The Center for Neutrino Physics

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Study of Neutron Rates in MiniCHANDLER Experiment

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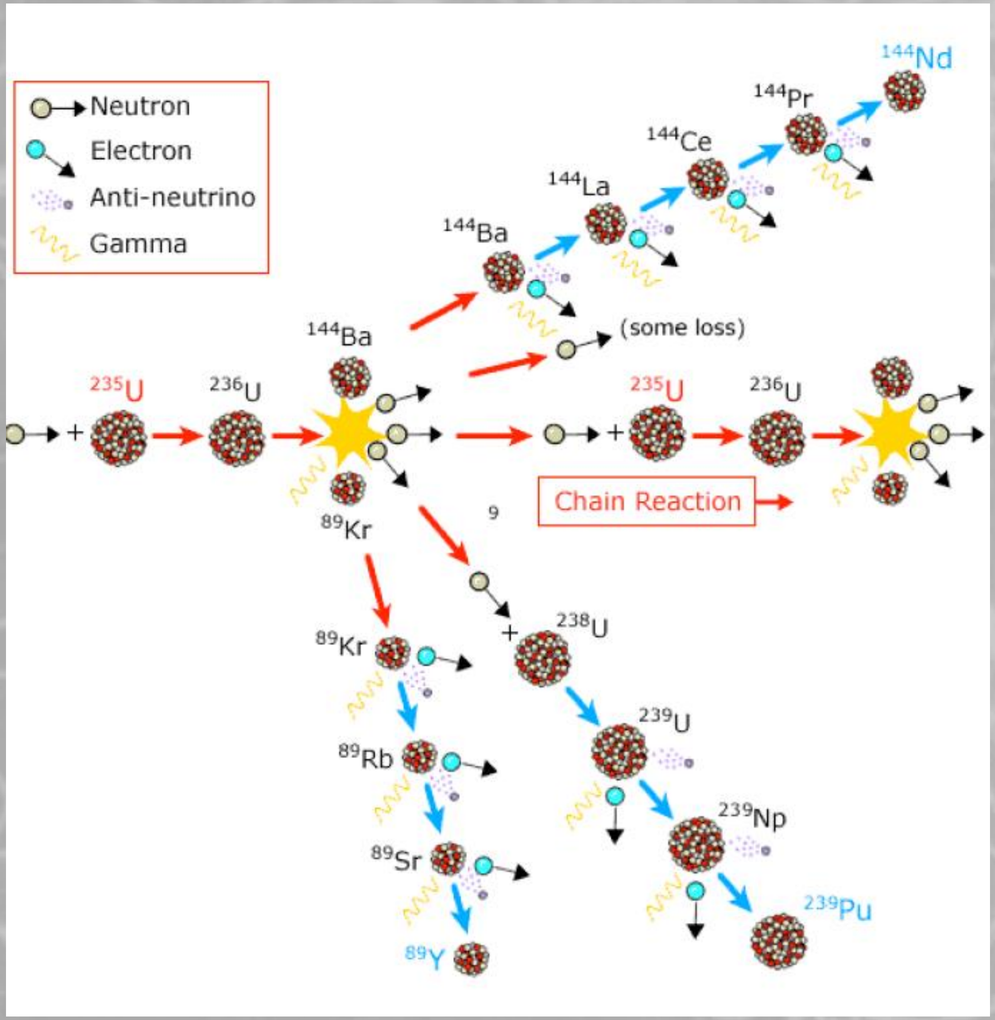
Reactor Antineutrinos

- The first neutrino was discovered in reactor experiment at Savannah River (1956)
- Fission produces neutron-rich daughters, and they produce $\bar{\nu}_e$ through beta decay
- Detecting reactor neutrino rate and energy spectrum from the reactor core can **track the reactor power** and the **composition of nuclear fuel** (for example, plutonium vs uranium would give different energy spectra)
- Therefore, $\bar{\nu}_e$ detection in the vicinity of nuclear reactors can be used for nuclear nonproliferation safeguards
- However, the detector for this purpose must have **minimal shielding** and **be compact**

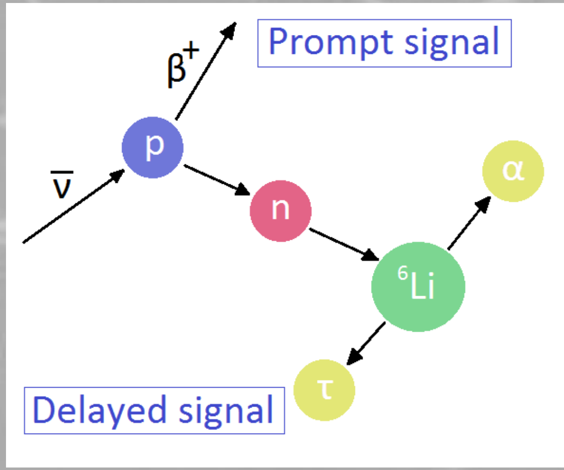


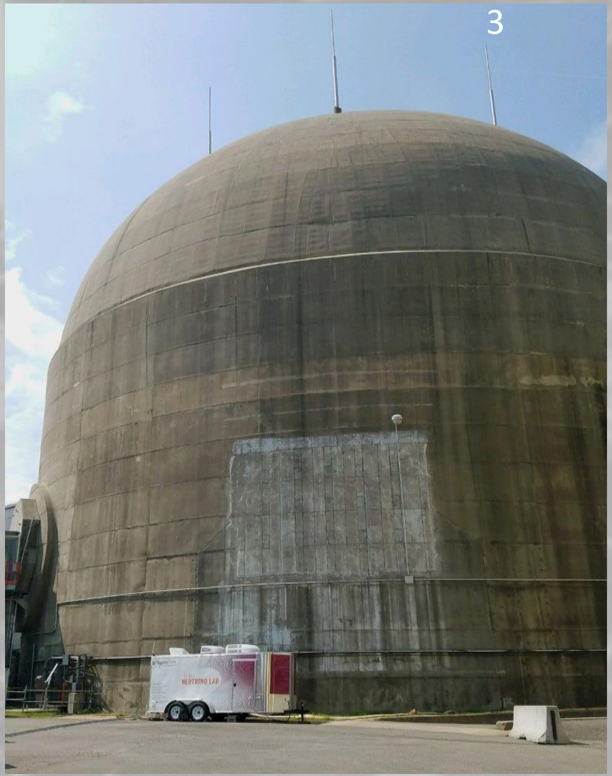
Antineutrino Detection

Inverse Beta Decay (IBD) Mechanism:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

- Prompt (annihilation of positron) and delayed (neutron capture on ^{6}Li) signals coincidence create efficient background rejection



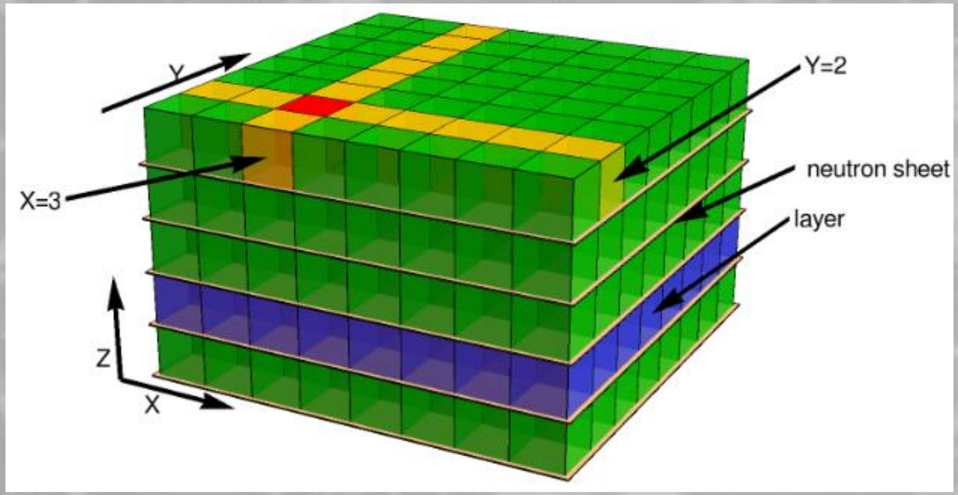


Reactor:

- North Anna Nuclear Power Plant in Mineral, VA
- Two pressurized water reactor cores of 2940 MW each
- MiniCHANDLER was deployed at 25 m from the center of reactor core number 2

CHANDLER Technology

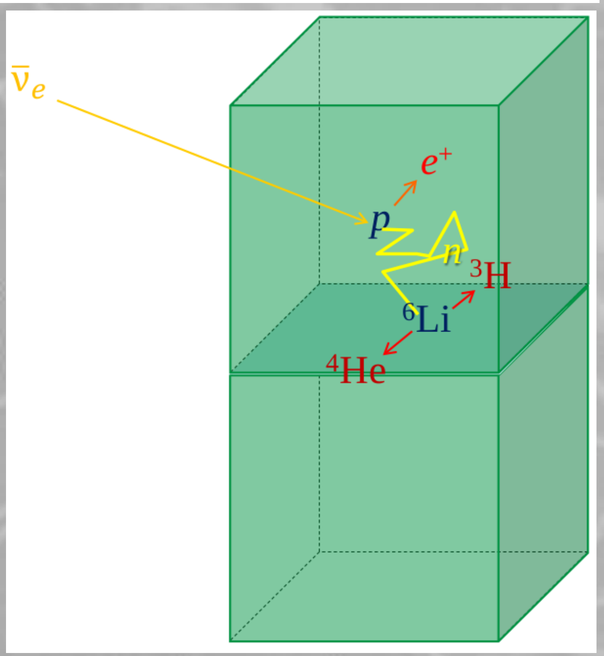
- Utilizes **Raghavan Optical Lattice (ROL) detector** technology that transports light by **total internal reflection** along columns and rows of cubes made of wavelength shifting plastic scintillator



- 3D segmentation: solid plastic scintillator cubes with a size of 6.2 cm; no liquid scintillator.

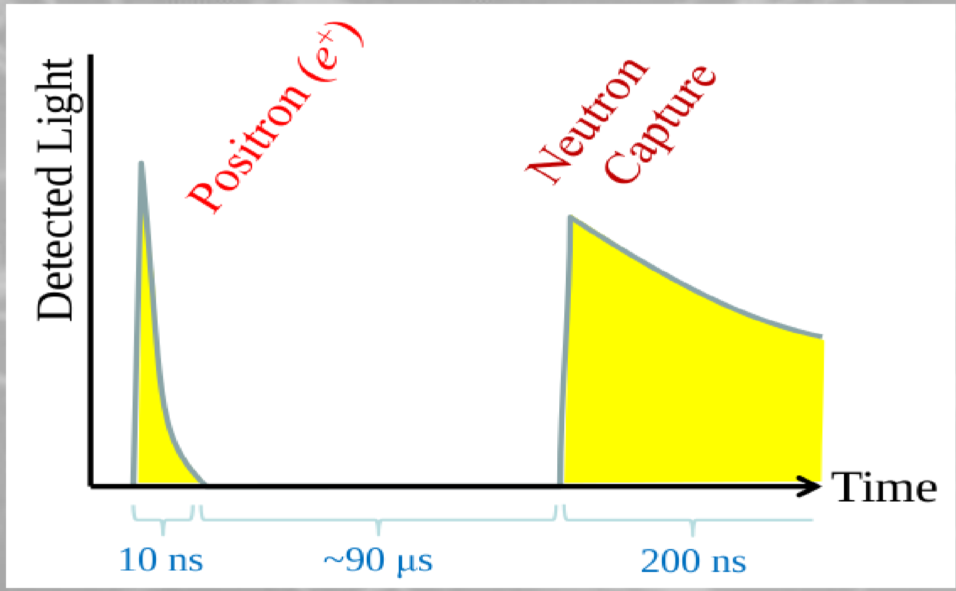
- Between the layers of cubes – sheets from a mix of ^{6}LiF and ZnS:Ag scintillator to detect thermal neutrons

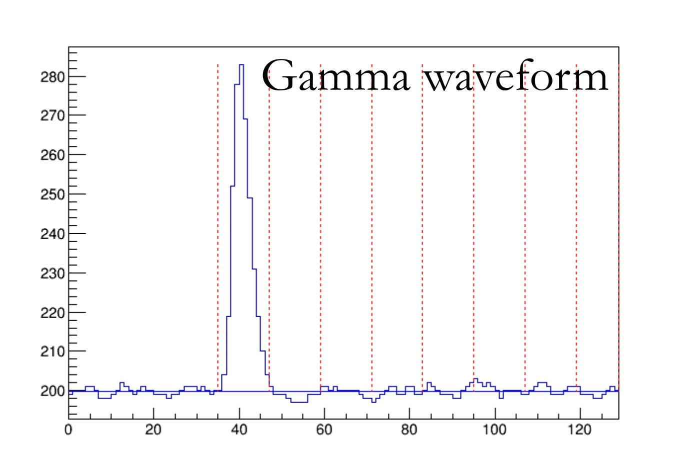
- Prompt signals are produced in the cubes while delayed – in neutron sheets



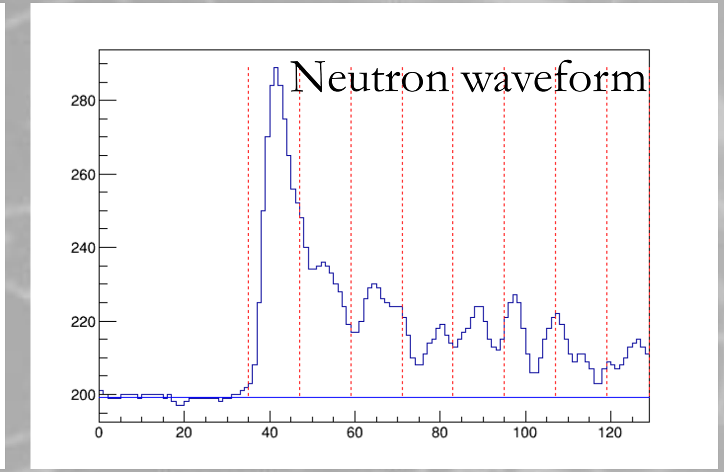
CHANDLER Technology

- Decay constant of plastic scintillator (EJ-260): ~10 ns
- Decay constant of ZnS:Ag scintillator (EJ-426): ~200 ns
- This differences allows to tag positrons and neutrons separately
- The signals are processed with **template-based χ^2 method** (T. Subedi): Waveforms are divided into time bins and bin-by-bin the χ^2 is calculated between the waveform and the previously created template for gamma-like and neutron-like waveforms
- Selection criteria – the waveform is tagged as either of **gamma-like** or **neutron-like** event





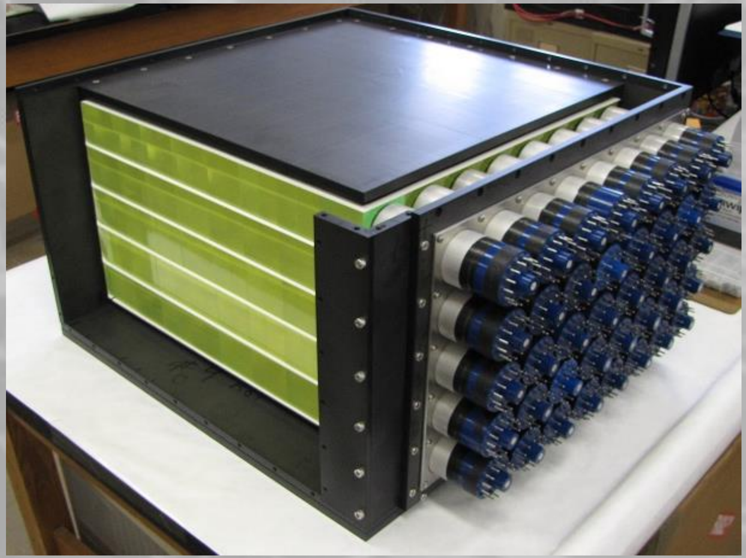
Time (16 ns bins)



Time (16 ns bins)

MiniCHANDLER Experiment

- 80 kg prototype of full scale CHANDLER detector
- 8×8×5 array of cubes and 6 neutron sheets
- PMTs on only one end of each column and row of cubes
- 14 ft trailer that has quiet power supply, Wi-Fi, AC
- Deployed at North Anna NPP and was data taking from August 9th, 2017 – November 2nd, 2017
- 2 reactor-on periods + 1 reactor-off period
- Change in trigger threshold due to extra background from parked trailers with activated equipment



MiniCHANDLER Neutrons Study

MiniCHANDLER Neutron Signal

- **Thermal neutrons** from the reactor core during reactor-on periods and ramp-up and ramp-down of the reactor
- Cosmogenic background from cosmic rays and showers – **fast neutrons**
- Possible background from the reactor core number 1 (90 m)
- Inverse beta decay neutrons (small comparing to other rates)

MiniCHANDLER Shielding:

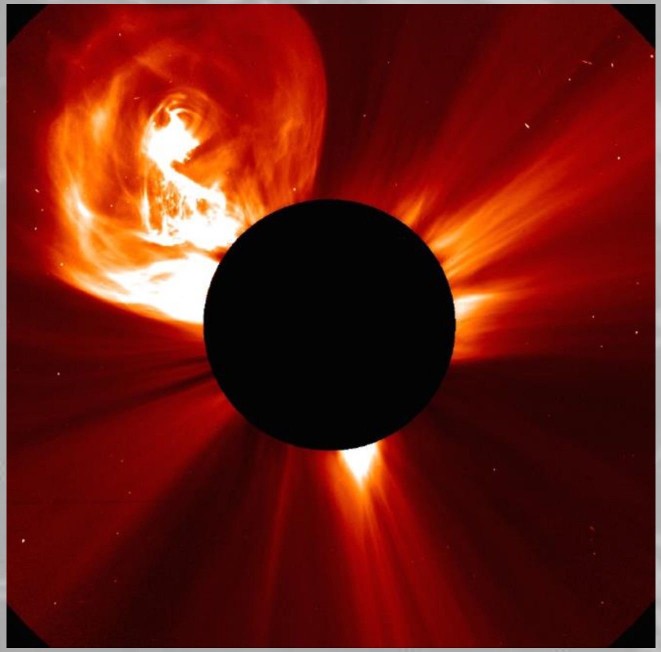
- A layer of 1-inch-thick **boron-loaded polyethylene** with holes for PMTs
- + 1 inch of **lead shielding** – below the detector and on the 2 sides closest to the containment building – to decrease gamma rate from the reactor.

Primary Cosmic Rays

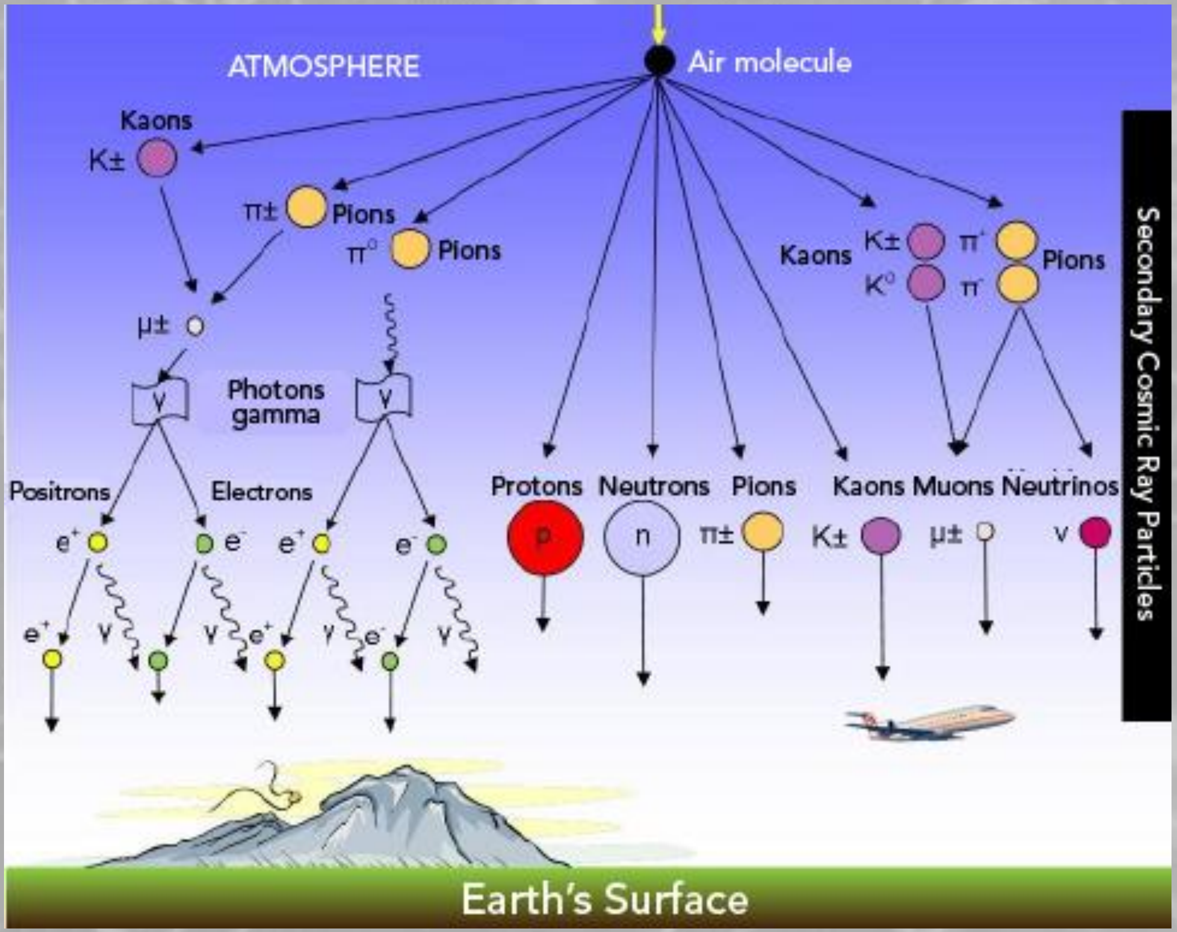
- High energy particles: 90% are protons, 9% are α-particles, 1% are heavier nuclei
- The majority is from outside of Solar System but from within our Galaxy
- Solar activity and Solar modulation deflect the plasma of primary cosmic rays
- When the Sun is "quiet", more cosmic rays reach Earth
- The Sun's activity goes through **11-years cycle** with complete flip of magnetic poles during solar activity minimum
- The Solar activity can be characterized with **sunspot numbers**: at the highest activity, the numbers of the sunspots is the maximum
- Some portion of cosmic rays come from the Sun (**solar flares**) and coronal mass ejections (**CME**)

Seen on Earth:

- Violent solar events can be seen on Earth as **Forbush decrease** in cosmic rates or Ground Level Enhancement (**GLE**)



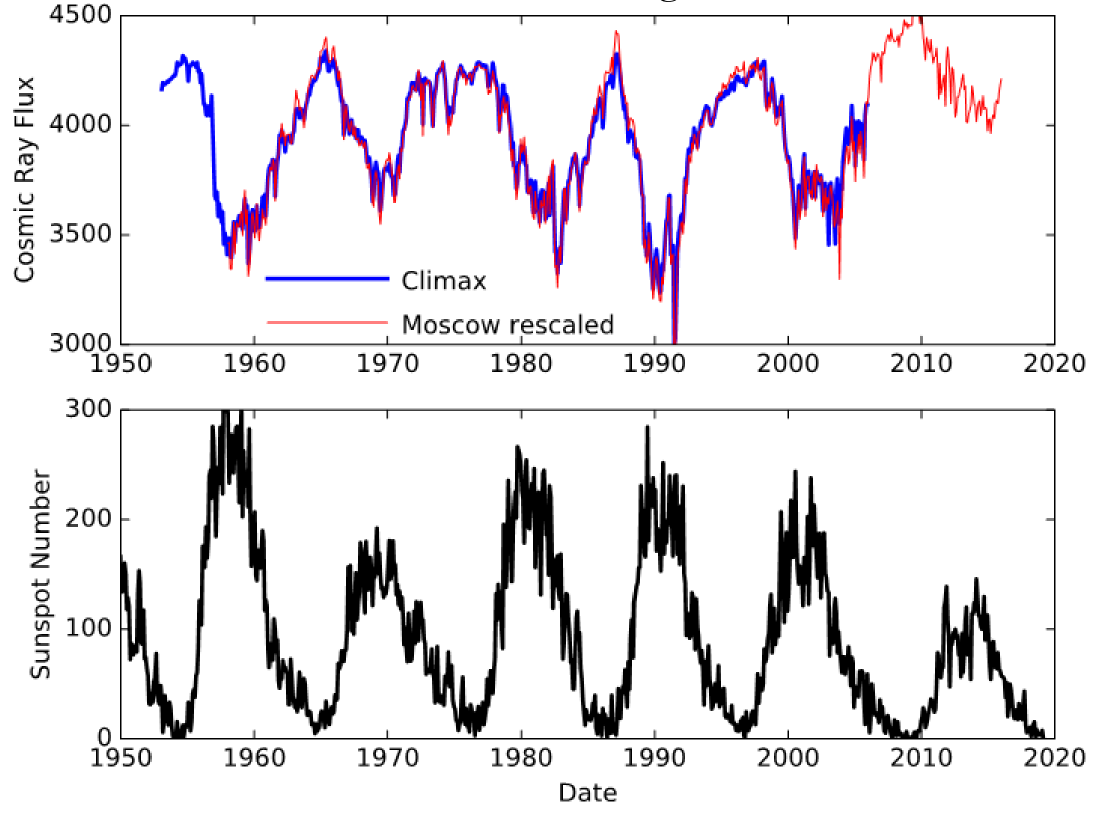
Secondary Cosmic Rays



- Born during interaction of primary cosmic rays with the atmosphere
- Typically: γ-rays, protons, α-particles, pions, kaons, muons, positrons, electrons, neutrons, neutrinos
- Neutron is next abundant particle detected at sea level after muons because being neutrally charged, they lose the least energy while traveling down

Solar Activity in 2017

Image credit: David Hathaway



- MiniCHANDLER operated closer to Solar activity minimum (2017) but according to publications, the solar activity during that months was "exceptional"

The Solar Eruption of 2017 September 10: Wavy with a Chance of Protons

Curt A. de Koning[1,2], V. J. Pizzo[2], and Daniel B. Seaton[1,3]

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Citation Curt A. de Koning *et al* 2022 *ApJ* **924** 106

PAPER • OPEN ACCESS

Investigation of exceptional solar activity in September 2017: GLE 72 and unusual Forbush decrease in GCR

L. Dorman[1,2], Y. Tassev[3], P. I. Y. Velinov[3], A. Mishev[4,5], D. Tomova[6] and L. Mateev[3]

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Abstract

The exceptional solar activity in early September 2017 at minimum of solar cycle 24 is analyzed. Intensive solar-terrestrial disturbances was caused by Active Region AR2673, which produced four powerful eruptions class X, including the strongest flare X9.3 of Solar Cycle 24 on September 6, 2017, after which began G4 – Severe geomagnetic storm on 07-08.09.2017 with Ap = 96, and also the second strongest flare X8.2 of Solar Cycle 24 on September 10, 2017, which generated Ground Level Enhancement (GLE) of cosmic rays. This was GLE72 with increase of solar cosmic ray flux 6% in Oulu Station (Finland) (effective vertical geomagnetic cutoff rigidity: 0.8 GV), and increase 9% in DOMC Antartica and 14% in DOMB Antartica (in the latter case - lead free neutron monitors with effective vertical cutoff rigidity <0.01 GV). The GLE72 develops under the conditions of a deep Forbush decrease (around 15%) in South Pole cusp caused by September 7th Coronal Mass Ejection. The Forbush effect ends on September 11th (http://cosmicrays.oulu.fi). But cosmic ray measurements by flying balloons to the stratosphere over California show that after solar eruptions in September 2017 the radiation levels in stratosphere took more than two months to fully rebound to the conditions of minimal solar activity. This is interesting fact which deserves to be explored in detail. It is precisely the study and interpretation of this process that is concerned with this work.

Neutron Monitors

- **Newark Neutron Monitor**:

Coord: 39.68, -75.75, Altitude: 50 m

- **Athens Neutron Monitor**:

Coord: 37.97, 23.78, Altitude: 260 m

- **Oulu Neutron Monitor** :

Coord: 65.0544, 25.4681, Altitude: 15 m

- **Fort Smith Neutron Monitor** :

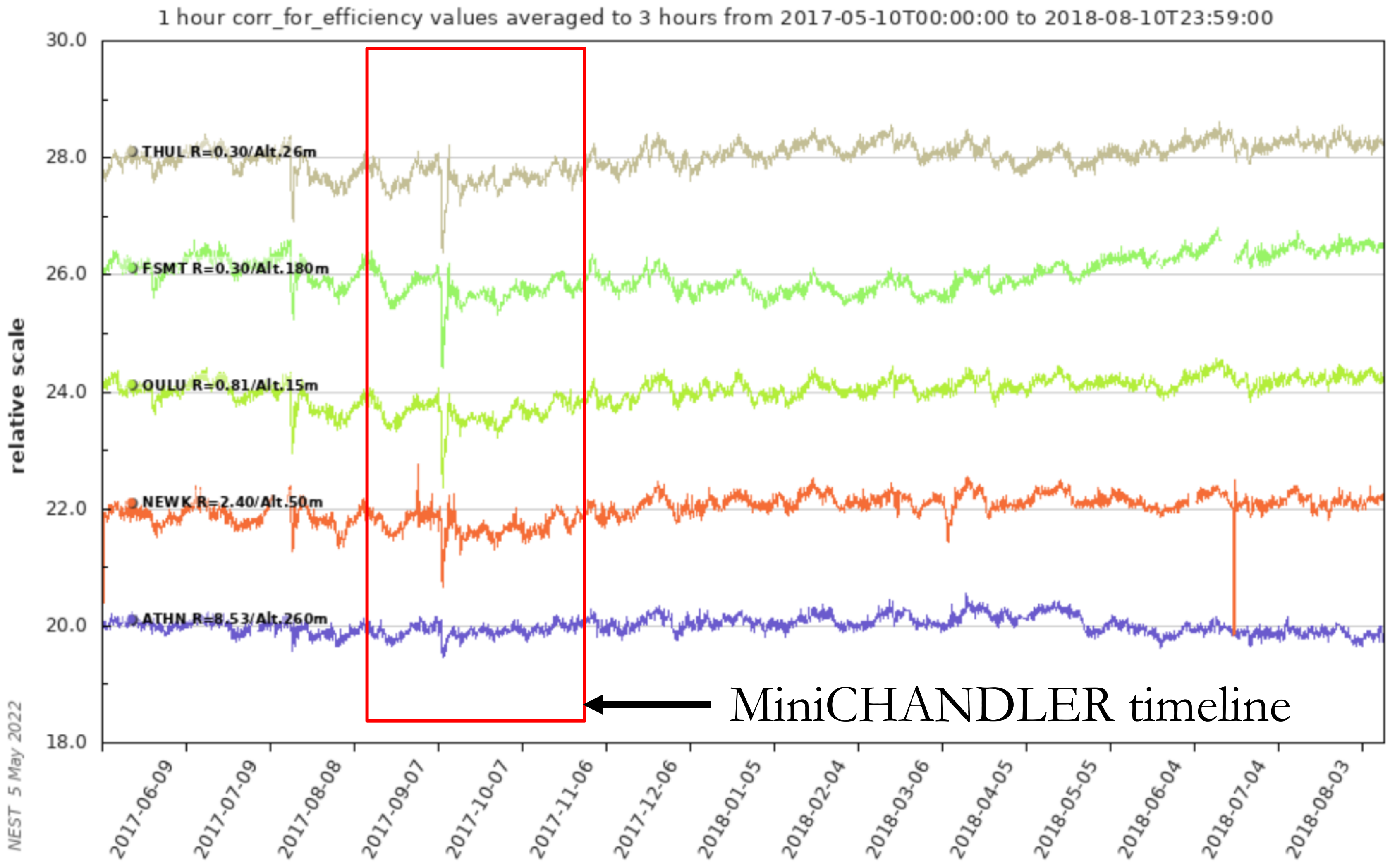
Coord: 60.02, -111.93, Altitude: 180 m

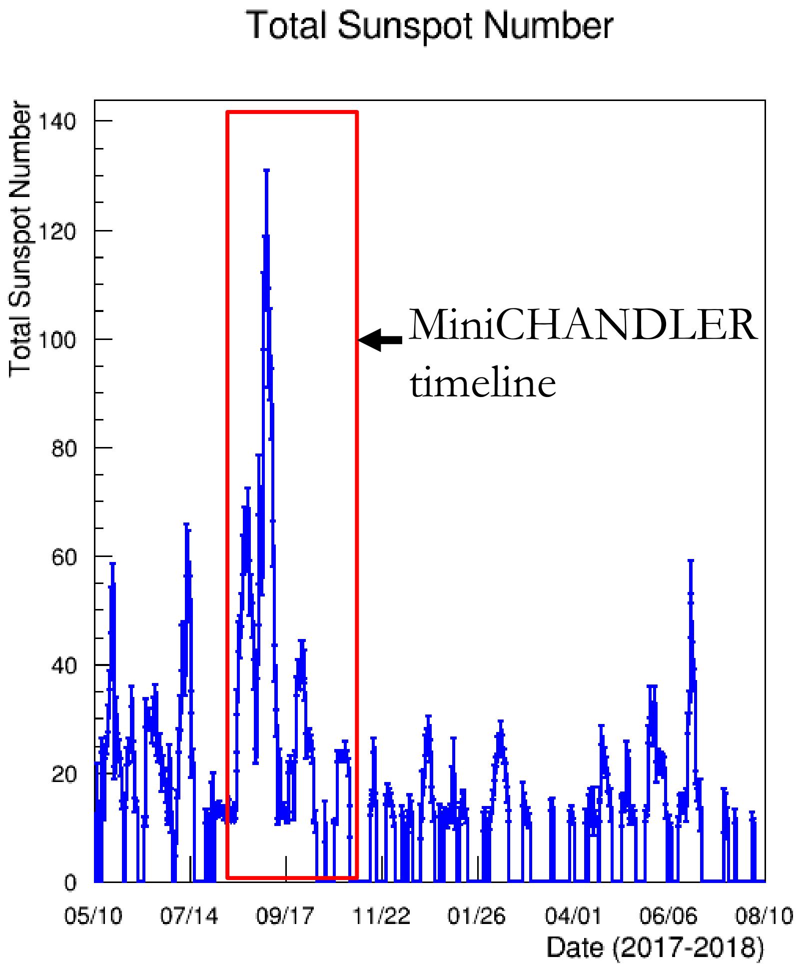
- **Thule Neutron Monitor** :

Coord: 76.5, -68.7, Altitude: 26 m

- **North Anna Nuclear Power Plant** coordinates: 38.06443, -77.79015
- Newark monitor is the closest

Neutron Monitors Data





Oulu Neutron Monitor (NM) count rate variations in September 2017. It is clearly visible the Forbush decrease (–8%) of galactic cosmic rays on September 08, 2017 caused by CME on September 7th, and also the Solar Cosmic Ray increase – i.e. the Ground Level Event No 72 (GLE72) on September 10, 2017 caused by the flare X8.2 slightly earlier that day.

Cosmic Rays and Atmospheric Pressure

- Thickness of atmosphere affects the absorption of the cosmic rays before they reach the ground
- The higher the atmospheric pressure, the higher the probability for a particle to be absorbed

$$dN = -\beta N dP$$

$$N = N_{initial} e^{\beta(P_0 - P)}$$

$$N = aP + b$$

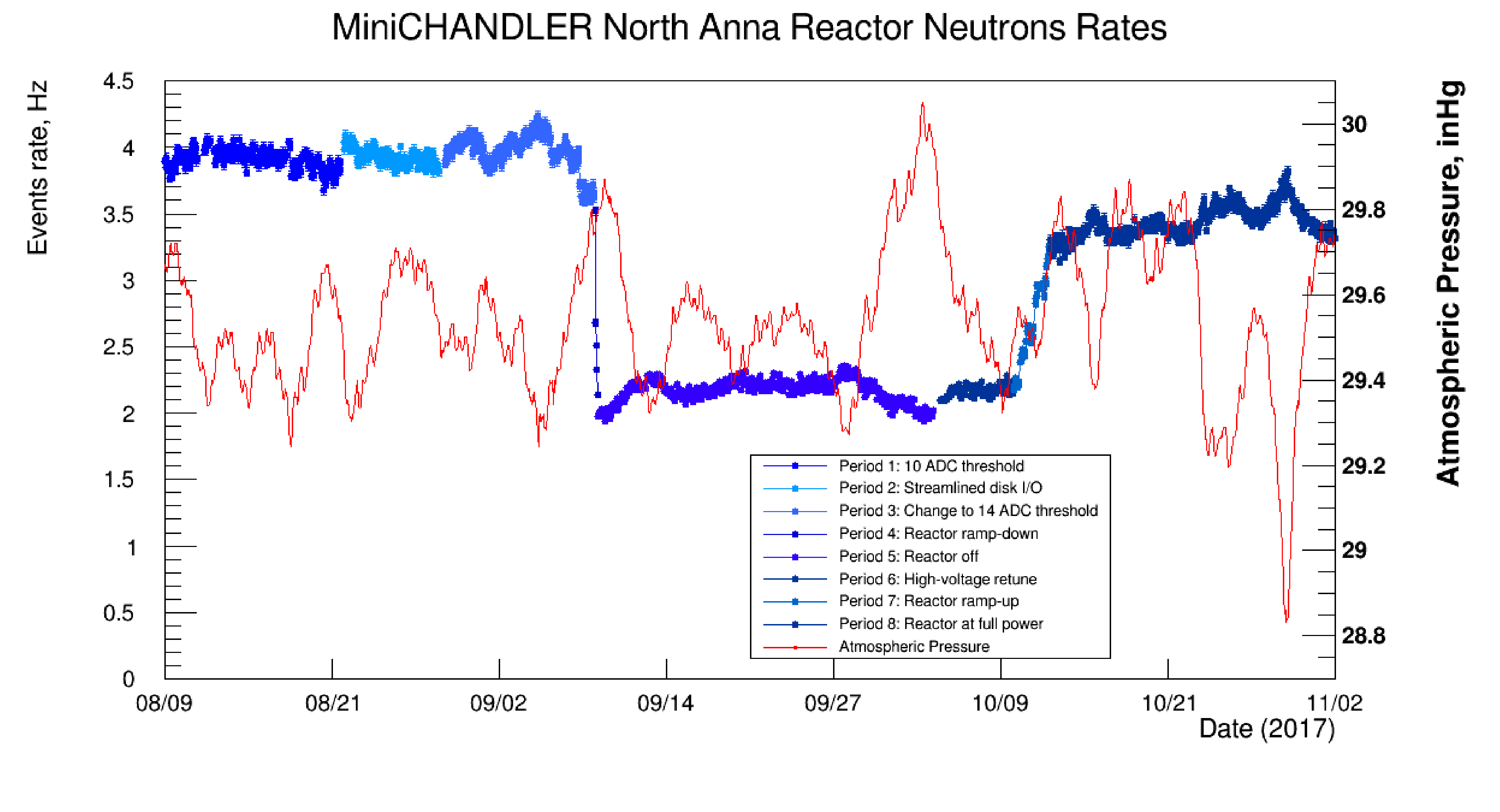
dN – change in measured intensity N
β – barometric coefficient
dP – difference in atmospheric pressure P
P_0 – reference pressure
a, b – linear coefficients

Barometric coefficient from neutron monitors:

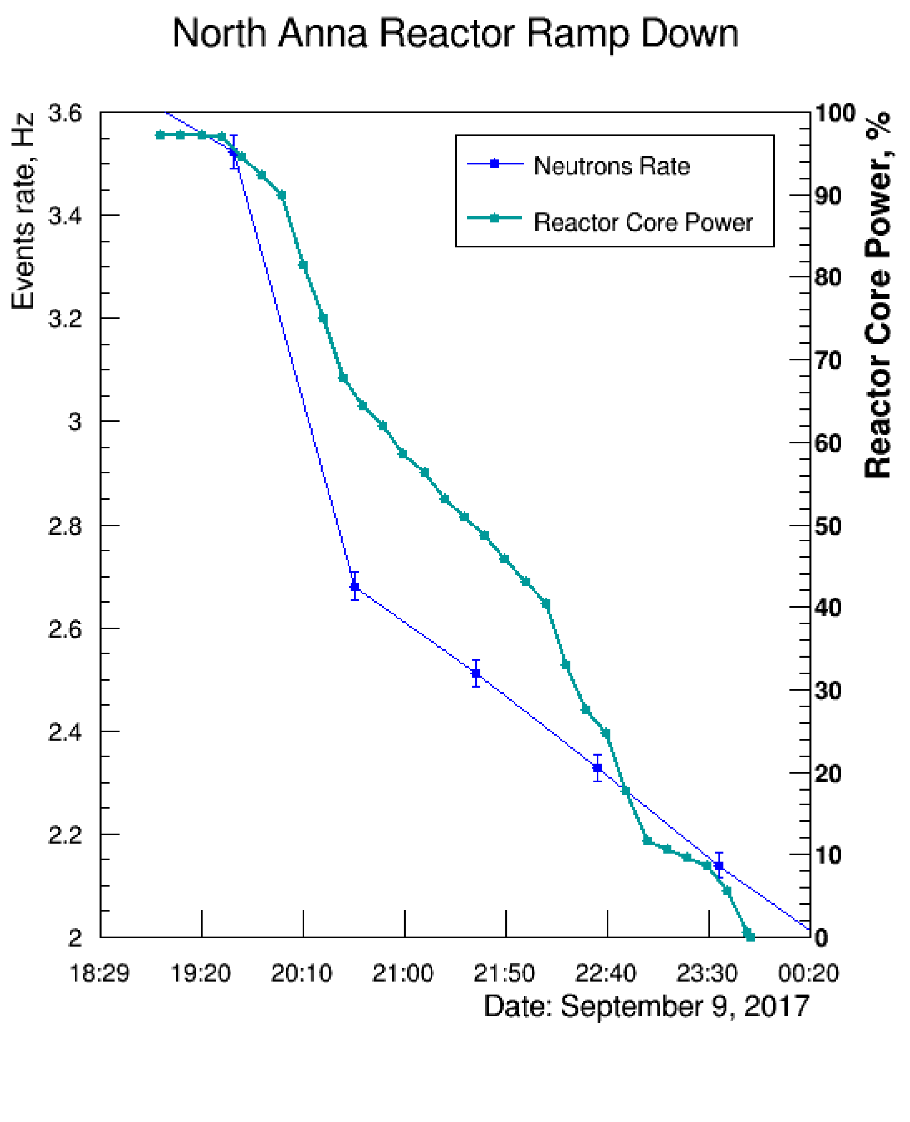
- Newark: $-0.73 \pm 0.01\ \%/mbar$
- Oulu: $-0.75 \pm 0.01\ \%/mbar$
- Thule: $-0.75 \pm 0.00\ \%/mbar$
- Athens: $-0.68 \pm 0.01\ \%/mbar$
- Fort Smith: $-0.75 \pm 0.01\ \%/mbar$

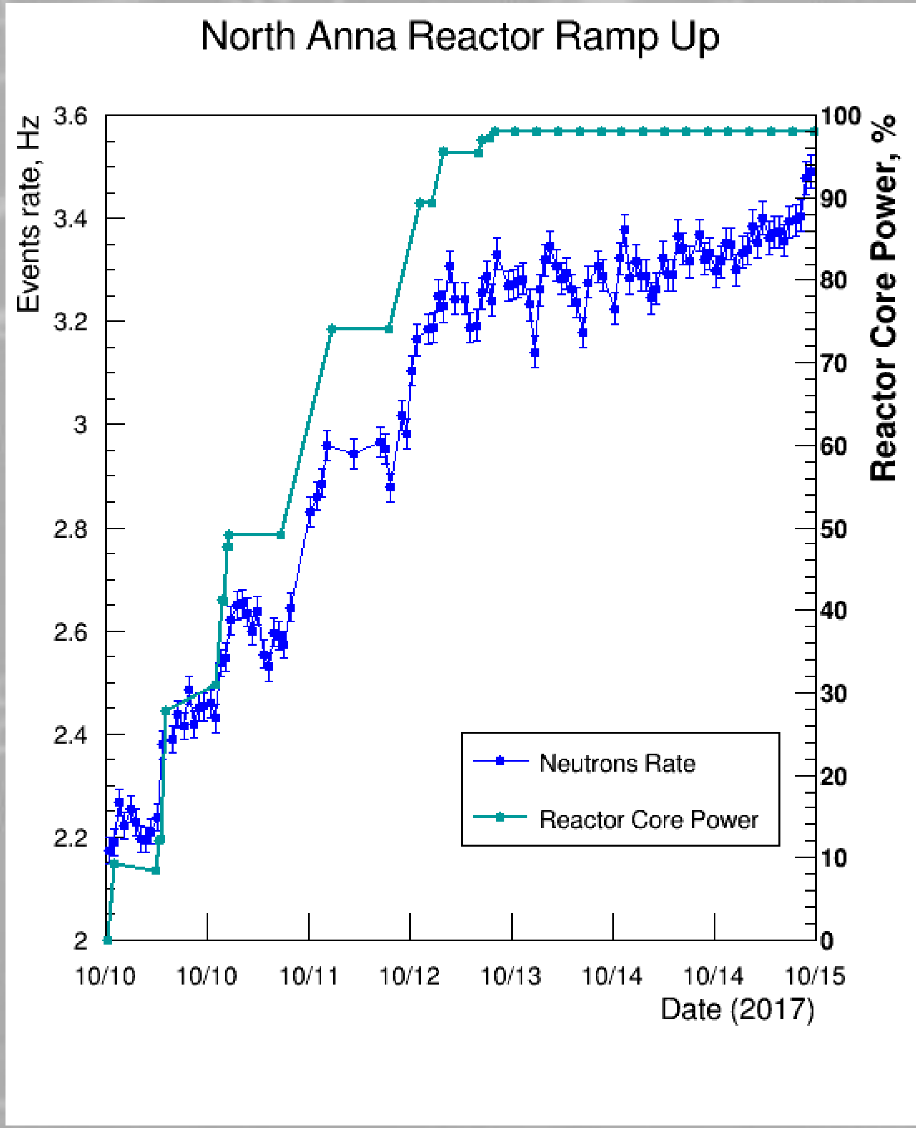
Results

MiniCHANDLER Neutron Rates Dataset

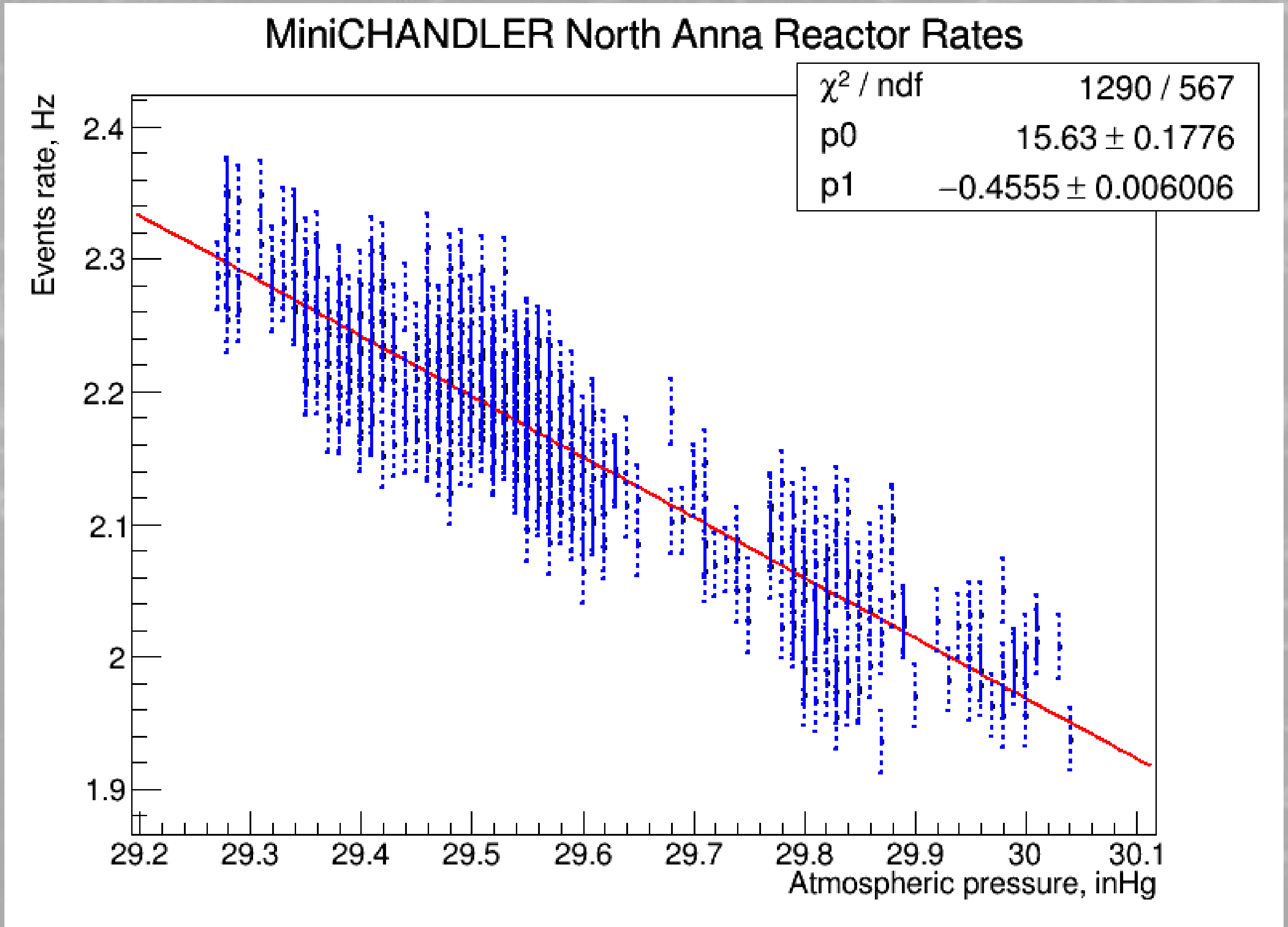


Reactor Power Tracking





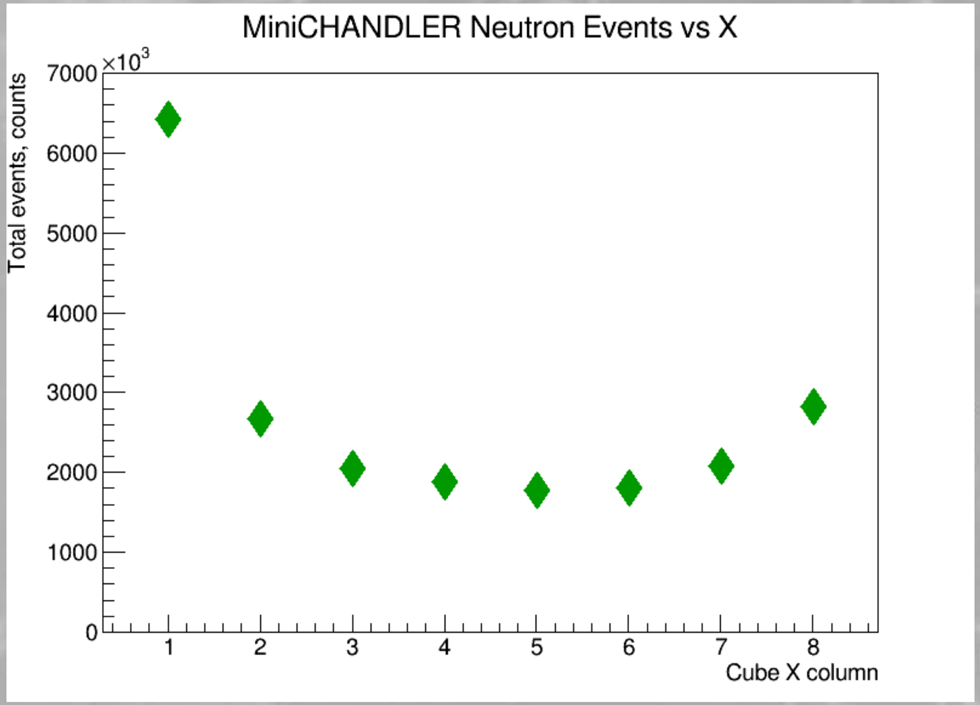
Neutron Rates Pressure Dependence

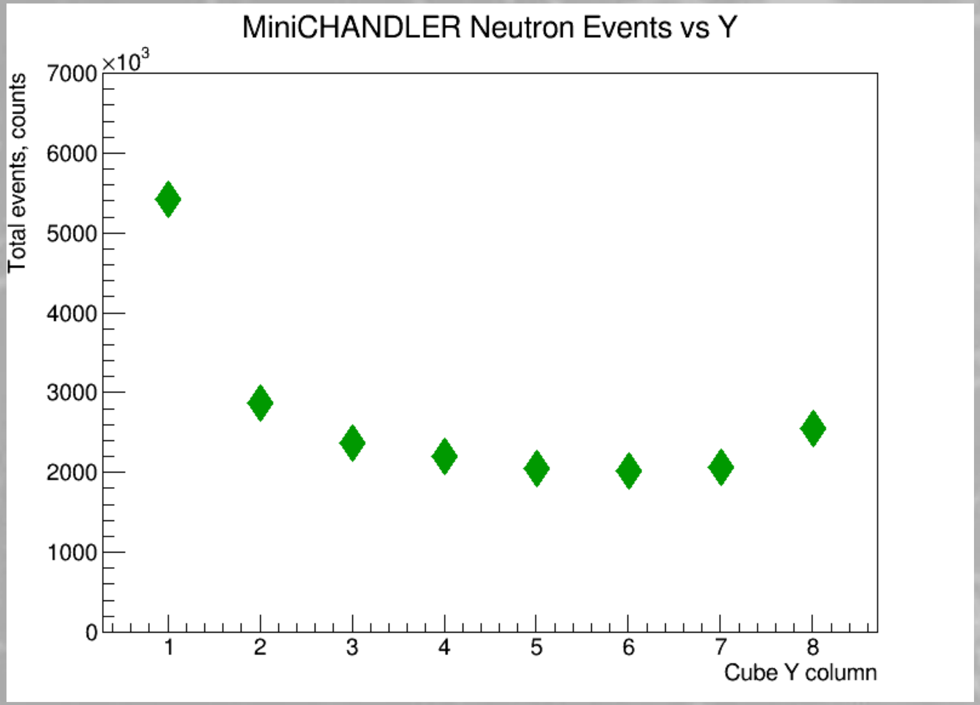


- Full detector, reactor off data
- Atmospheric pressure data: Louisa County weather station (11 miles from North Anna NPP)
- Reactor-off neutron rates/pressure correlation coefficient: **-0.901**
- Reactor-off barometric coefficient: **-0.63 ± 0.01 %/mbar**

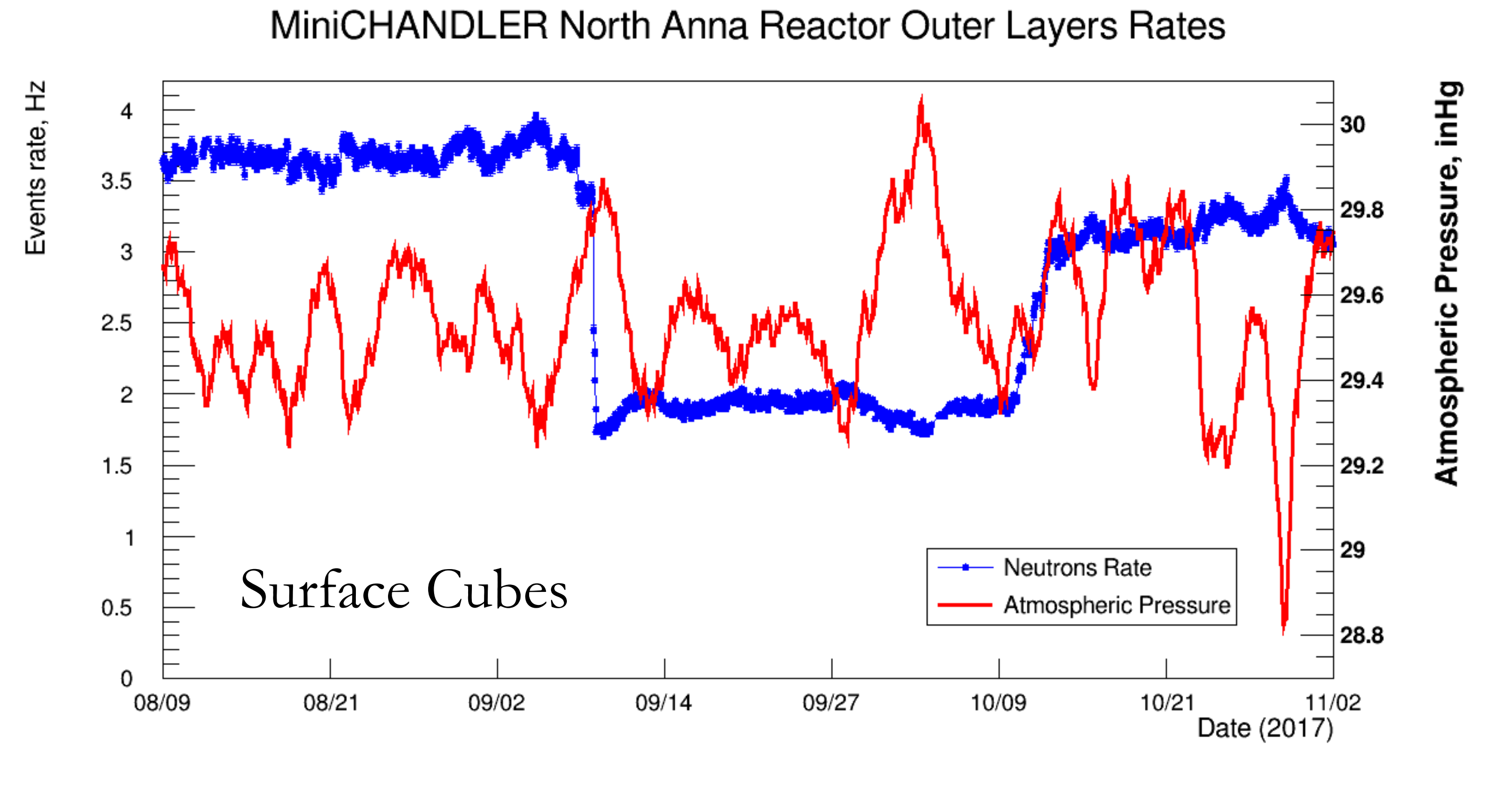
Neutron Rates Spatial Distribution

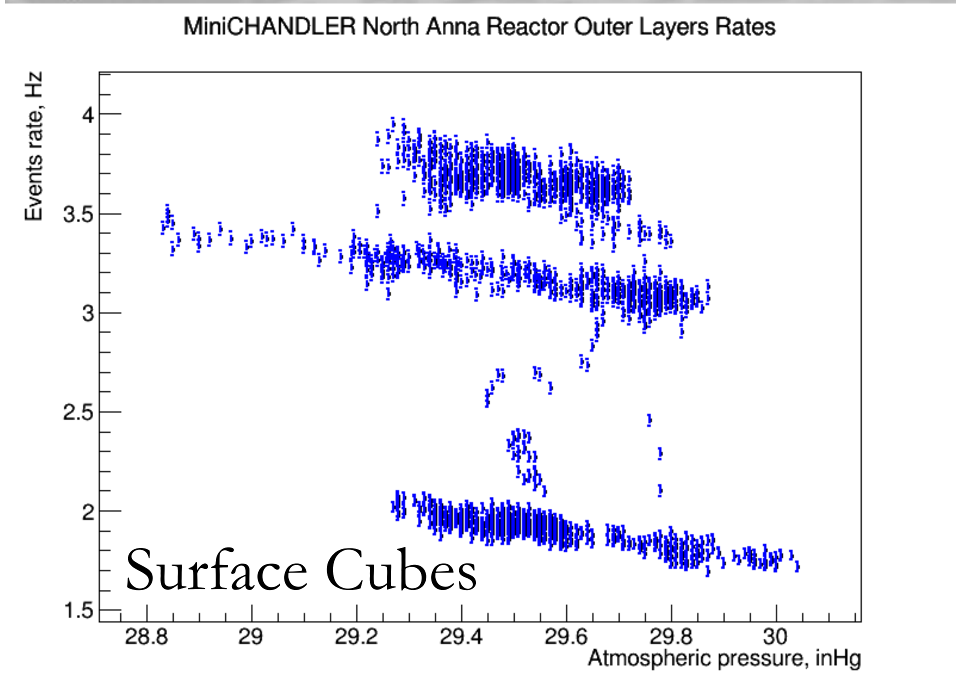
- Total number of counts over the whole dataset
- However, the behavior is consistent from run to run
- Cube X = 1 and cube Y = 1 – the side with PMTs and holes in the borated polyethylene shielding





Surface Cubes vs Inner Detector Cubes

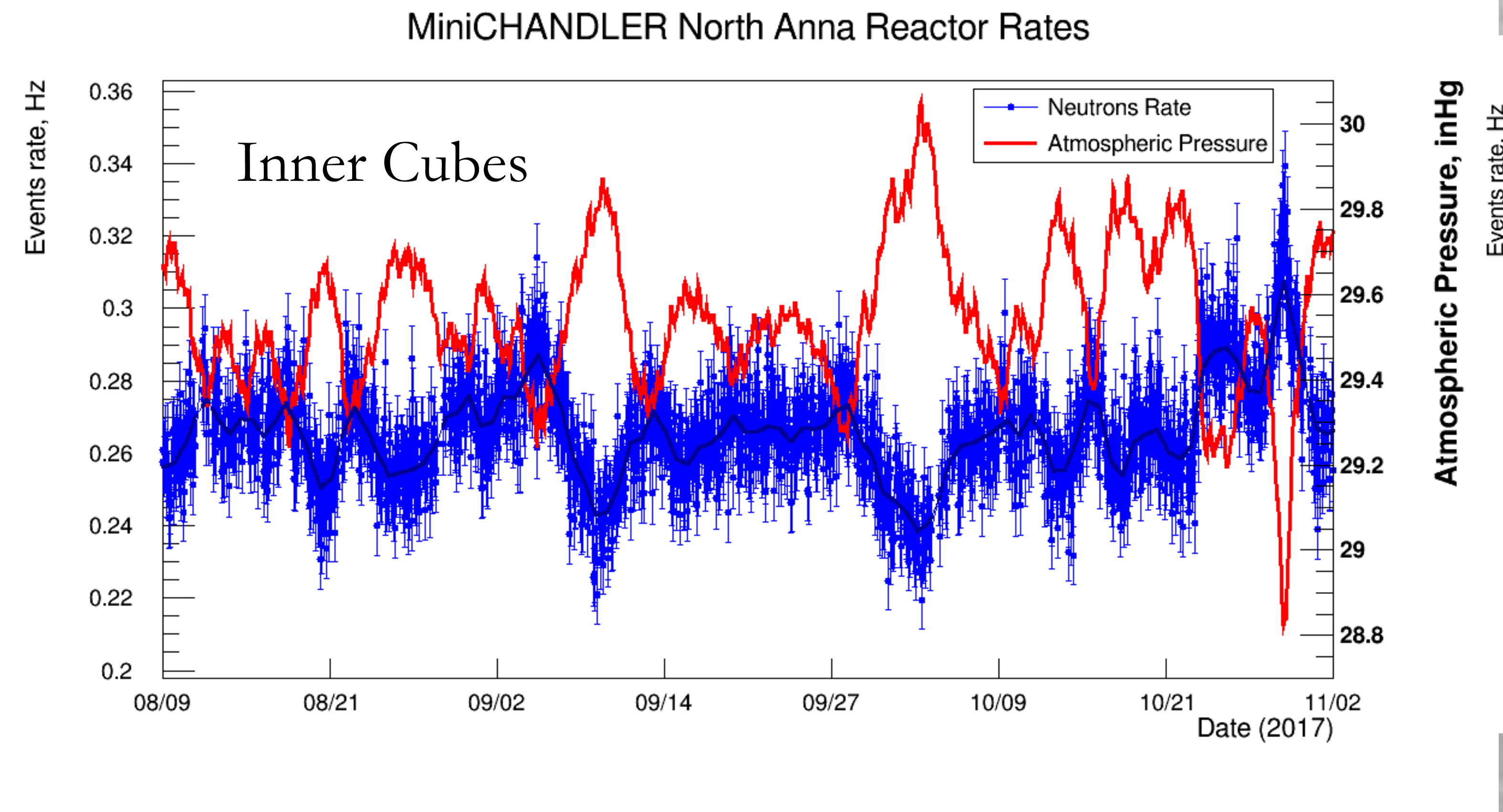


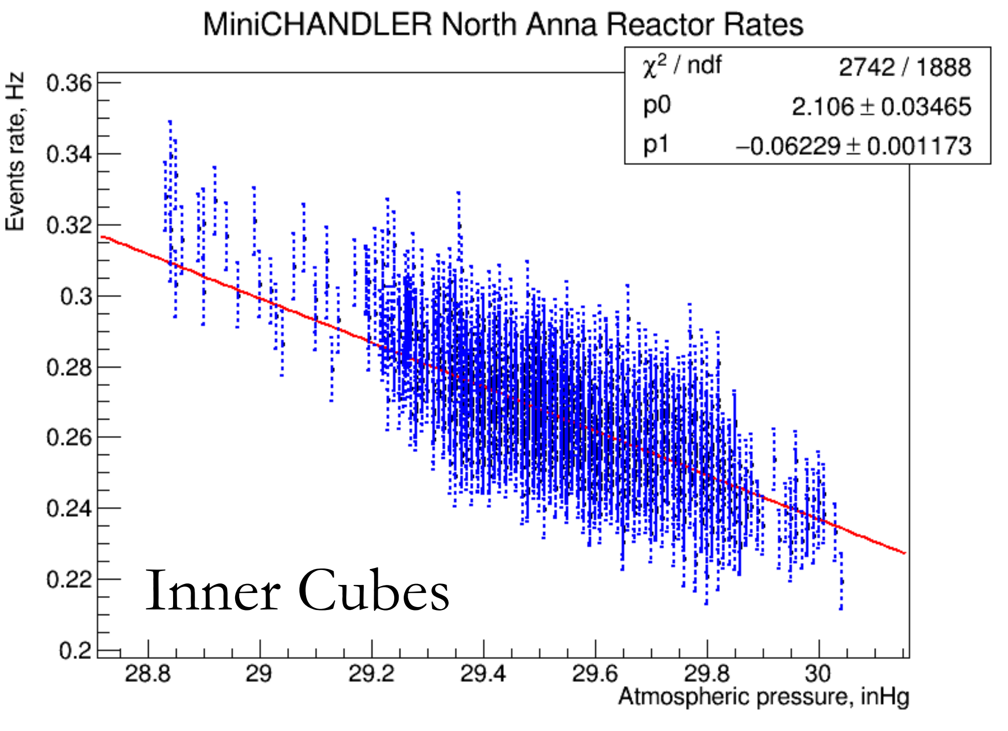


- X = 1, 2, 8
- Y = 1, 2, 8
- Z = 1, 5
- Reactor on/off difference is the most prominent

- 2 reactor-on periods rates differ – the reason is yet unknown

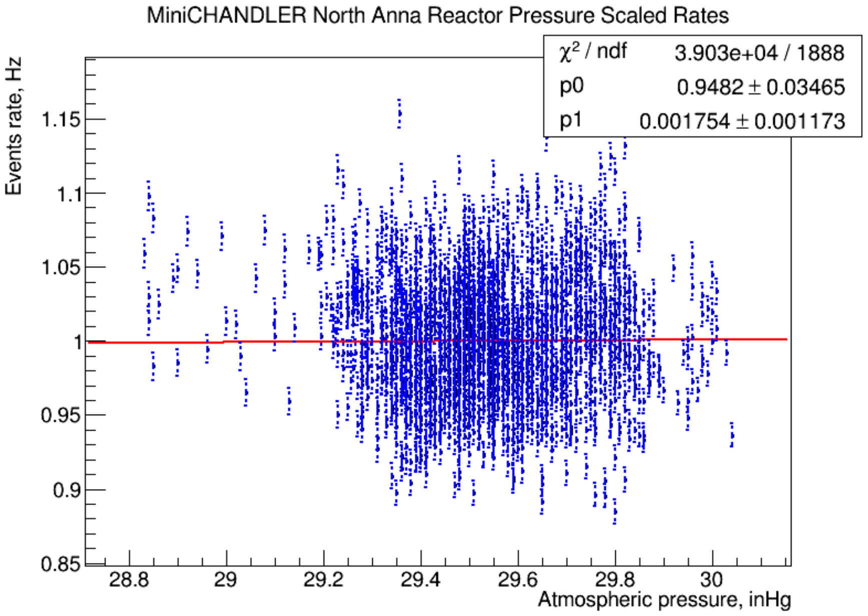
Surface Cubes vs Inner Detector Cubes

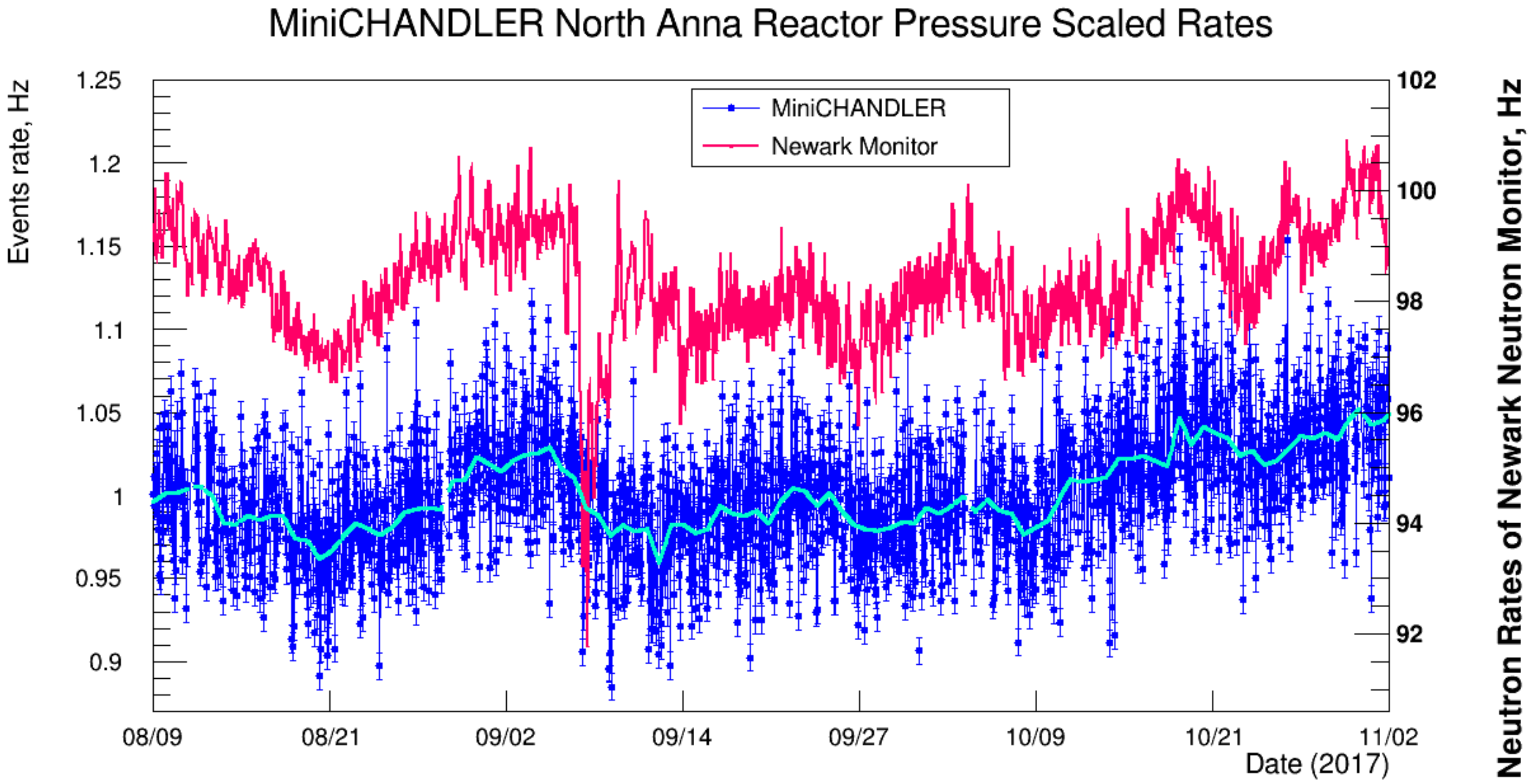




- X = 3, 4, 5, 6, 7
- Y = 3, 4, 5, 6, 7
- Z = 2, 3, 4
- Reactor on/off difference almost disappears due to self-shielding

MiniCHANDLER Pressure Corrected Neutron Rates





- Inner detector cubes to exclude the reactor on/off effect
- Pressure correction applied
- The cause of non-statistical "noise" is yet unknown

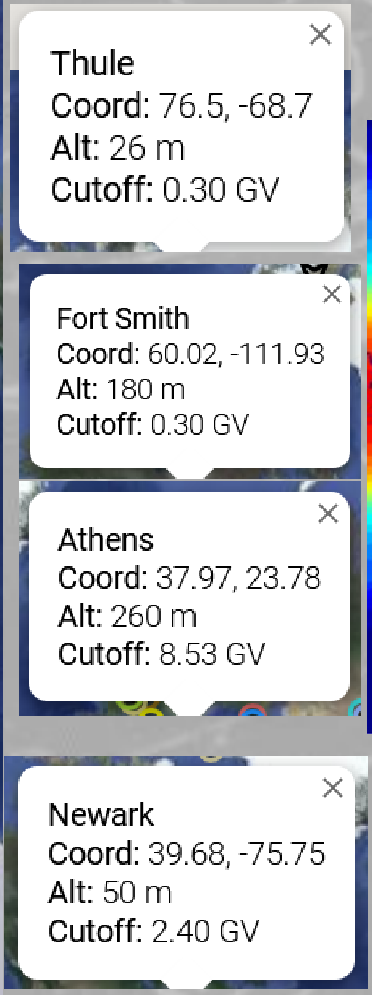
- Correlation with Newark Monitor data: 0.416
- To compare, correlation between different neutron monitors : 0.177 – 0.561
- **However, the Forbush decreases is missing**

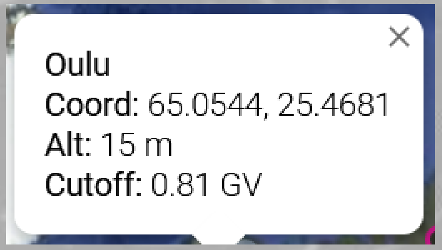
Final Remarks

- Neutron rates in MiniCHANDLER prototype track the **reactor power**, **change in atmospheric pressure** and, questionably, cosmic weather
- The unstatistical fluctuations in neutron rates are being investigated
- The reason for a difference in neutron rates between first and second reactor-on periods is being studied
- The absence of Forbush decrease in neutron rates around September 9-10 is being investigated

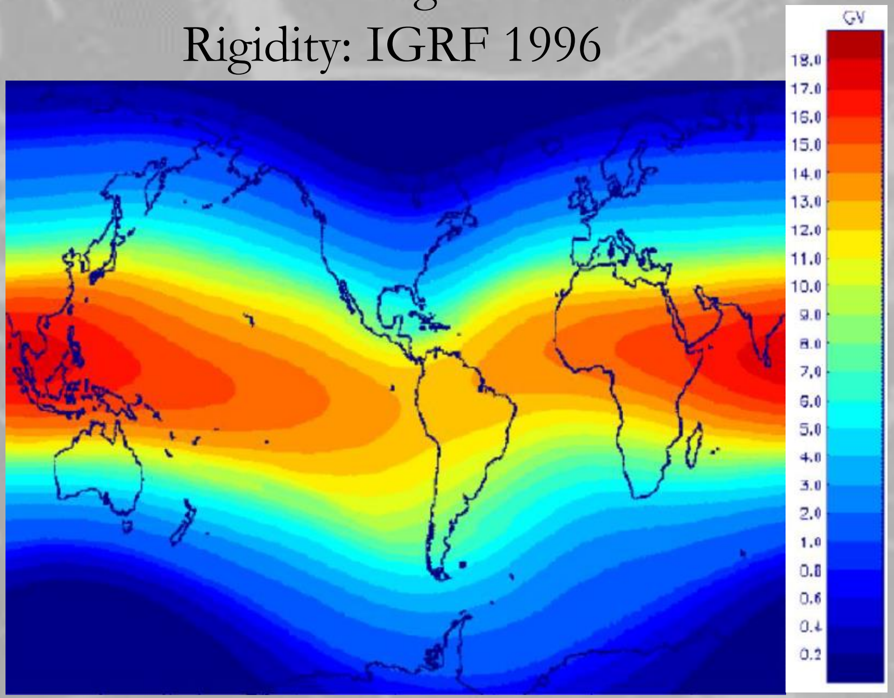
Back up

Neutron Monitors





Vertical Geomagnetic Cutoff Rigidity: IGRF 1996



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