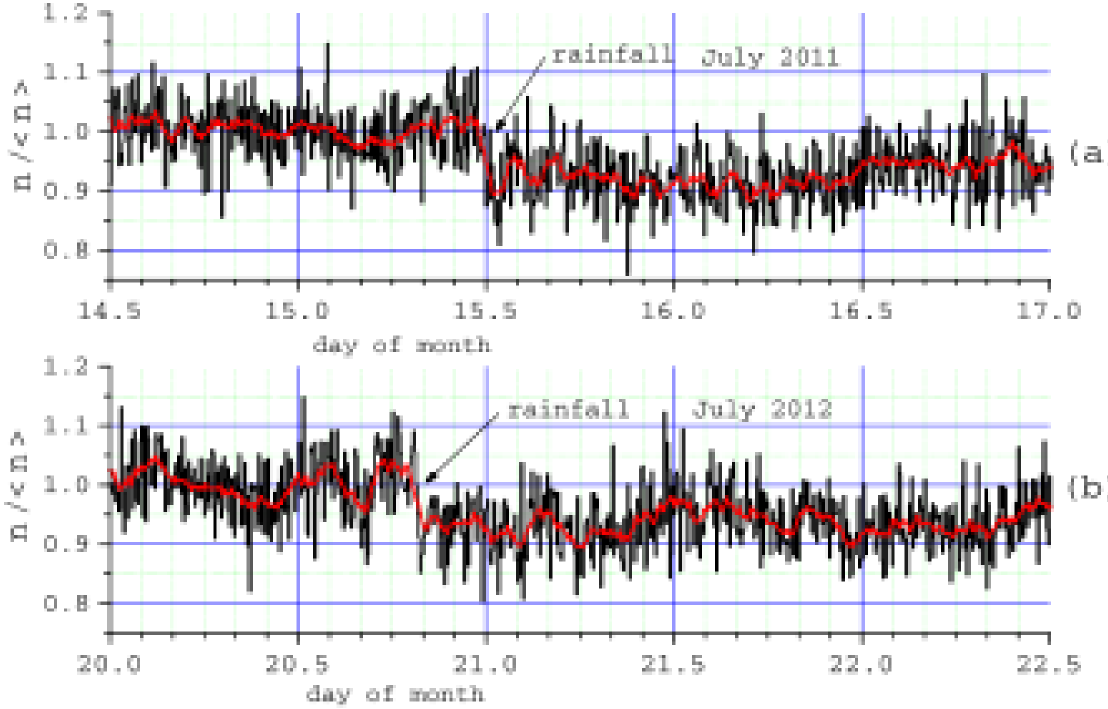


FIG. 5 (color online). Neutron counting rate as a function of the time for two different rainfalls [panels (a) and (b)]. Pressure corrected data.

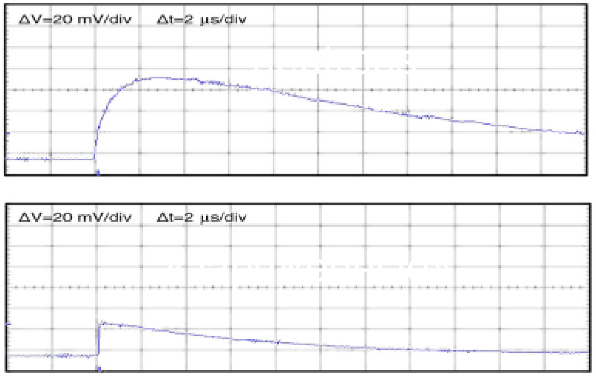


FIG. 2 (color online). Pulse induced by neutron capture ("neutrons," top panel) and background "sharp" pulse (bottom panel).

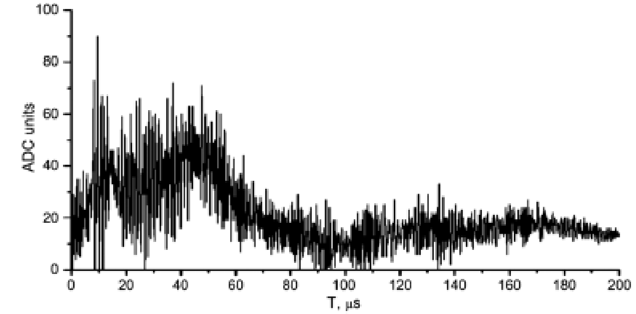
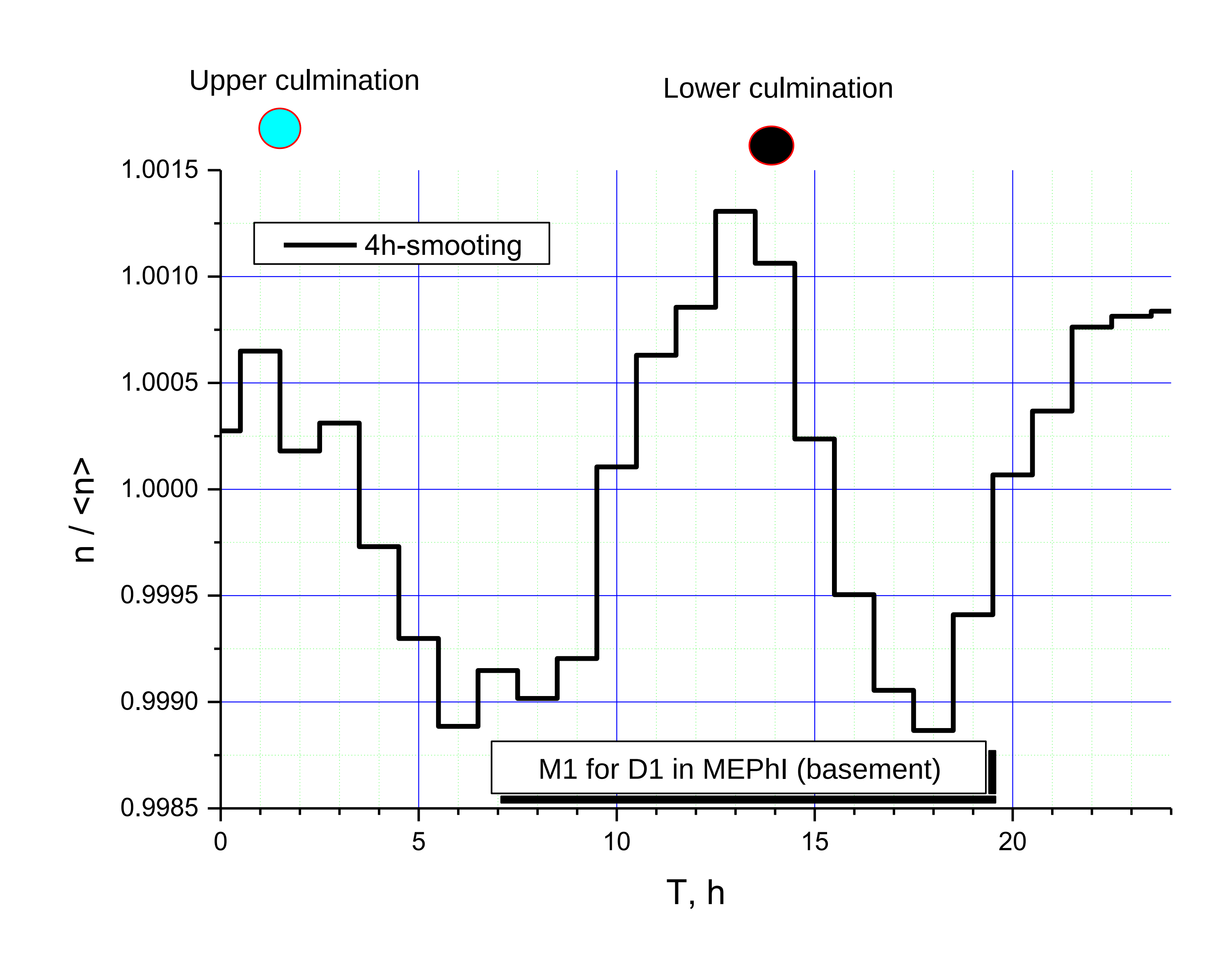


FIG. 3. Noise pulse shape produced by lightning.

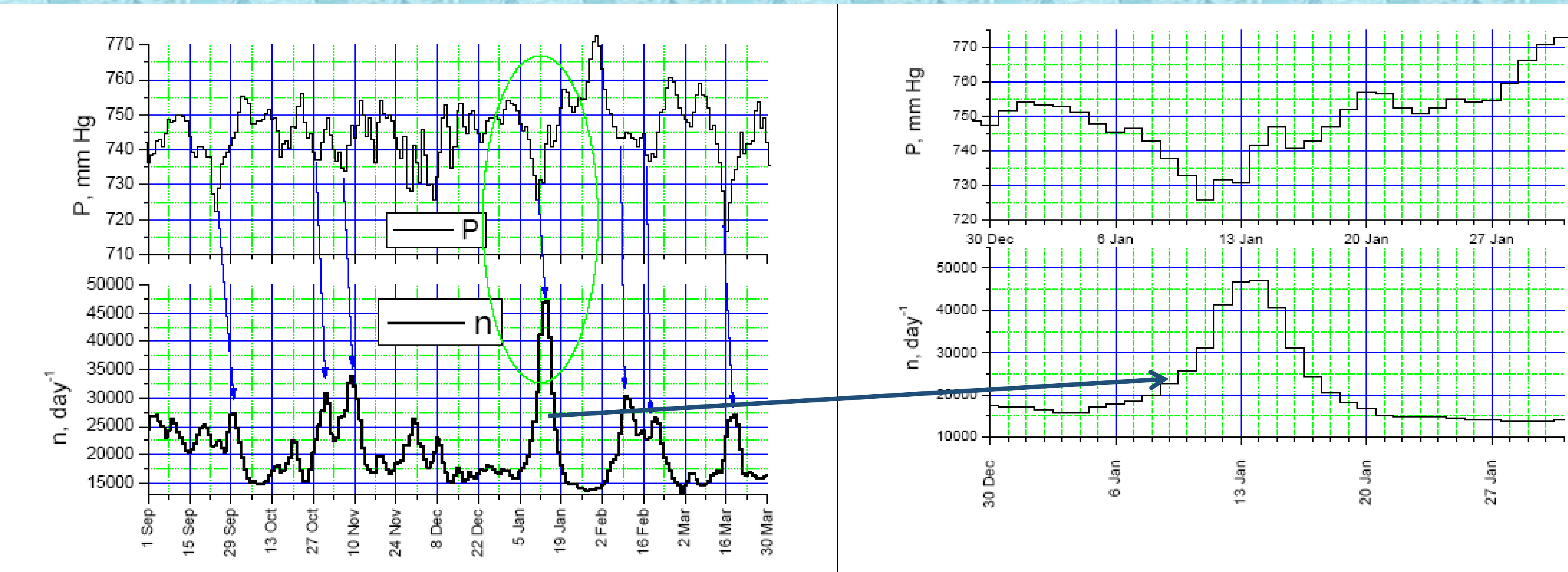
Summary: no any neutron excess during thunderstorms but instead sometimes we see decrease of neutron flux (after a dry period)

M2 tidal lunar wave



Barometric pumping effect in underground neutrons

Thermal neutrons underground, 25 m of w. e. (MSU basement)



Yu. V. Stenkin, V. V. Alekseenko, D. M. Gromushkin,V. P. Sulakov and O. B. Shchegolev. Underground Physics and the Barometric Pumping Effect Observed for Thermal Neutron Flux Underground. //Journal of Experimental and Theoretical Physics, 2017, Vol. **124**, No. 5, pp. 718–721.

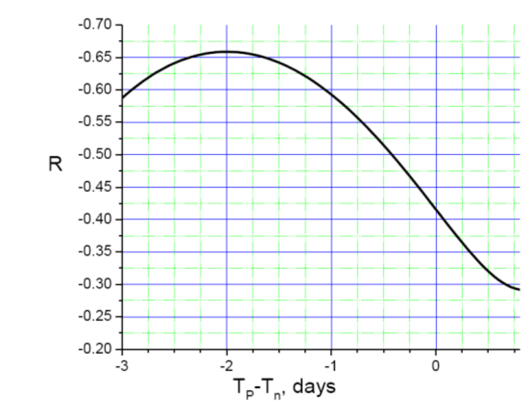
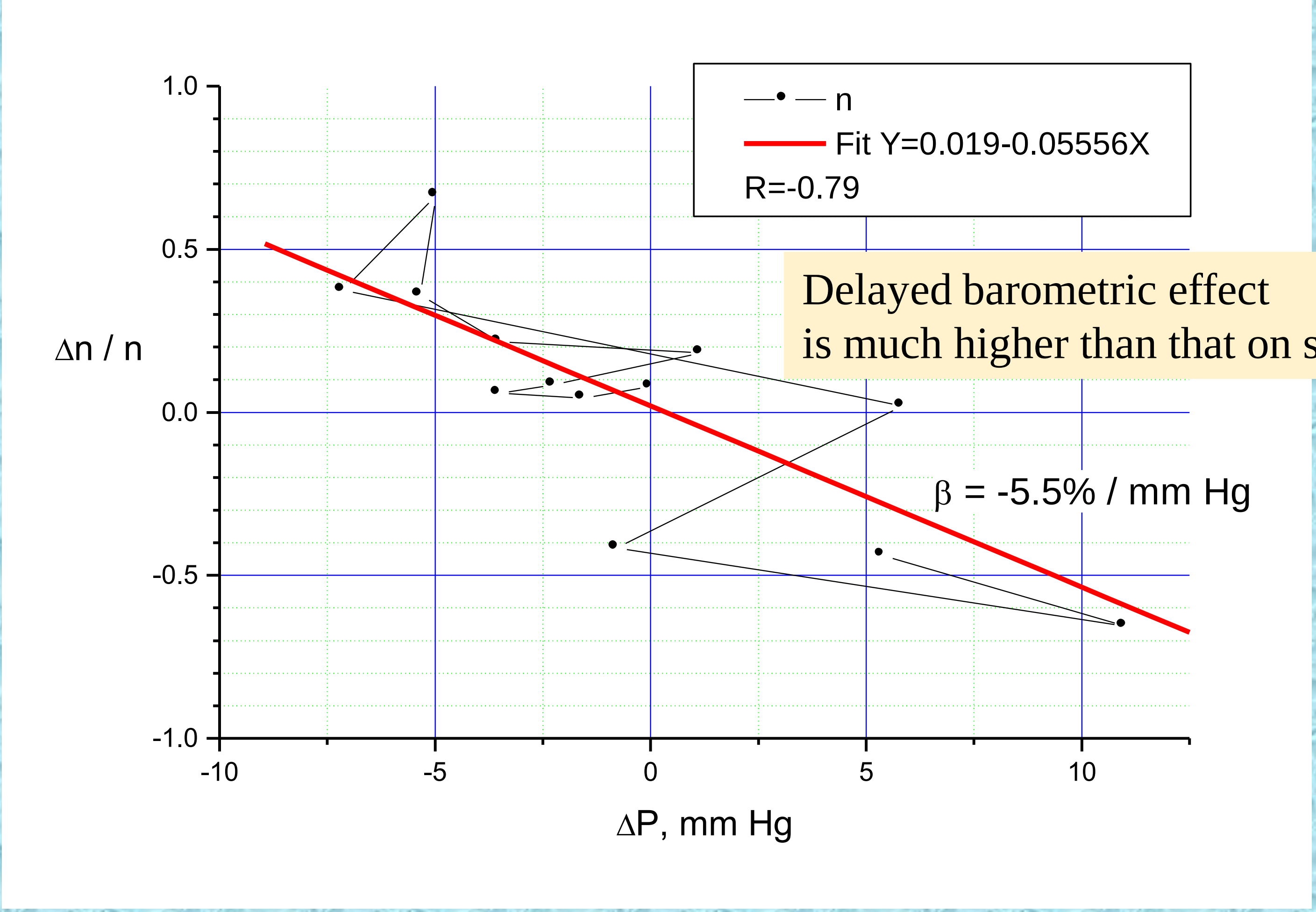


Fig. 2. Correlation coefficient R as a function of time shift in data.

Delayed correlation



This effect should be taken into account in underground experiments (DM or 2β, etc)

Some additional results will be shown later in Xinhua Ma presentation (next Session)

Summary

- Thermal neutron fluxes study makes it possible to study EAS hadronic component and geophysical processes as well
- EAS neutrons recording was proposed by Greisen many years ago but only at now days it is realised
- Continuous monitoring of environmental neutron background with a precise accuracy is now carrying out using our global net of en-detectors
- The ENDA-LHAASO project will include geophysical researches
- Special attention will be paid to Solar-Moon-Earth connections phenomena (space weather) and to correlations between Eqs, FEO and environmental thermal neutrons

Thank you!