A preliminary study of solar modulation for muons

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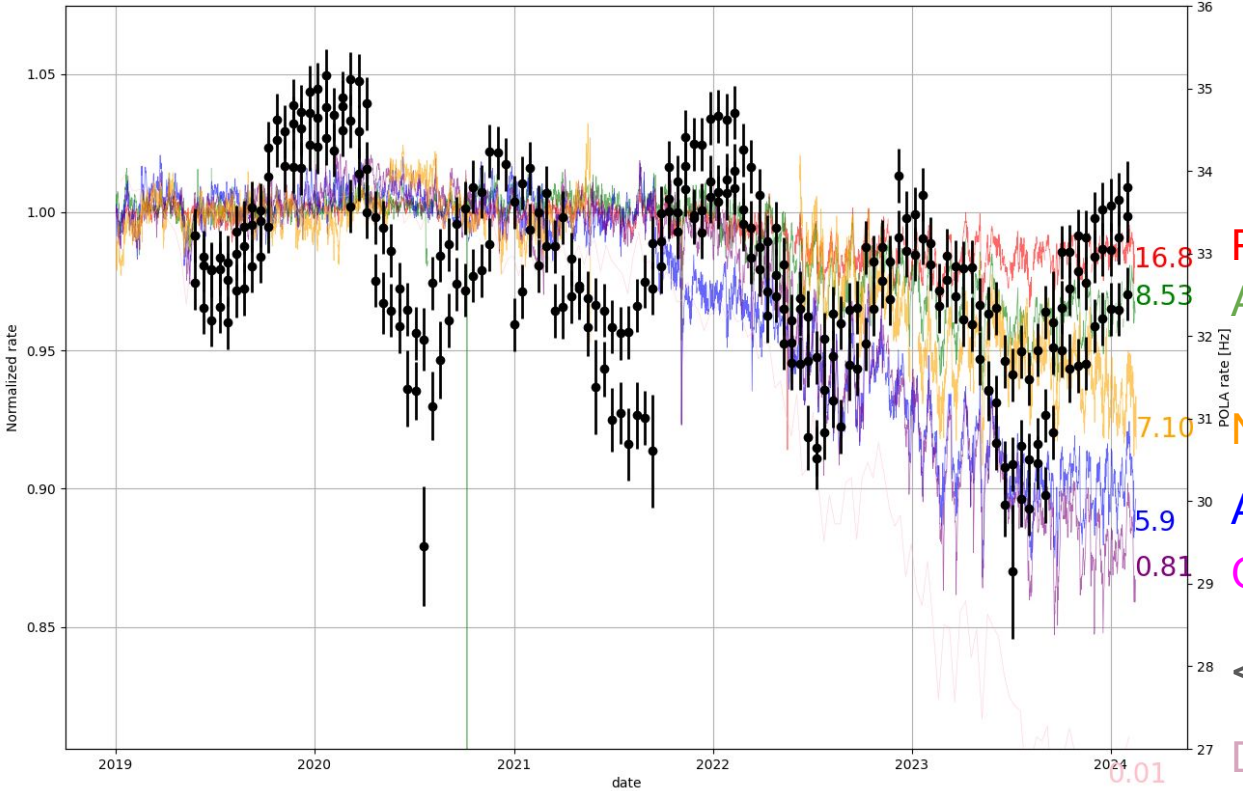
Motivations:

1) Convince myself that POLA-R rates are affected by solar modulation thanks to an educated guess (or a prejudice)
2) Understand if POLA-R can provide new information on this subject

Outlook:

1) a solar modulation effect is measured by POLA-R ?
2) a temptative toy model (seems wrong, to be improved)
3) solar modulation measured by KACST muon detector
4) solar modulation measured by YangBaJing muon detector
5) solar modulation measured by Nagoya muon detector

1) a solar modulation effect is measured by POLA-R ?



Solar modulation affects strongly neutron monitors "located" at low Rigidity cutoff (https://www.nmdb.eu/nest/)

PSNM (Thailand) E_k>15.9GeV

ATHN (Athens) E_k>7.6GeV

NANM (Armenia) E_k>6.2GeV

AATB (Kazakhstan) E_k>5GeV

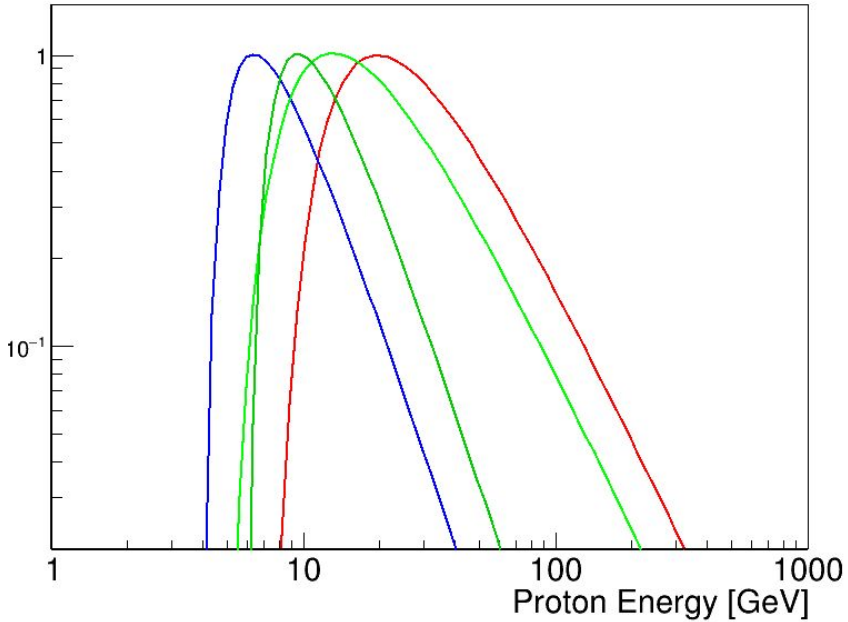
OULU (Finland) E_k>300MeV

<= Svalbard NM expected

DOMB (Concordia south pole)

Assuming a solar modulation effect the "effective" μ cutoff is of the order of 7GV (that is much larger than Svalbard Rigidity cutoff that is << 0.8 GV)

2) a toy model to evaluate energy of primary protons

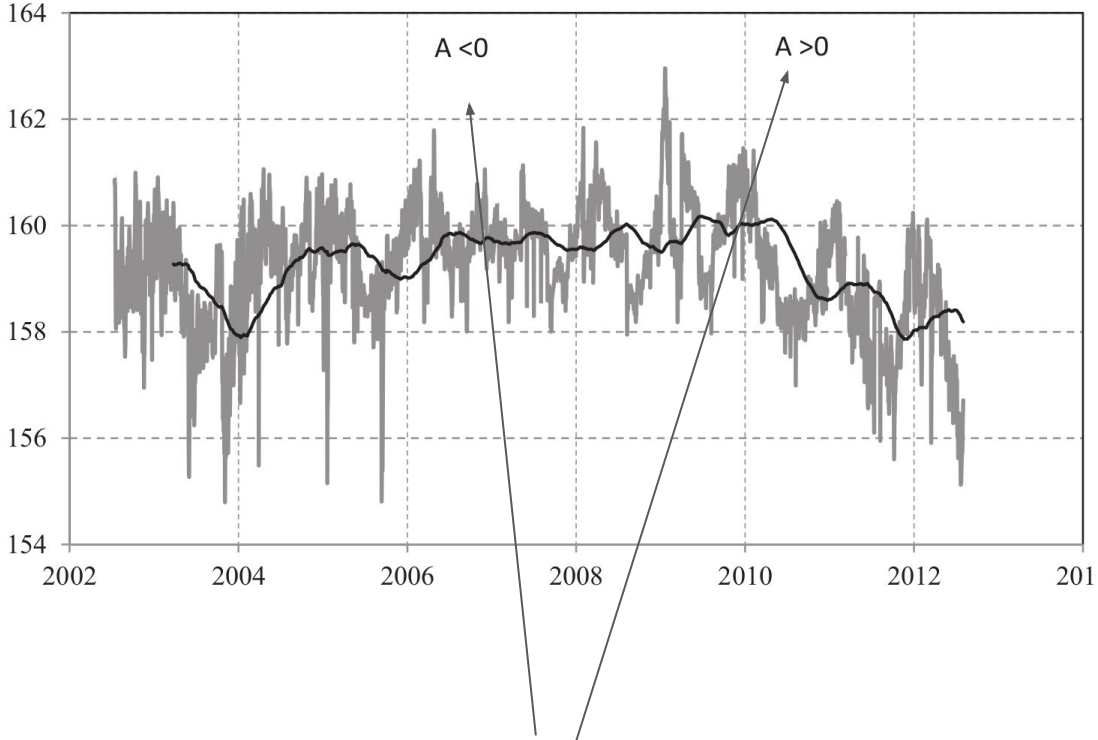


Raw assumptions (red curve):
-Proton spectrum is power law: $N_P=kE^{-2.7}$
-Produced #muon/P grows as: $N_\mu/N_P=E^{0.85}$
-Muon takes ⅓ of proton energy
-Muon energy loss = 1.8GeV (MIP 1000g/cm^3)
-Muon removed only by decay

Blue curve “extreme” case:
-Produced #muon/P is flat with E (n=0)
-Muon takes ½ of proton energy.

This raw toy-model suggests an “effective μ cutoff” in the range 4-10 GV
A check with montecarlo simulation is required.
I would be quite surprised to found Muon “effective cutoff” below 4GV

3) solar modulation measured by KACST muon detector



Data taken from:
https://doi.org/10.1016/j.asr.2020.12.008

King Abdulaziz City for Science and Technology (KACST) Saudi Arabia
Riyadh alt. 613 m 24°N Rc = 14.4 GV

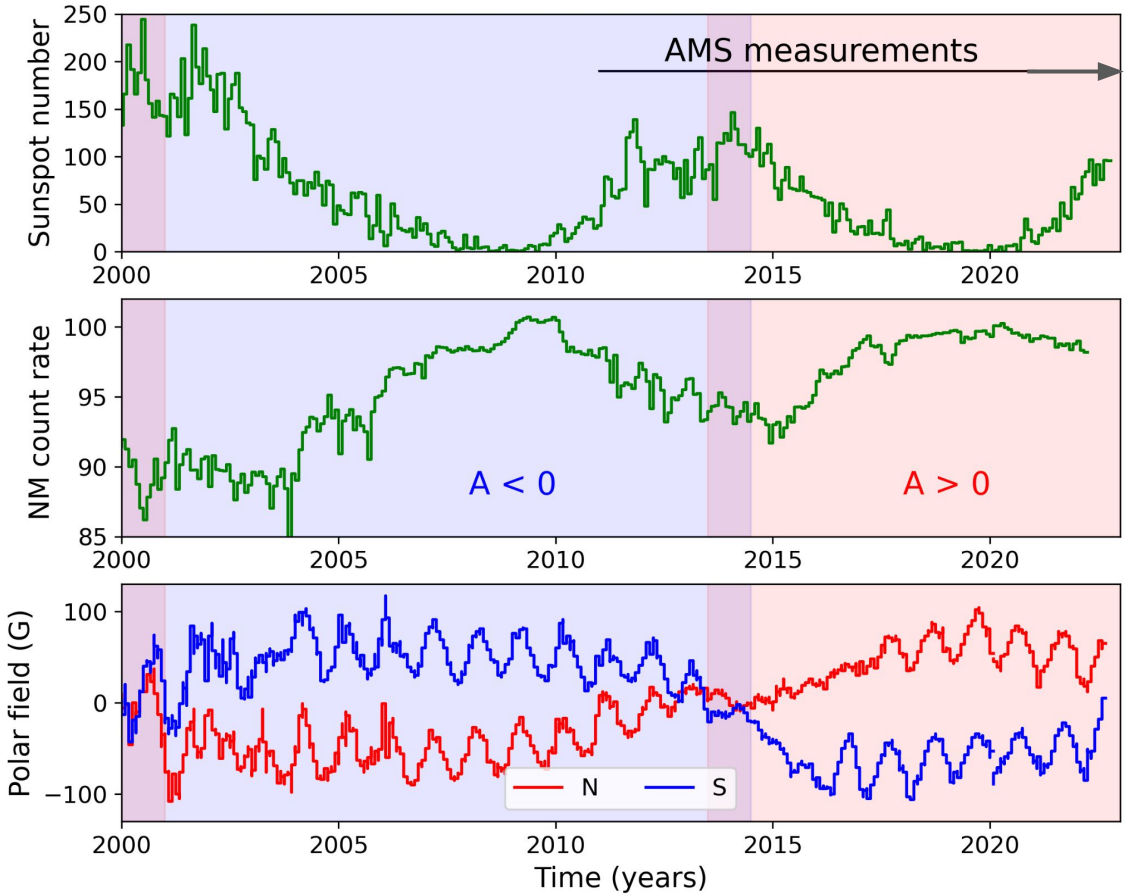
In the article they compare with Lomnický štít NM (Rc = 3.84 GV) and Oulu (Rc = 0.8 GV)

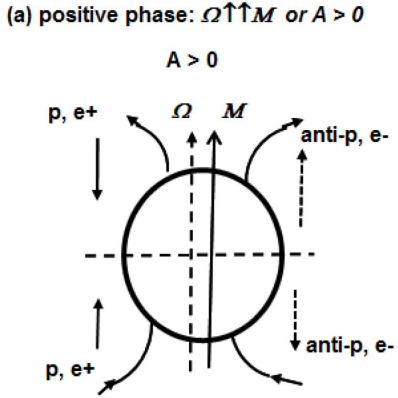
- "small" Annual modulation ~0.5%
- Annual mod. maximum in winter
- Wrong/puzzling smoothing proc.
- Study of many quasi-periodicity

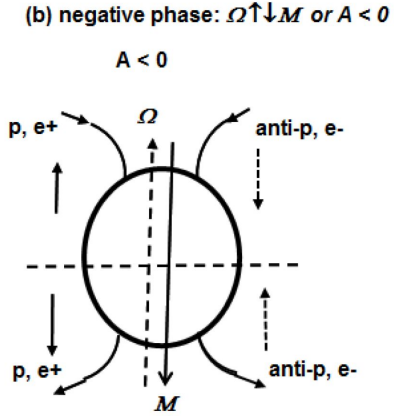
What?? This article is full of errors!
No polarity flip in 2008!!!!

time. The time period of analysis, 2002–2012, covers the two opposite polarity states ($A > 0$, 2009–2012 and $A < 0$, 2002–2008).

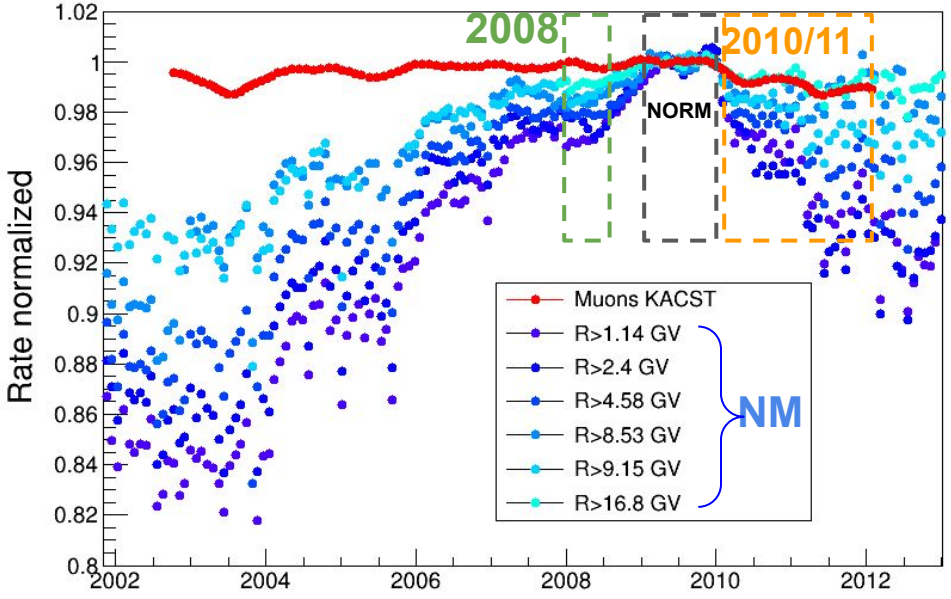
… the last polarity change was not in 2008

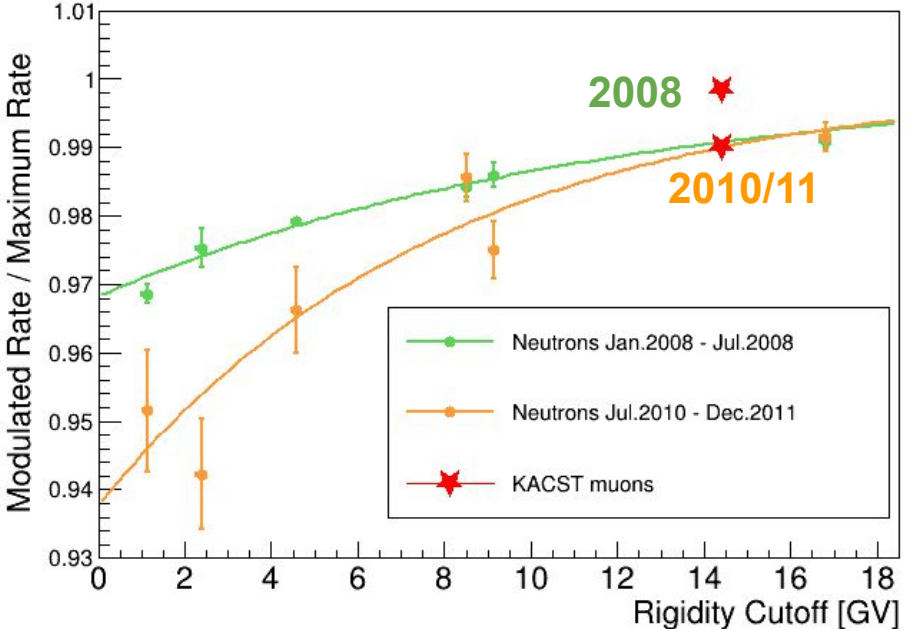






3) solar modulation measured by KACST muon detector





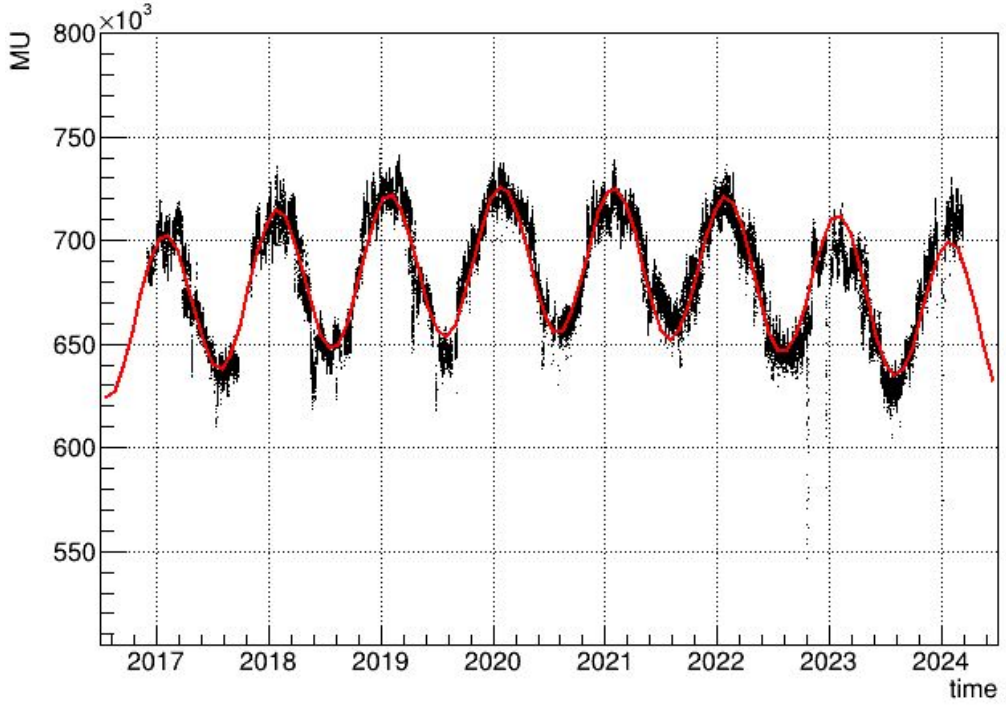
The period 2009 is used as normalization

(2010/11)/(2009) modulation amplitude as expected for Rc=14.4GV

(2008)/(2009) no effect of solar modulation is observed!!! A larger effect was expected

... the whole period 2002-2009 is PUZZLING!

4) solar modulation measured by YangBaJing μ detector



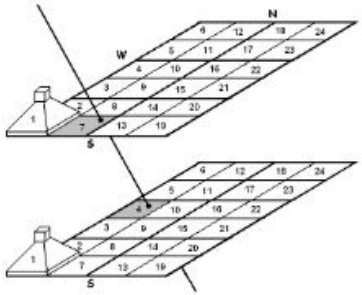
Data (vertical direction) taken from:
http://ybjnm.ihep.ac.cn/mu/
(data before 2016 are “strange”)

YangBaJing (Tibet)
altitude 4300m 30°N Rc = 14.1 GV

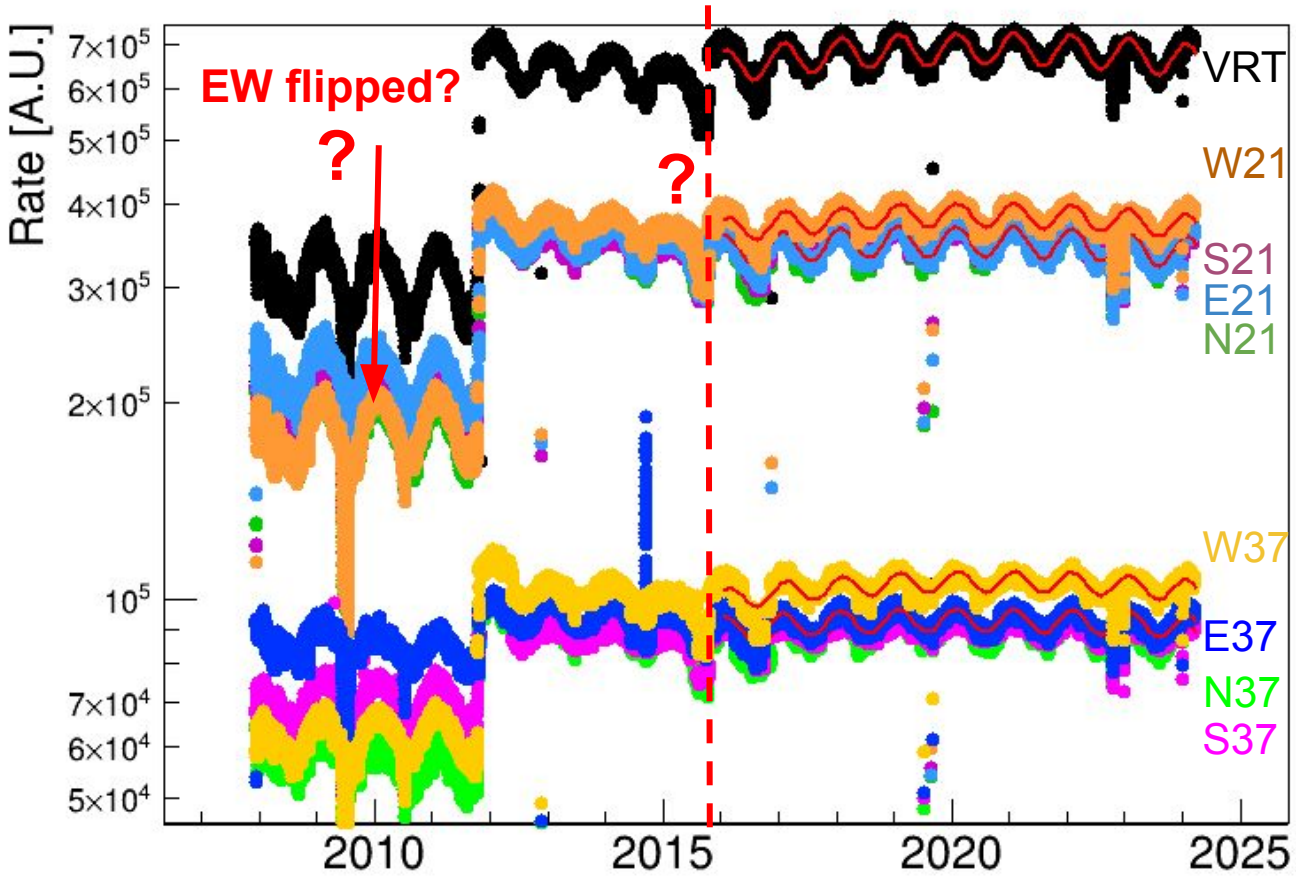
- Annual modulation 5.6%
- Annual mod. maximum 29 Jan

Not understood if corrected for pressure
Units are not given

Published rates from 9 directions:
-vertical
-4 x 21°
-4 x 37°



4) solar modulation measured by YangBaJing μ detector



VRT 690 AM5.6% PK29.4 SM3.1

W21 385 AM4.2% PK33.1 SM2.9
(west is larger of 9%)

S21 357 AM4.2% PK34.4 SM2.7

E21 352 AM5.4% PK27.7 SM2.2

N21 354 AM5.7% PK28.3 SM3.2

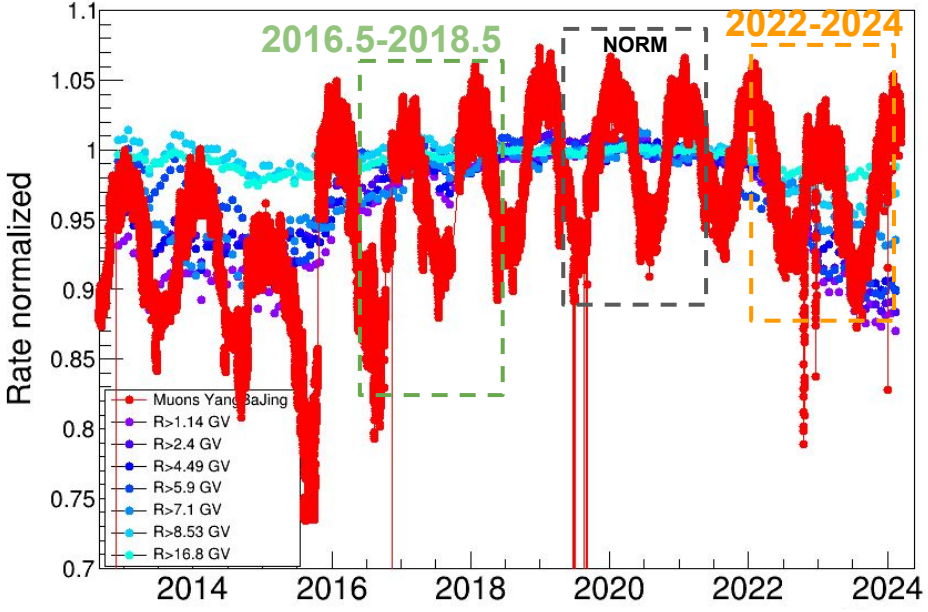
W37 106 AM3.7% PK36.2 SM2.8
(west is larger of 16%)

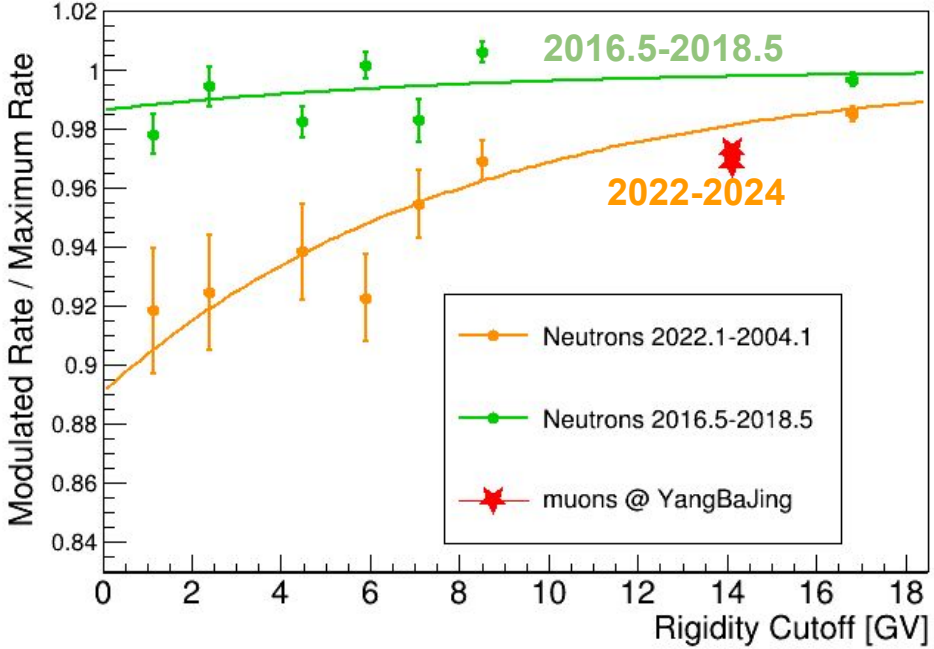
E37 93 AM4.1% PK28.0 SM1.6

N37 91 AM4.9% PK30.2 SM3.1

S37 90 AM3.2% PK36.6 SM1.6

4) solar modulation measured by YangBaJing μ detector





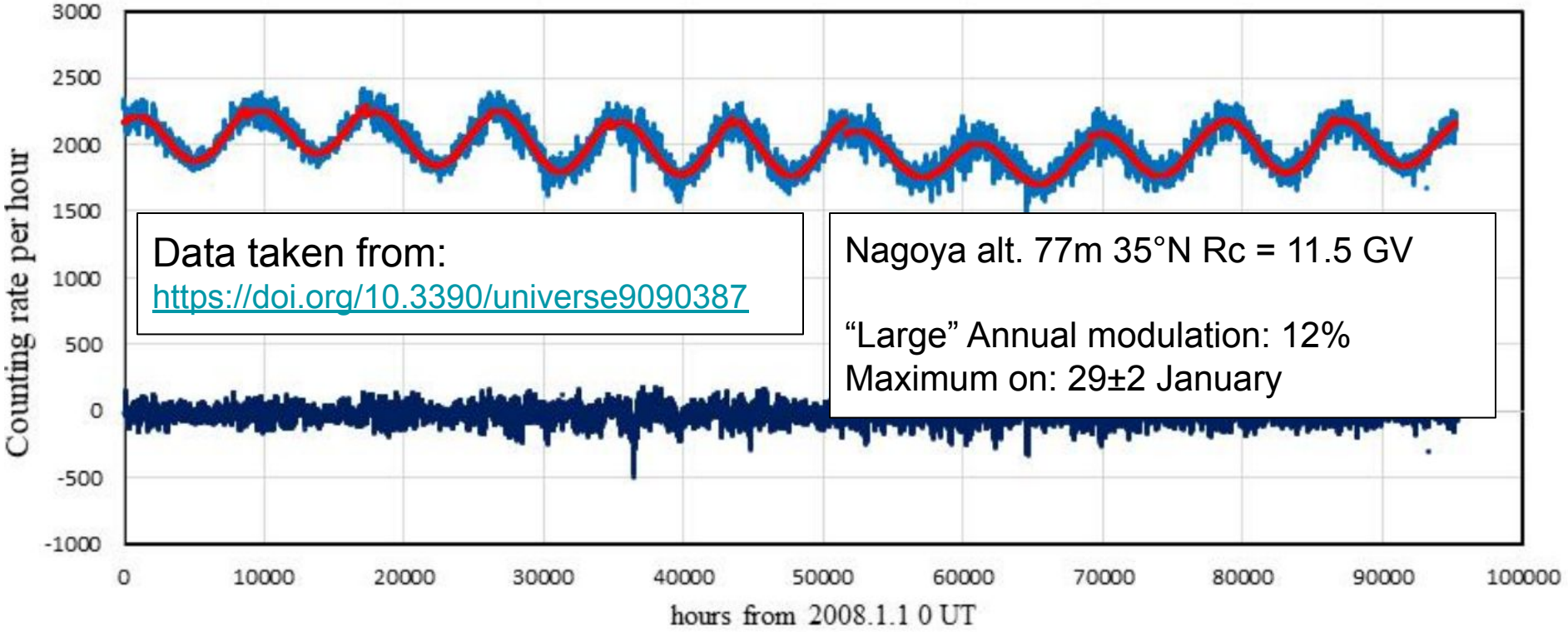
The period 2019.5-2021.5 is used as normalization

(2016.5-2018.5) μ modulation amplitude is larger than expected from neutron monitors

(2022.1-2024.1) μ modulation amplitude is similar to the one expected for **Rc=7GV not 14.1GV**

OBSERVED A LARGER THAN NAIVELY EXPECTED SOLAR MOD. AMPLITUDE!

5) solar modulation measured by Nagoya muon detector



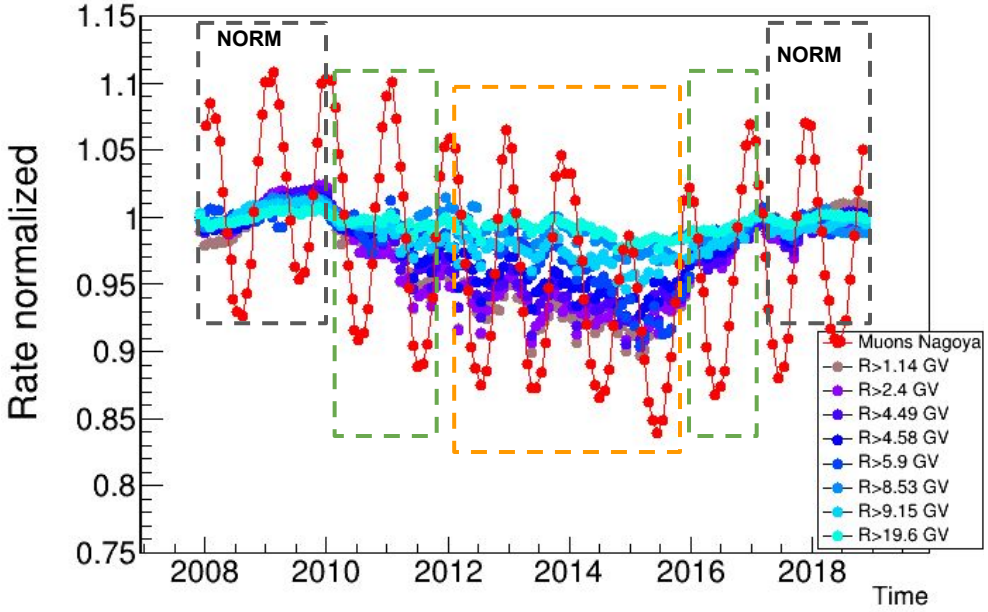
Data taken from:
https://doi.org/10.3390/universe9090387

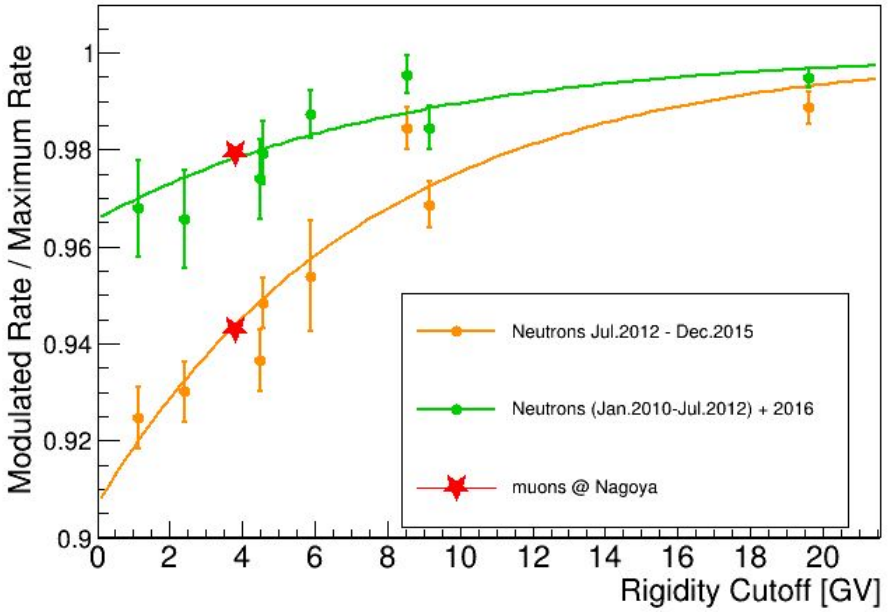
Nagoya alt. 77m 35°N Rc = 11.5 GV

"Large" Annual modulation: 12%
Maximum on: 29±2 January

Also they provide a table with annual counting rate from 1970.
The article study the periodogram: claim of a 125±45 day cycle
They seems very excited, maybe we can test this effect

5) solar modulation measured @ Nagoya 2008-2019





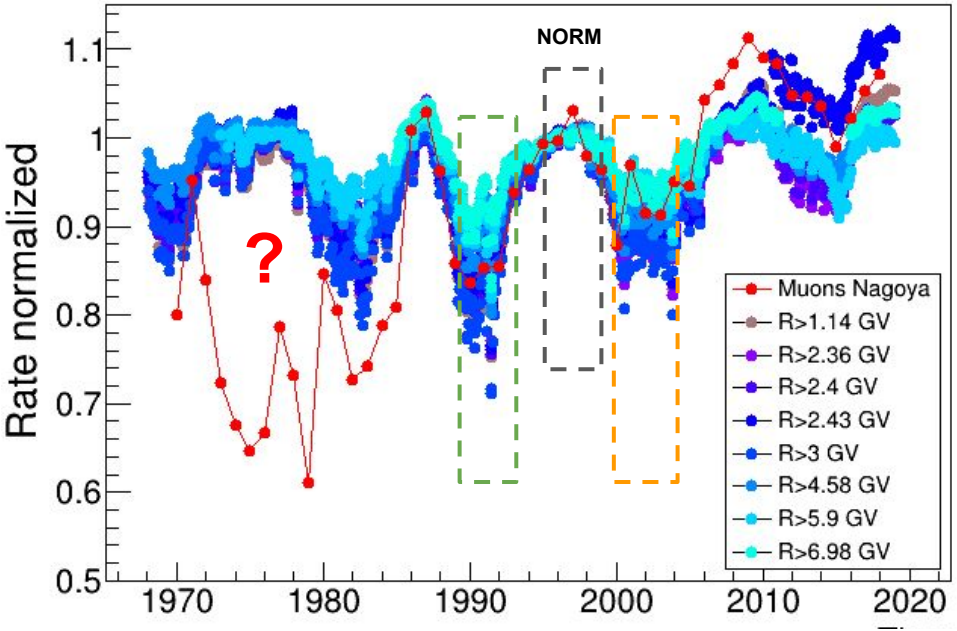
The period 2008-2009 + 2017-2018 is used as normalization

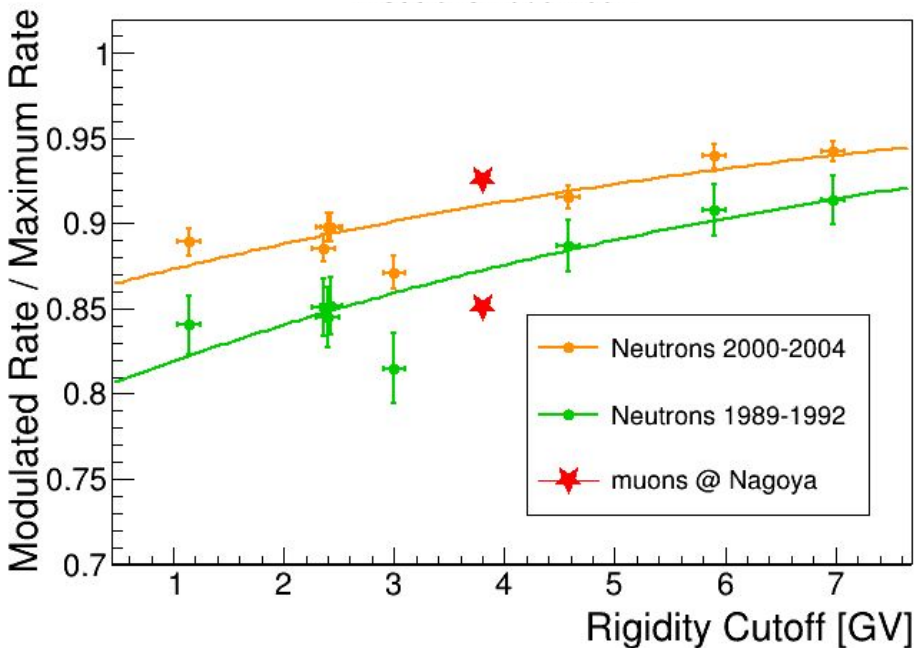
(2010-2012+2016)/(2008-2009) modulation amplitude as expected for **Rc=3.8GV not 11.5GV**

(2012-2015)/(2008+2009) modulation amplitude as expected for **Rc=3.8GV not 11.5GV**

... 3.8GV is very small and Rc=11.5GV (>7GV) was expected by the "naive" model.
OBSERVED A PUZZLING LARGE SOLAR MOD. AMPLITUDE!

5) solar modulation measured @ Nagoya 1970-2019





The period 1995-1998 is used as normalization

(1989-1992)/(1995-1998) modulation amplitude as expected for **Rc~4GV not 11.5GV**

(2000-2004)/(1995-1998) modulation amplitude as expected for **Rc~4GV not 11.5GV**

The whole long-period behaviour is puzzling

there is something more than (the quite large) solar modulation.

Conclusions:

1) POLA-R observe 5% annual mod. and maximum ~20 Jan
2) POLA-R observe a trend similar to solar mod. of neutron Rc=7GV
   (a simple and wrong “raw toy model” could explain a so large cutoff)
3) Not clear solar modulation @ KACST (but Rc=14.4GV is big)
   “very small” 0.5% annual modulation & maximum in winter
4) Solar modulation @ YangBaJing is larger than expected for 14.1GV
   YangBaJing 5.6% annual modulation and maximum in 29Jan
5) Despite Rc=11.5GV is big, Nagoya see a “large” solar modulation
   Nagoya 12% annual modulation with maximum 29Jan

My “raw toy model” for expected μ solar modulation is too bad, I cannot give predictions for none of the other muon detectors. Other effects are on top of my “naive” model of solar modulation that use the shapes of neutron monitor. This is quite interesting, I think POLA-R data are useful.