SUPERNOVA NEUTRINOS SEARCH WITH LVD - A 30 YEARS LEGACY

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On behalf of the LVD Collaboration

SNνD 2023@LNGS
International conference on Supernova Neutrino Detection
May 29th to June 1st, 2023
Gran Sasso National Laboratory
Assergi, L'Aquila [Italy]

The outline

- A bit of history of LVD
- The Detector Performances
- The Strategy to catch SN Neutrinos
- The Expected Signal & Detector Sensitivity
- Data & Results
- Summary

The Large Volume Detector

Astrophysical observatory
@ LNGS since 1992

Heir of LSD

International collaboration since 1986
26 Institutions and 6 countries
USA,USSR,Brazil,China, Japan and Italy

Once upon a time….

IL NUOVO CIMENTO VOL. 9 C, N. 2 Marzo-Aprile 1986

The Large-Volume Detector (LVD) of the Gran Sasso Laboratory.

Summary. — We describe here the LVD experiment (Large-Volume Detector) of the Gran Sasso Laboratory, which is the natural improve-
nent of the LSD experiment (Liquid Scintillation Detector) running in
he Mont Blanc Laboratory. The LVD ((31 × 13) m² area, height 12 m)
onsists of ~1800 tons of liquid scintillator and of a system of streamer
tubes on 5 layers for reconstructing tracks of charged particles. As any
experiment in an underground laboratory, which has a low statistics
of events and requires long running times, the LVD is a multipurpose
experiment but with different priorities of the researches. The main
goal is neutrino astronomy, firstly detection of neutrinos from collapsing
and secondly high-energy neutrinos and solar neutrinos. Si
pected number of interactions of neutrinos from a stellar colla
y high (of order of 900 for a collapse at the distance of the gala
), the LVD is, contrary to the present experiments, a real neu-
trino observatory, able to make a detailed analysis of the energy and
temporal distributions of the burst. In addition to neutrino astrophysics,
with the LVD experiment excellent possibilities exist to perform re-
searches in cosmic-ray and high-energy elementary-particle physics.

PACS. 94.40. – Cosmic rays.

Scaled from LSD
20x

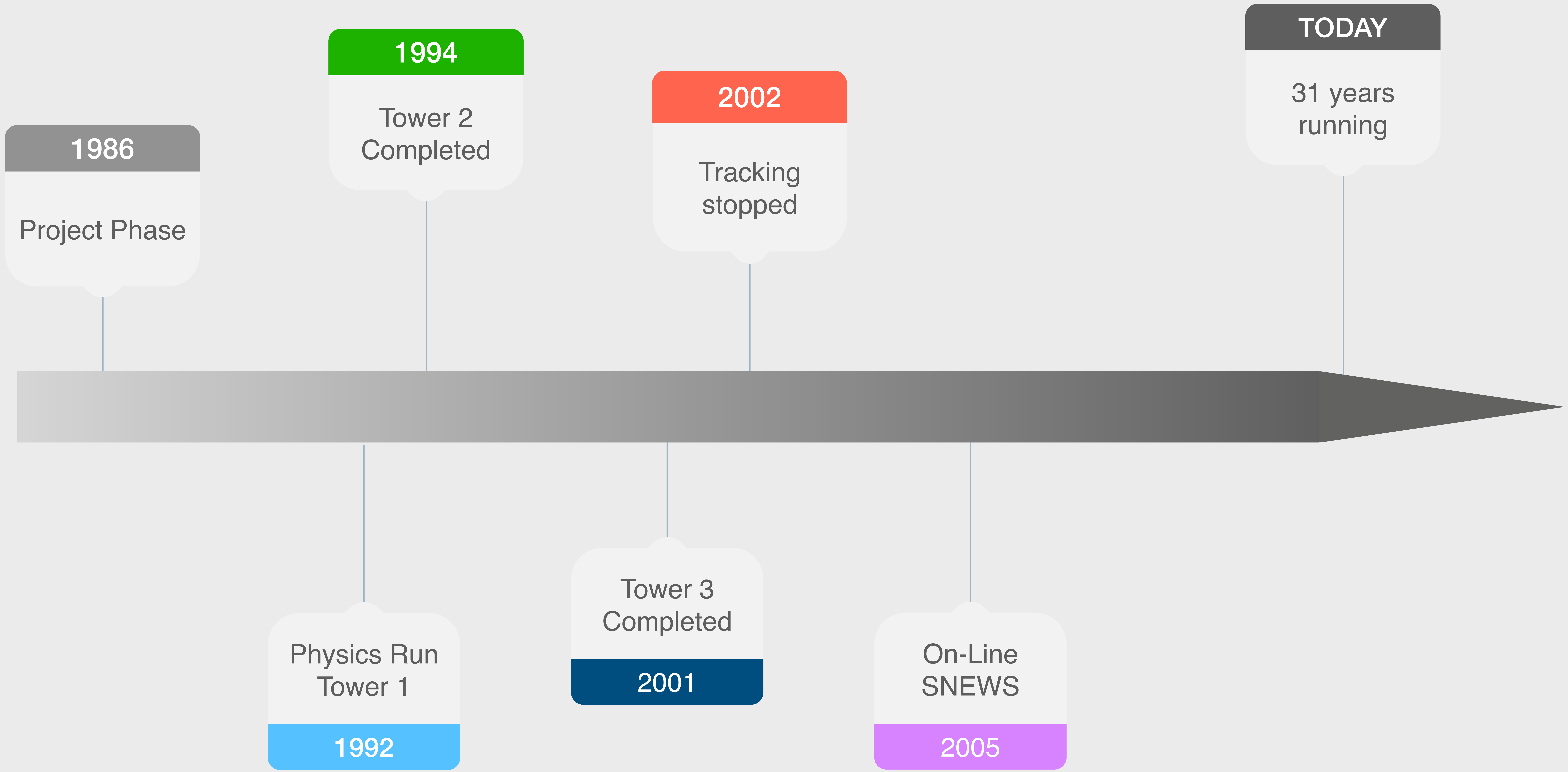
Liquid scintillator 1.8 kton
Streamer tubes layers

SN Neutrino Astronomy
et al.

Real time DAQ

Designed to be Robust, Reliable & Long Duration

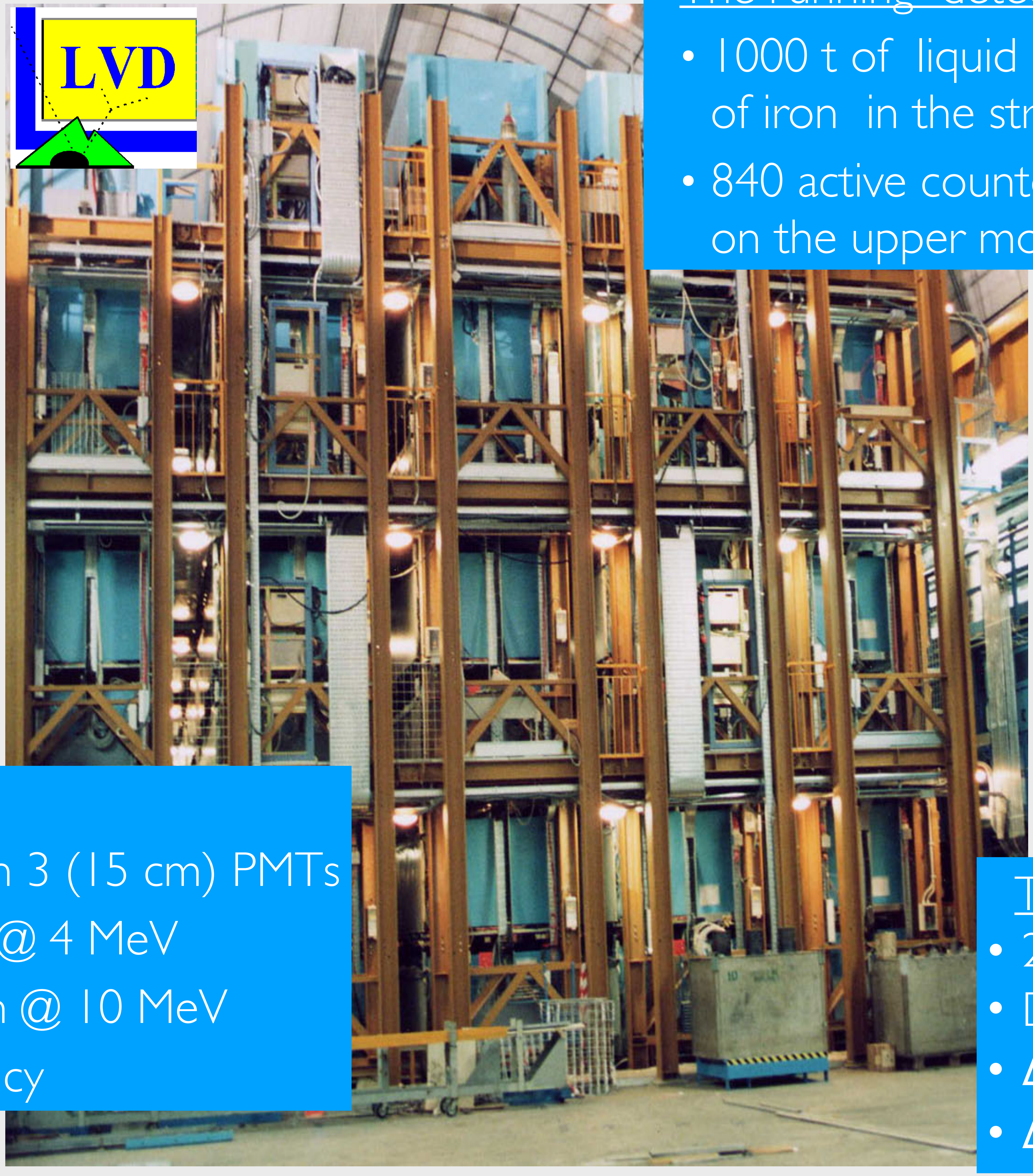
The Experiment Timeline



The LVD Modularity At Glance

Mounting LVD in hall A, early in the 90s

The LVD Features



The running detector:

- 1000 t of liquid scintillator (C_nH_{2n+2}, n~9.6) & 800 t of iron in the structure
- 840 active counters & 72 passive counters (ex LSD) on the upper most layer added in 2001

The counter:

- 1x1x1.5 m^3, 1.2 t with 3 (15 cm) PMTs
- 50% trigger efficiency @ 4 MeV
- 15% energy resolution @ 10 MeV
- 50% n-capture efficiency

The Front-End Electronics :

- 2520 ADC/TDC Channels
- Dead time on single channel 1 μs
- Δt_{abs} = 100 ns (GPS)
- Δt_{rel} = 12.5 ns (TDC)

The LVD Trigger

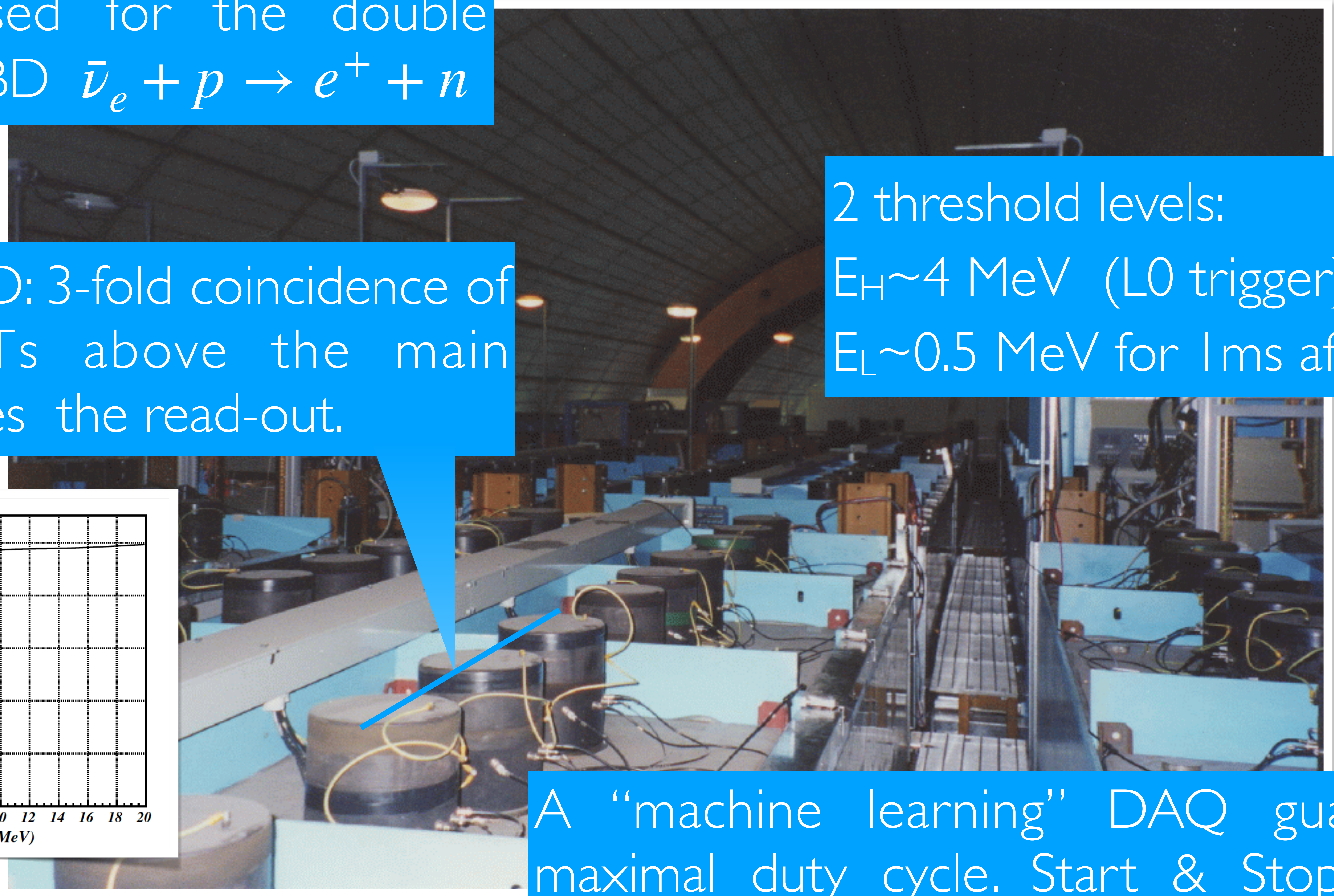
Strategy optimised for the double signature of the IBD $\bar{\nu}_e + p \rightarrow e^+ + n$

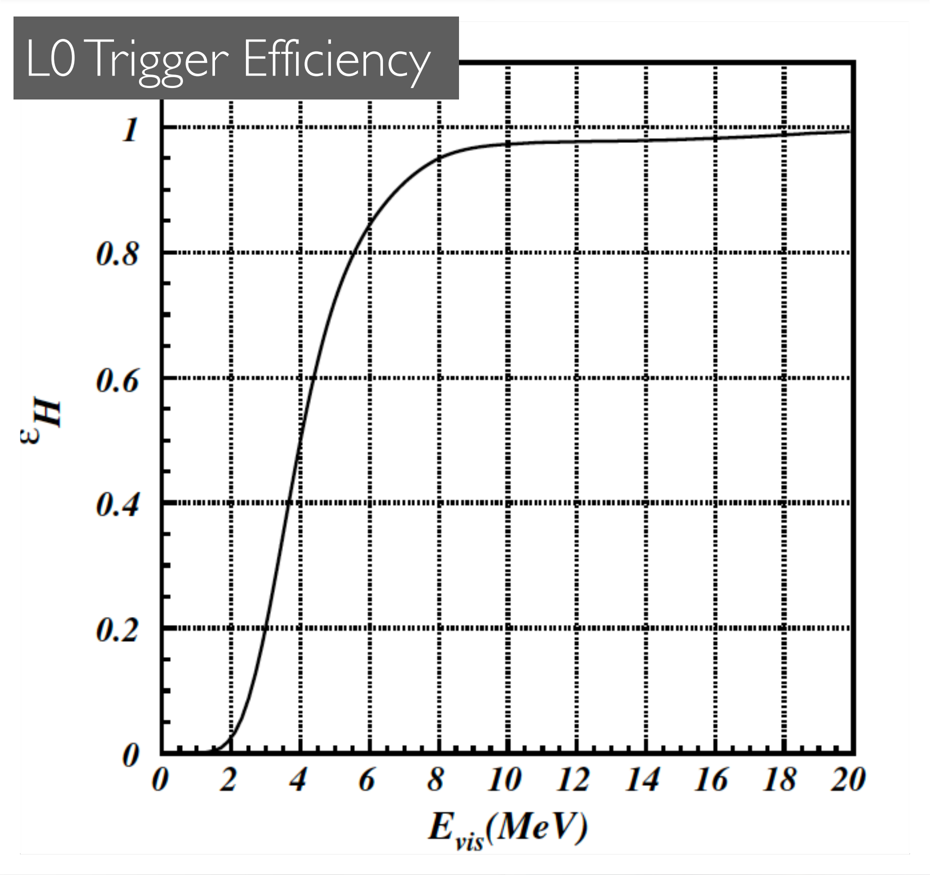
L0 trigger in LVD: 3-fold coincidence of counters PMTs above the main threshold enables the read-out.

2 threshold levels:

E_H~4 MeV (L0 trigger)

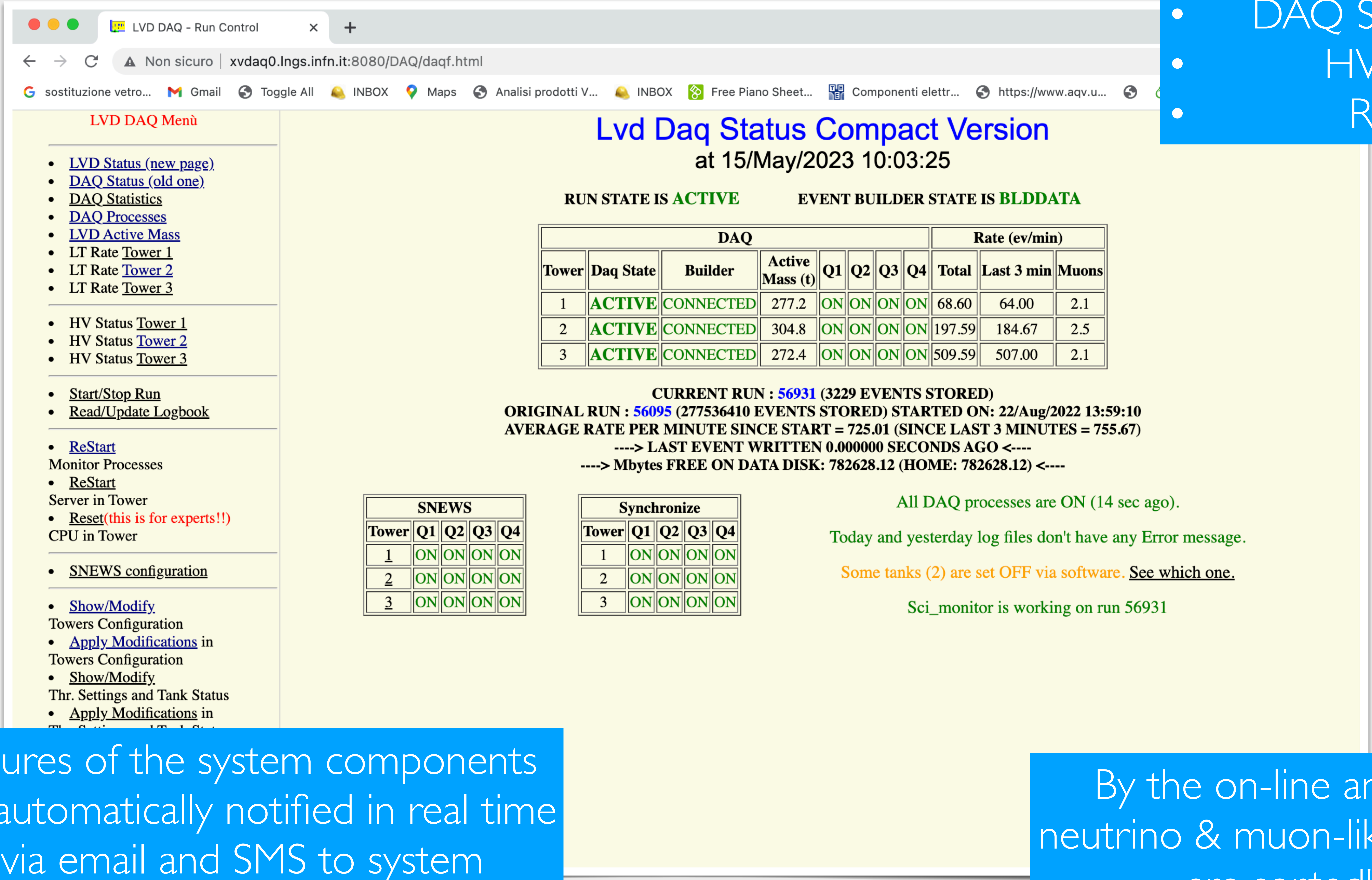
E_L~0.5 MeV for 1ms after the L0





A "machine learning" DAQ guarantees the maximal duty cycle. Start & Stop of the run occurs very rarely in LVD.

The LVD Remote Manager


LVD DAQ - Run Control
Non sicuro | xvdaq0.lngs.infn.it:8080/DAQ/daqf.html
sostituzione vetro... Gmail Toggle All INBOX Maps Analisi prodotti V... INBOX Free Piano Sheet... Componenti elettr... https://www.aqv.u...

LVD DAQ Menù

- LVD Status (new page)
- DAQ Status (old one)
- DAQ Statistics
- DAQ Processes
- LVD Active Mass
- LT Rate Tower 1
- LT Rate Tower 2
- LT Rate Tower 3

- HV Status Tower 1
- HV Status Tower 2
- HV Status Tower 3

- Start/Stop Run
- Read/Update Logbook

- ReStart
Monitor Processes
- ReStart
Server in Tower
- Reset(this is for experts!!)
CPU in Tower

- SNEWS configuration

- Show/Modify
Towers Configuration
- Apply Modifications in
Towers Configuration
- Show/Modify
Thr. Settings and Tank Status
- Apply Modifications in

Lvd Daq Status Compact Version

at 15/May/2023 10:03:25

RUN STATE IS ACTIVE **EVENT BUILDER STATE IS BLDDATA**

DAQ								Rate (ev/min)		
Tower	Daq State	Builder	Active Mass (t)	Q1	Q2	Q3	Q4	Total	Last 3 min	Muons
1	ACTIVE	CONNECTED	277.2	ON	ON	ON	ON	68.60	64.00	2.1
2	ACTIVE	CONNECTED	304.8	ON	ON	ON	ON	197.59	184.67	2.5
3	ACTIVE	CONNECTED	272.4	ON	ON	ON	ON	509.59	507.00	2.1

CURRENT RUN : 56931 (3229 EVENTS STORED)
ORIGINAL RUN : 56095 (277536410 EVENTS STORED) STARTED ON: 22/Aug/2022 13:59:10
AVERAGE RATE PER MINUTE SINCE START = 725.01 (SINCE LAST 3 MINUTES = 755.67)
----> LAST EVENT WRITTEN 0.000000 SECONDS AGO <----
----> Mbytes FREE ON DATA DISK: 782628.12 (HOME: 782628.12) <----

SNEWS				
Tower	Q1	Q2	Q3	Q4
1	ON	ON	ON	ON
2	ON	ON	ON	ON
3	ON	ON	ON	ON

Synchronize				
Tower	Q1	Q2	Q3	Q4
1	ON	ON	ON	ON
2	ON	ON	ON	ON
3	ON	ON	ON	ON

All DAQ processes are ON (14 sec ago).

Today and yesterday log files don't have any Error message.

Some tanks (2) are set OFF via software. See which one.

Sci_monitor is working on run 56931

On-line since 2001:
- DAQ Status Control
- HV Monitor
- Run infos

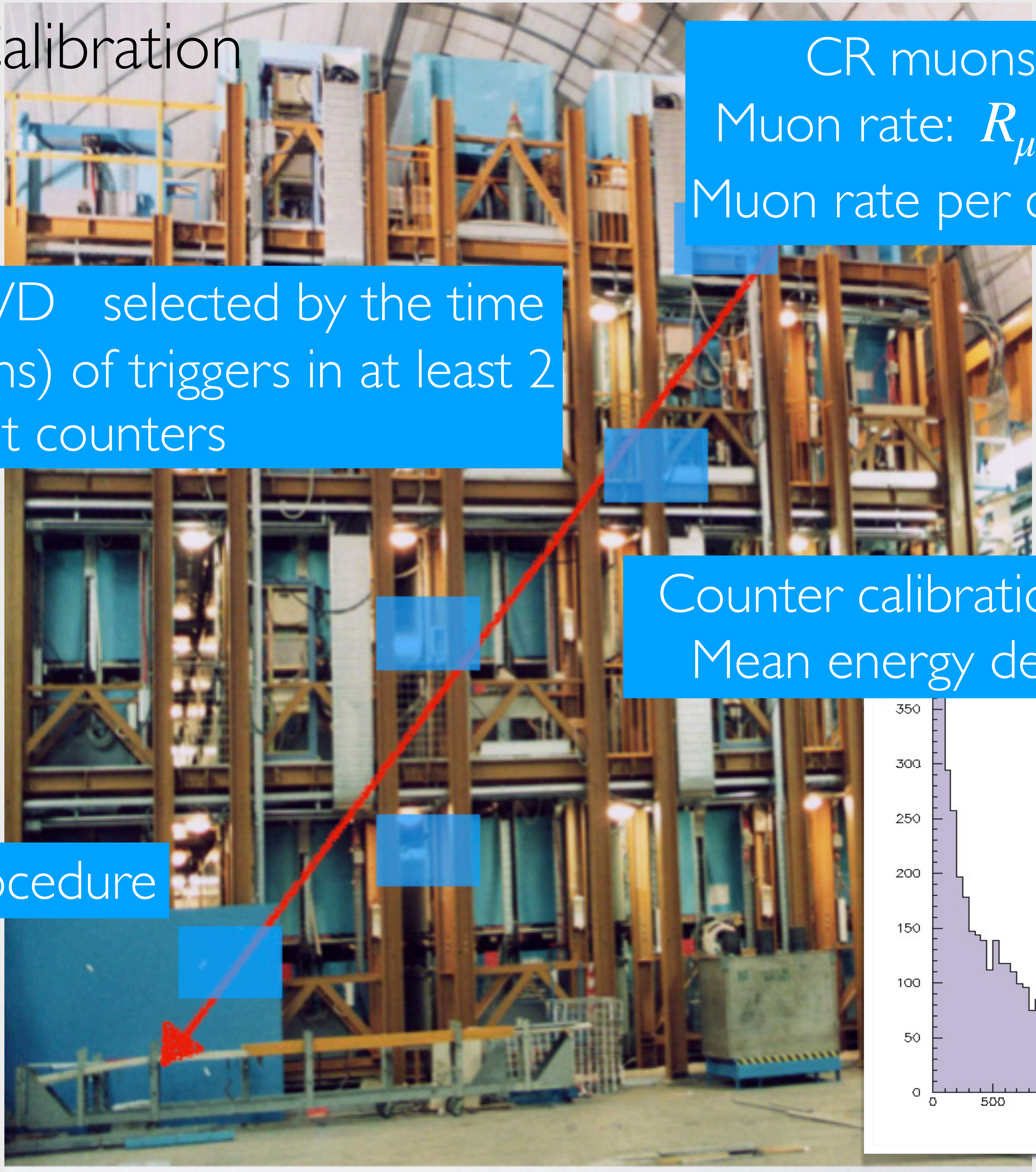
Failures of the system components are automatically notified in real time via email and SMS to system responsible/shifter

By the on-line analysis neutrino & muon-like events are sorted!

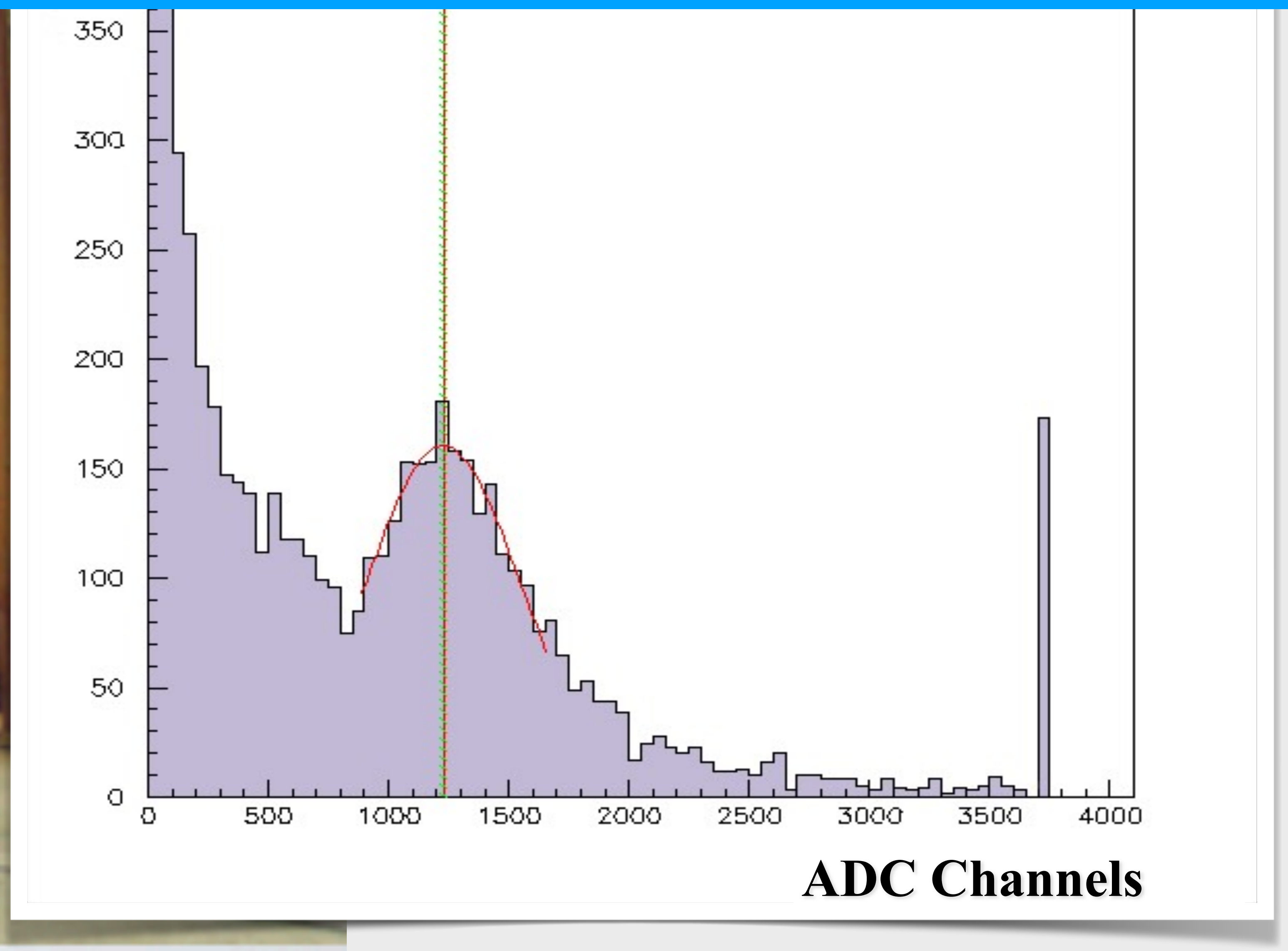
Muon & Energy Calibration

CR muons in LVD(E> 1 TeV):
Muon rate: $R_\mu = 0.097 \pm 0.010\ s^{-1}$
Muon rate per counter: $f_\mu \sim 50\ day^{-1}$

Muon-like events in LVD selected by the time coincidence (Δt=175 ns) of triggers in at least 2 different counters

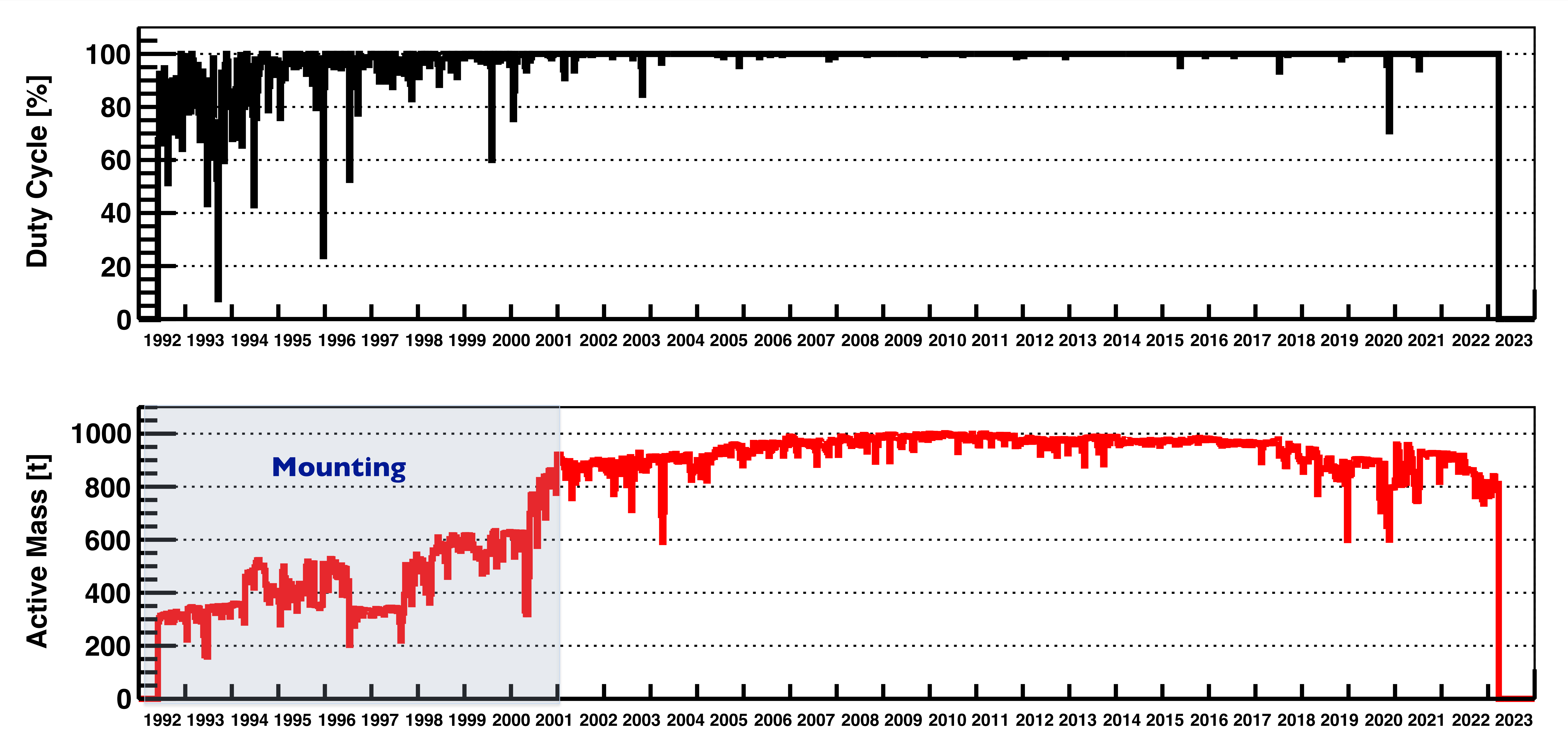


Counter calibration frequency: 1/ month
Mean energy deposit: $185 \pm 5\ MeV$



Fully automatised procedure

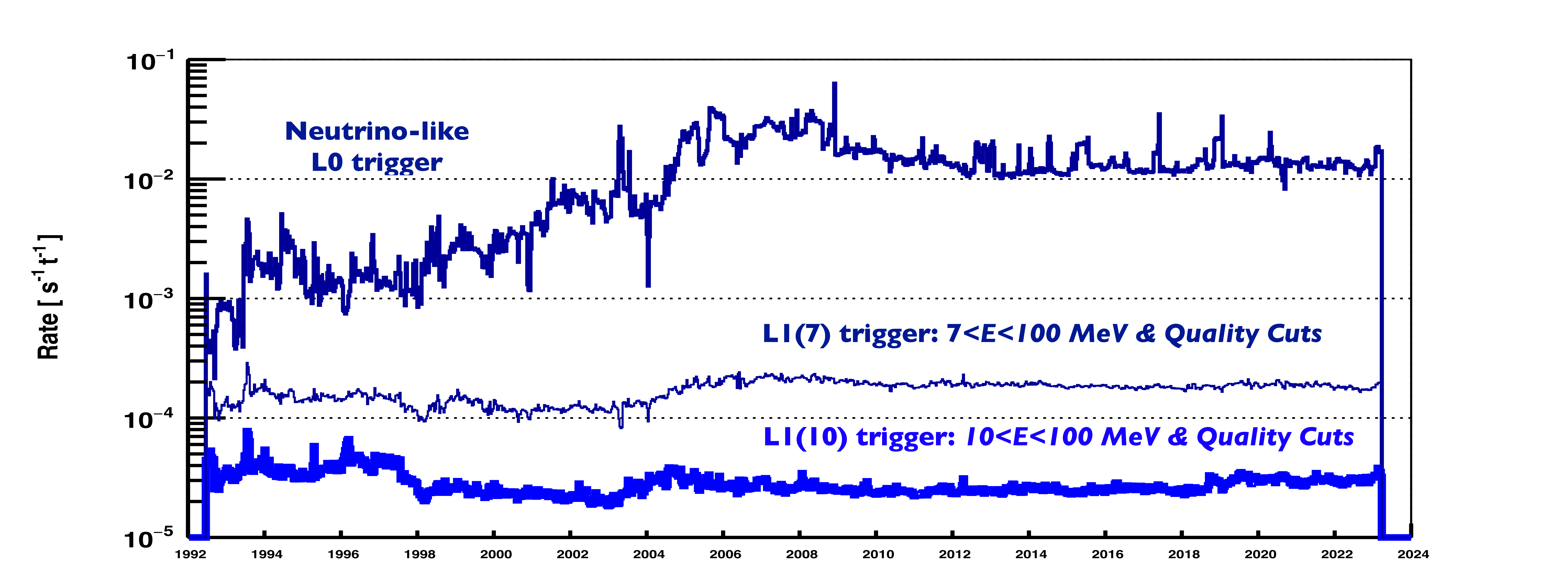
LVD Performances



Modularity provides *high duty cycle* > 99.5 % since 2001
Maintenance guarantees the *quality* of active mass over the years

Neutrino-like Trigger Rate

Neutrino pulse in LVD = All signals surviving the muon selection



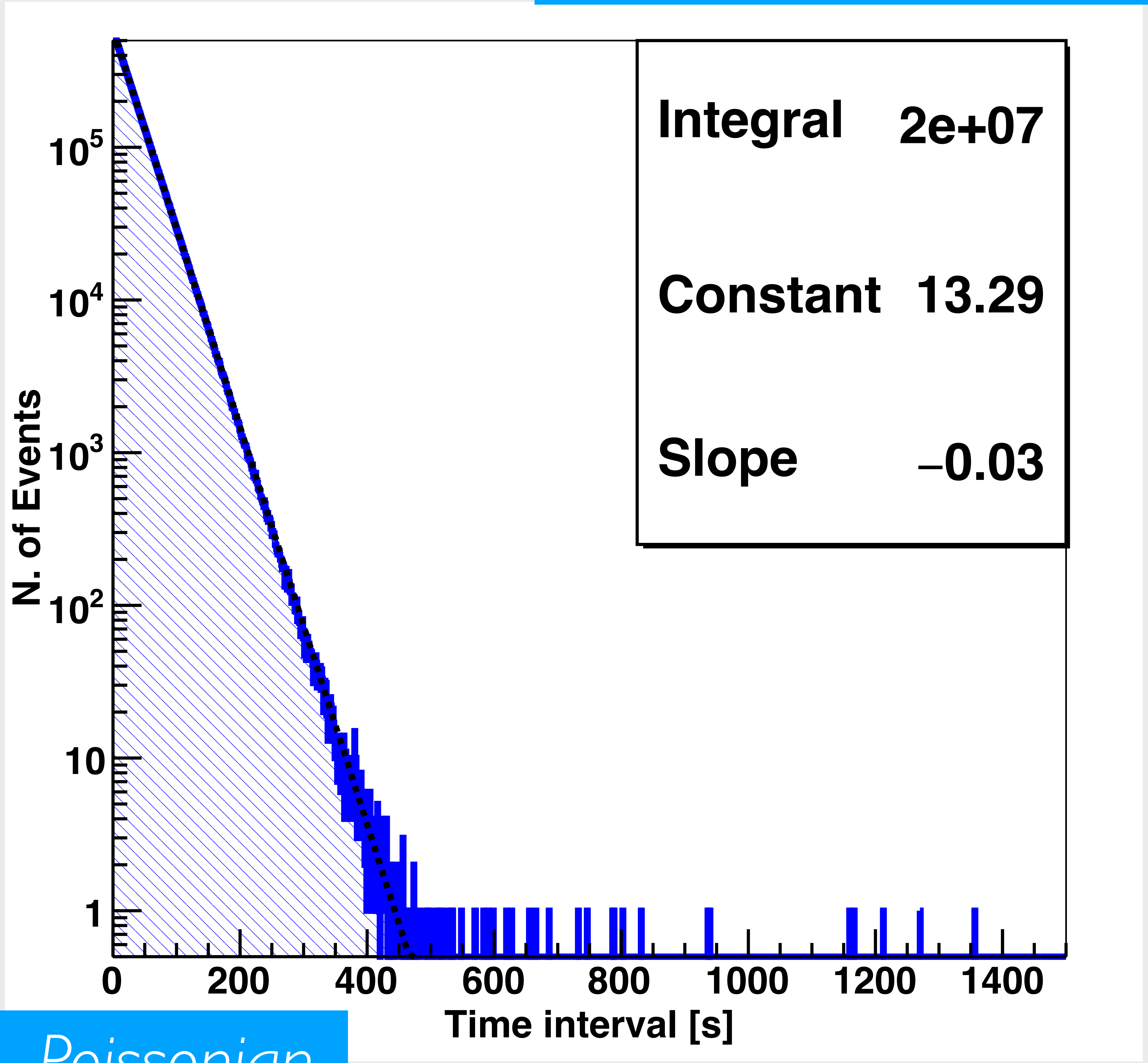
Energy & Quality cuts remove radioactivity background & electronics noise

L1(7 MeV)~0.28 Hz
L1(10 MeV)~0.03 Hz

Neutrino-like Trigger Rate

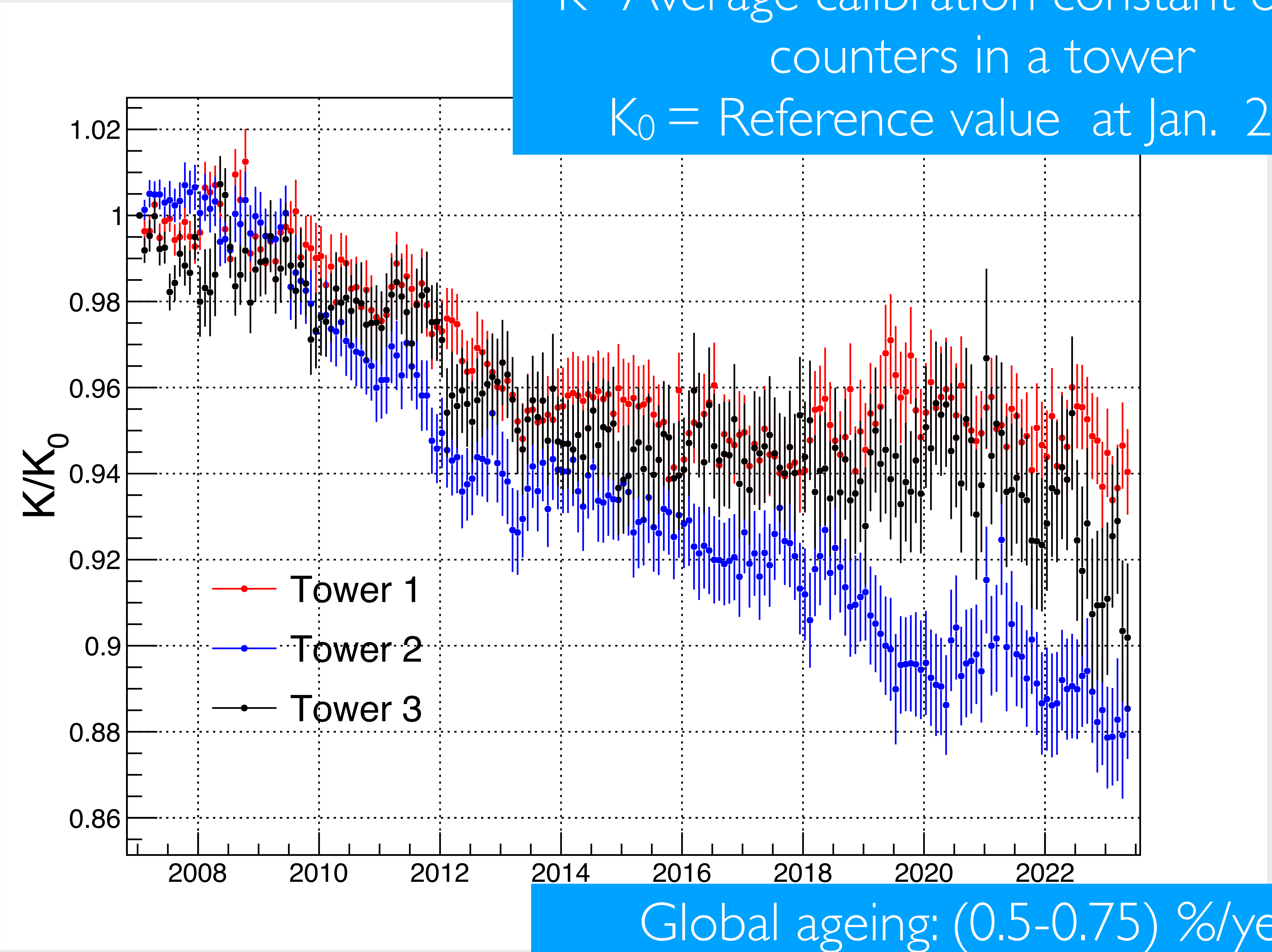
- Last update: 6/1992-2/2023

L1(10) Trigger - Time Delay



LVD trigger rate behaves as Poissonian distribution over 31 years

The Detector Ageing



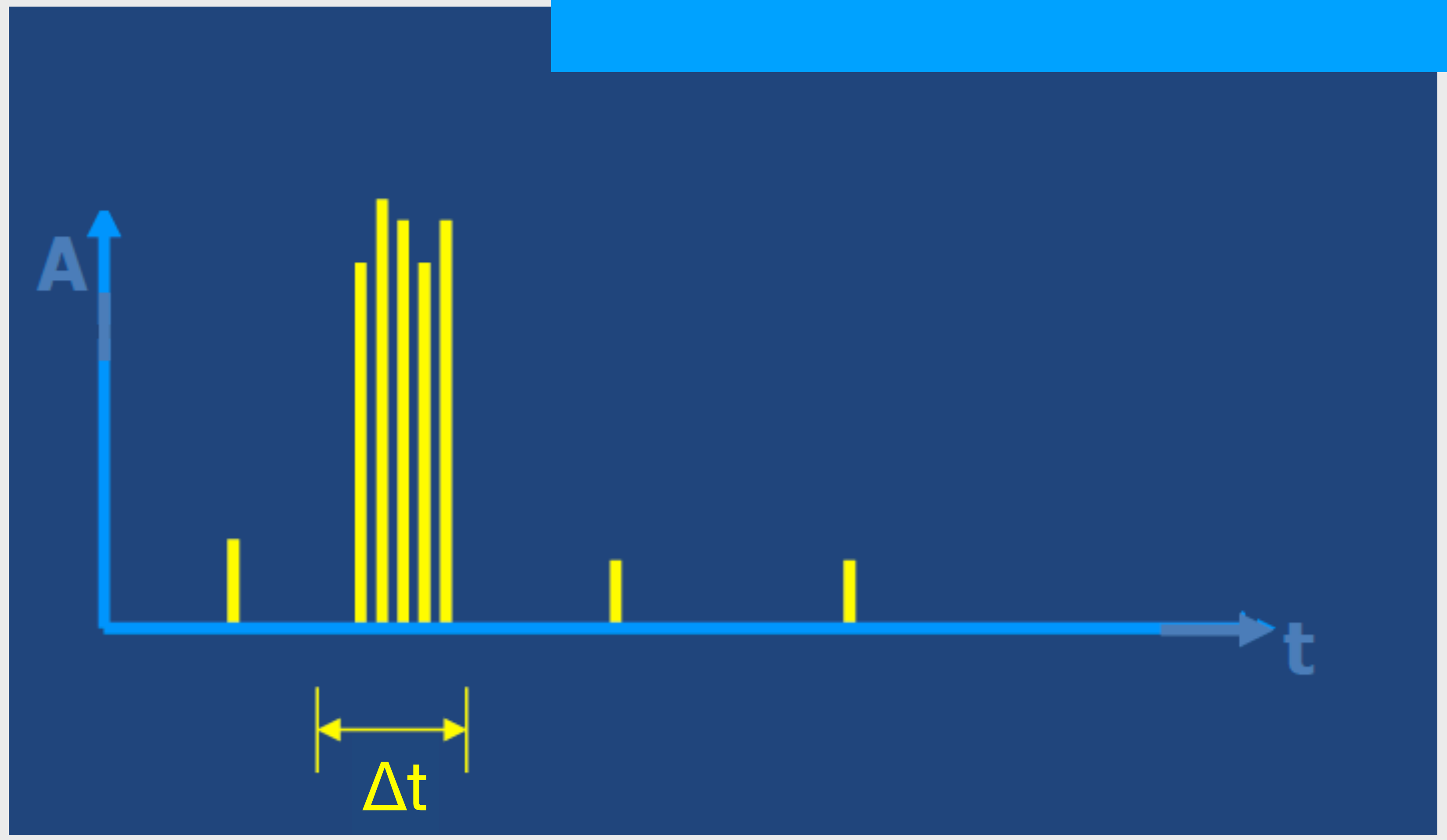
K=Average calibration constant over all counters in a tower
K_0 = Reference value at Jan. 2007

Global ageing: (0.5-0.75) %/year
(Scintillator, Photosensor, Electronics)

Search for SN Neutrino Burst with LVD

Three Steps Process

Trigger pulse vs Time



S1) Searching for clusters of events within the expected time window Δt / A cluster is a doublet: $(M, \Delta t)$

S2) Defining a ccSN candidate looking at the cluster statistical significance

The Imitation Frequency

S3) Check the consistency of selected candidate with the expected ccSN signal in the detector

One strategy /Two Methods:

M1) ***On-line*** with fixed time window $\Delta t = 20$ s

PROs: Fast & Reliable CONs: more model dependent

Real time / Prompt alert dissemination within minutes (Stand-alone and SNEWS network)

Astro Particle Ph., 28, 516 (2008)

Marginal use of the emission model in both methods

Model needed for performance estimate

M2) ***Off-line*** with variable time window $\Delta t < 100$ s

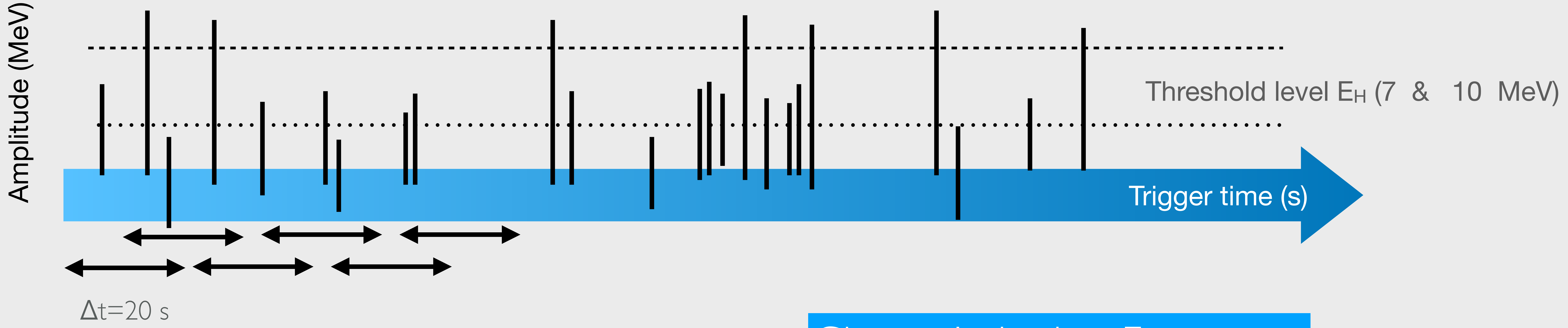
PROs: less model dependent CONs: Time consuming

Best sensitivity with source distance

ApJ, 802, 47 (2015)
NIMPA, 368, 512 (1996)

The On-line Selection

S1) Each data period T is scanned in "sliding" mode"



- Sampling time: Δt=20 s / 10 s overlap
- N.of trials depends on T
- $M_{cluster}$: Triggers @ $E > E_H$
- f_{bk}: Background rate @ $E > E_H$

Cluster Imitation Frequency

$$F_{\rm im}(m, f_{\rm bk}, 20\ {\rm s}) = 8640 \cdot \sum_{k \geqslant m}^{\infty} P\left(k; 20 \cdot \frac{f_{\rm bk}}{s^{-1}}\right)\ \text{event day}^{-1}$$

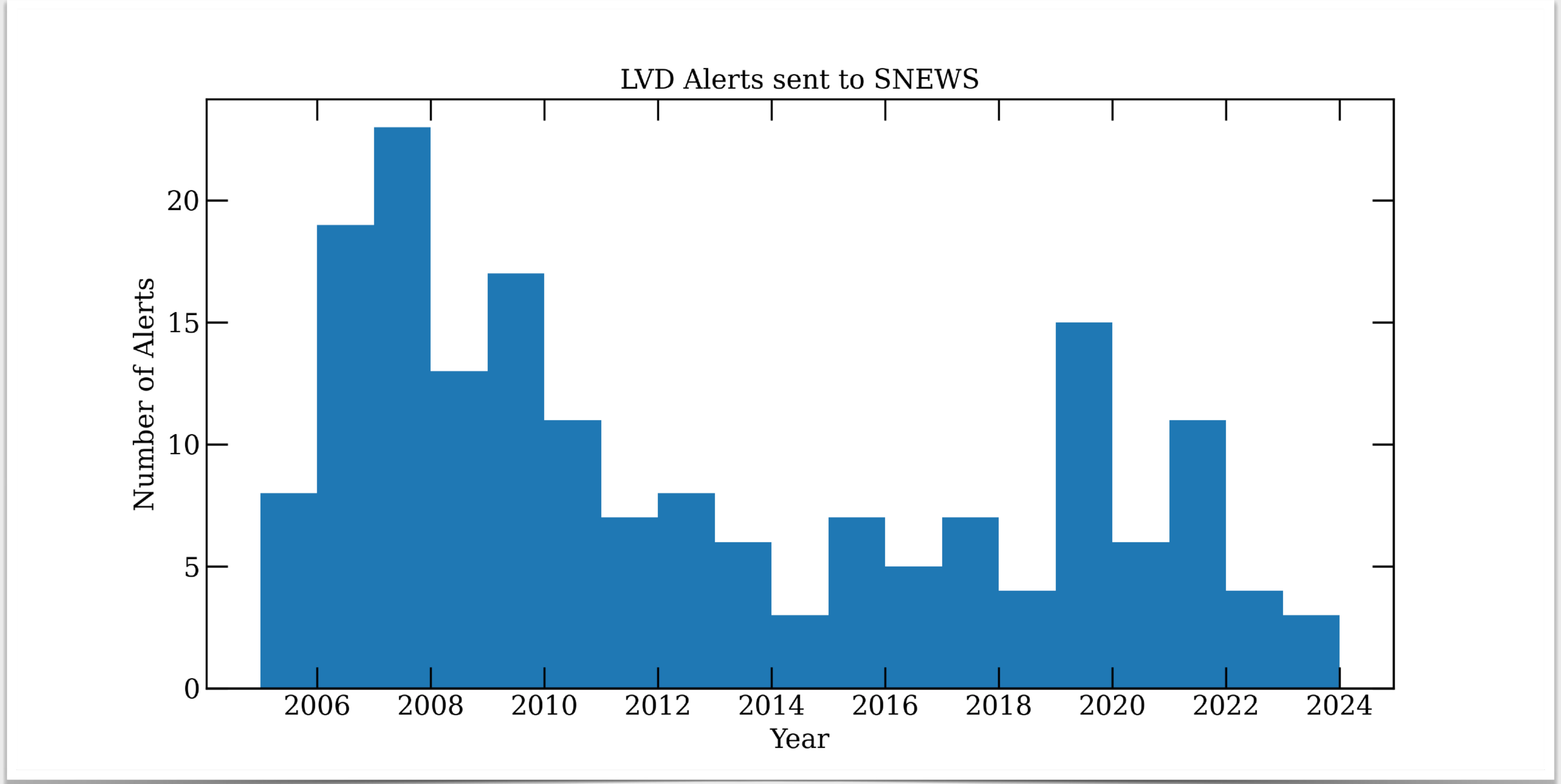
S2) Alert candidate

$F_{im} \leq 1/100\ y^{-1}$ LVD Standalone

$F_{im} \leq 1\ month^{-1}$ ***LVD in SNEWS***

On-line LVD Alerts to SNEWS

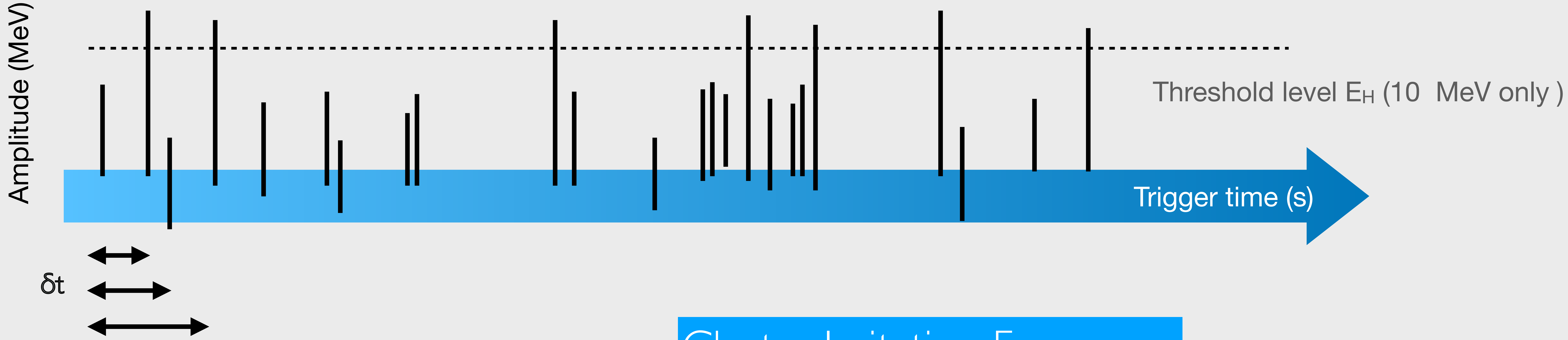
Start: July 1st 2005



A total of 177 Alerts, in average ~10/y

The Off-line Selection

S1) Each data period T is scanned in "event by event" mode"



- Cluster time: variable $\delta t < 100$ s
- $M_{cluster}$ $m_i \geq 2$
- f_{bk}: Background rate @ $E > E_H$
- N.of trials depends on f_{bk}

Cluster Imitation Frequency

$$F_{\mathrm{im_i}} = f_{\mathrm{bk}}^2 \, \Delta t_{\max} \sum_{k \geqslant m_{\mathrm{i}}-2} P\Big(k, f_{\mathrm{bk}} \; \Delta \mathrm{t_i}\Big)$$

S2) Alert candidate

$F_{im_i} \leq 1/100 \ y^{-1}$ LVD Standalone

$F_{im_i} \leq 1 \ day^{-1}, \ 1 \ week^{-1}, 1 \ month^{-1}$ ***Monitoring the tool***

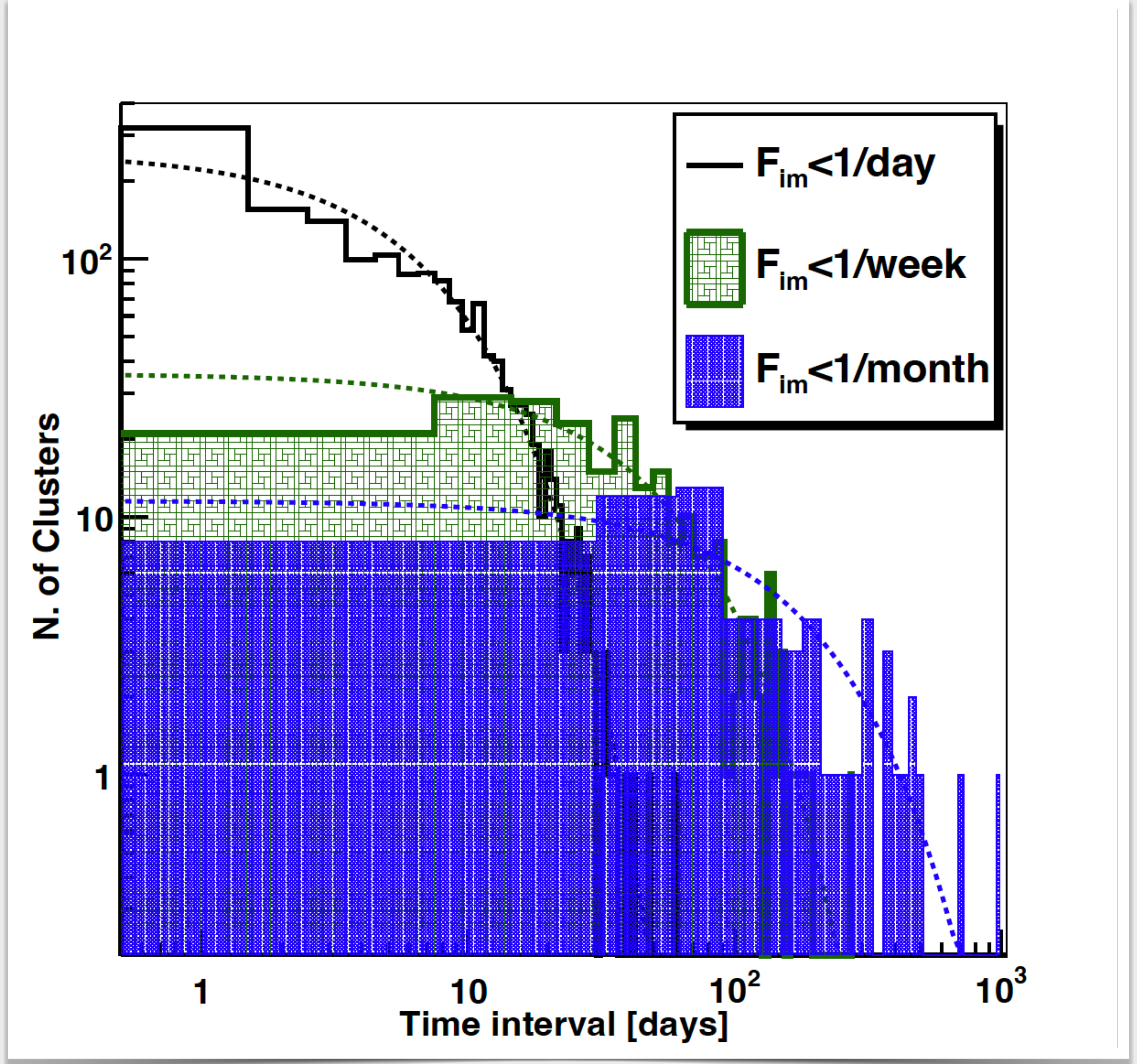
Monitoring the Off-line Selection

F_{im}	<1/day	<1/week	<1/month
N_{cls}	1578	236	66

LVD data:

- Last update: 6/1992-2/2023

Alert Time Delay

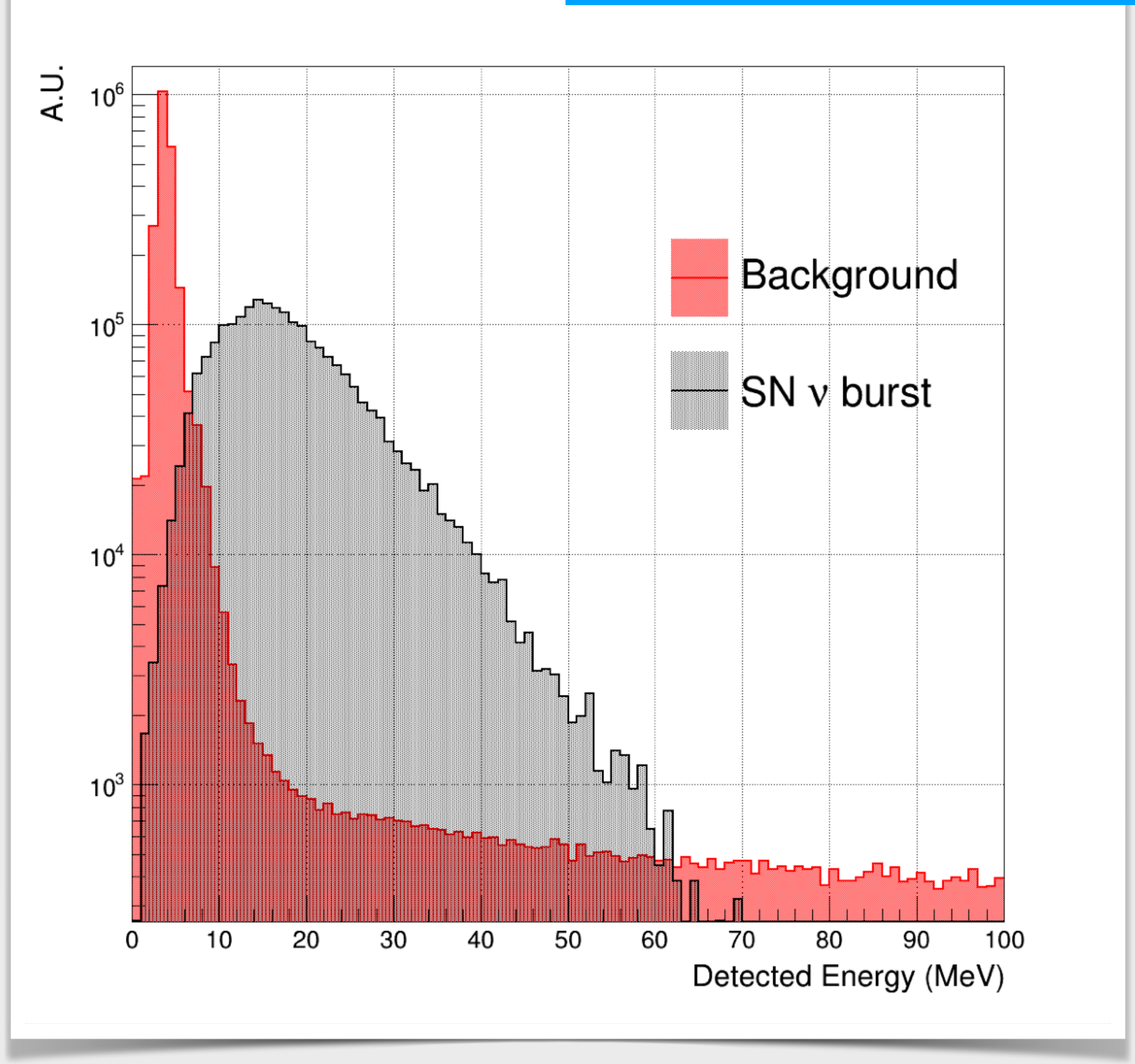


Algorithm stable & reliable over long time

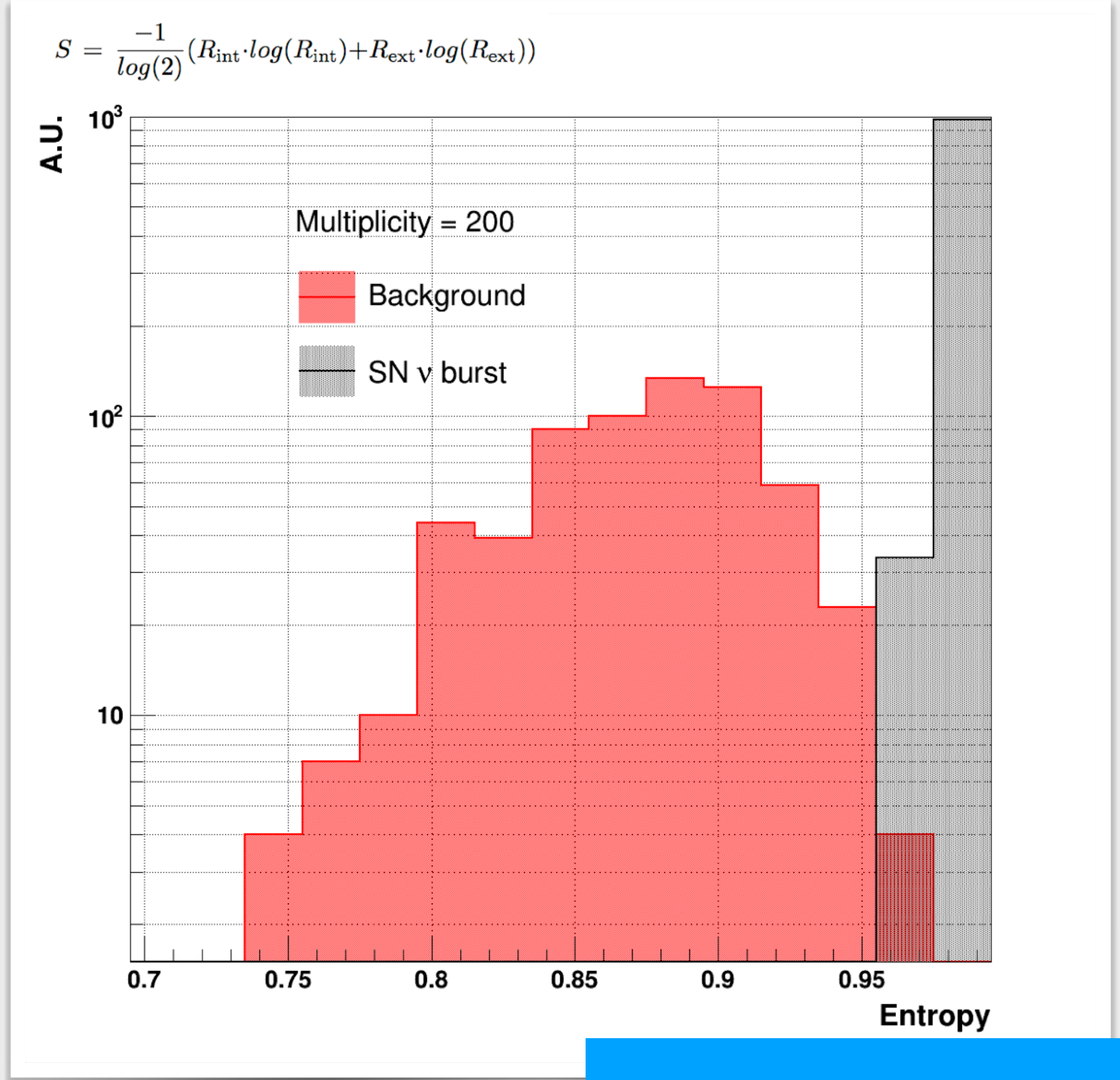
Consistency Checks

Looking at foot prints of real neutrino burst :

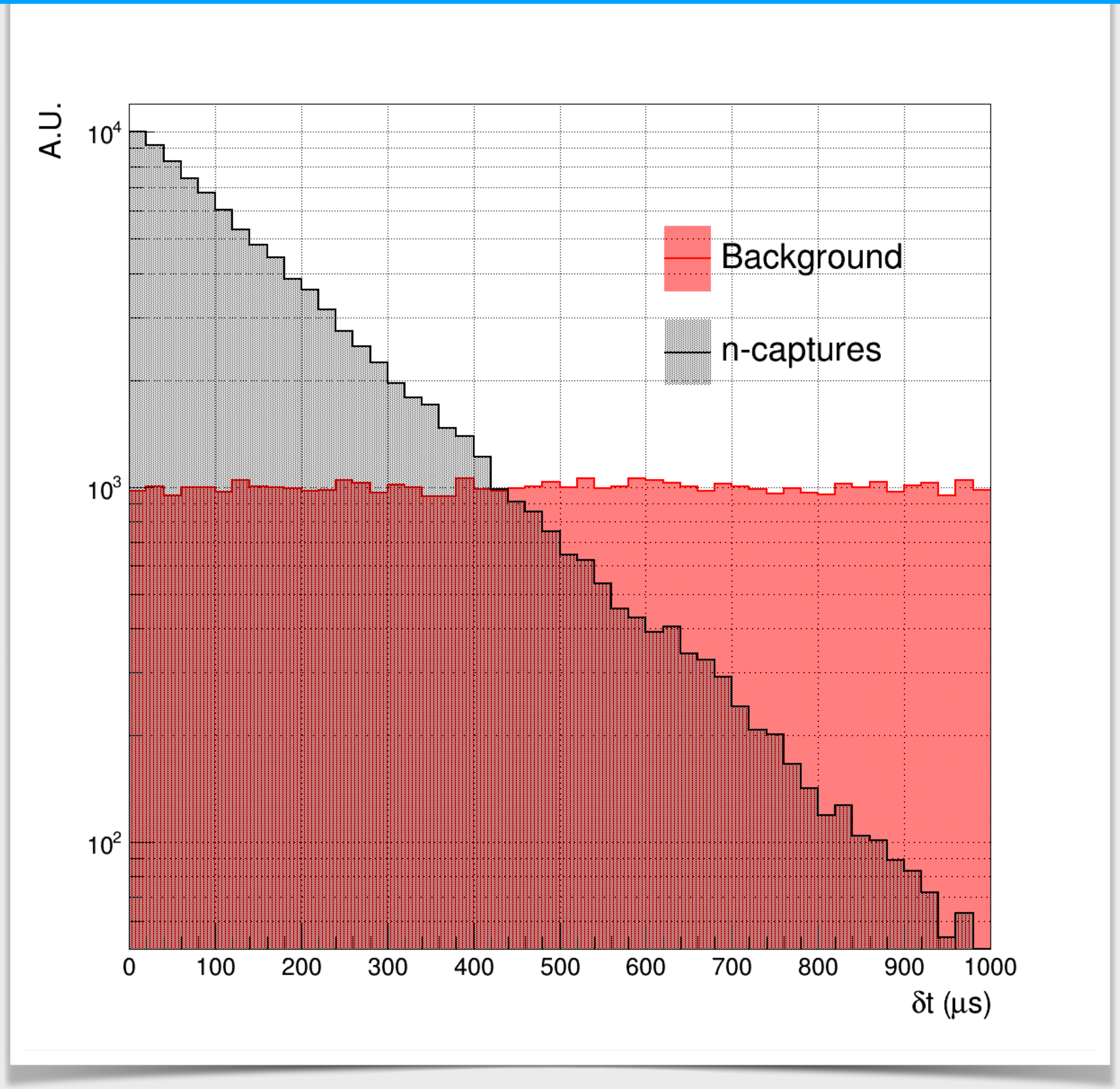
Energy spectrum



Time delay ($\Delta t \sim 185\ \mu s$) and multiplicity of n-captures in the gate



Entropy (Uniformity)



The LVD Expected Signal

Estimated by:

Modelling the neutrino flux for core collapse SN (ccSN)

Standard ccSN as in Pagliaroli et al. / Based on SN1987A observations

Aph, 31, 163 (2009)

+Oscillation effects

+Detector response function

SN neutrino search with LVD

Expected SN signal @ 10 kpc

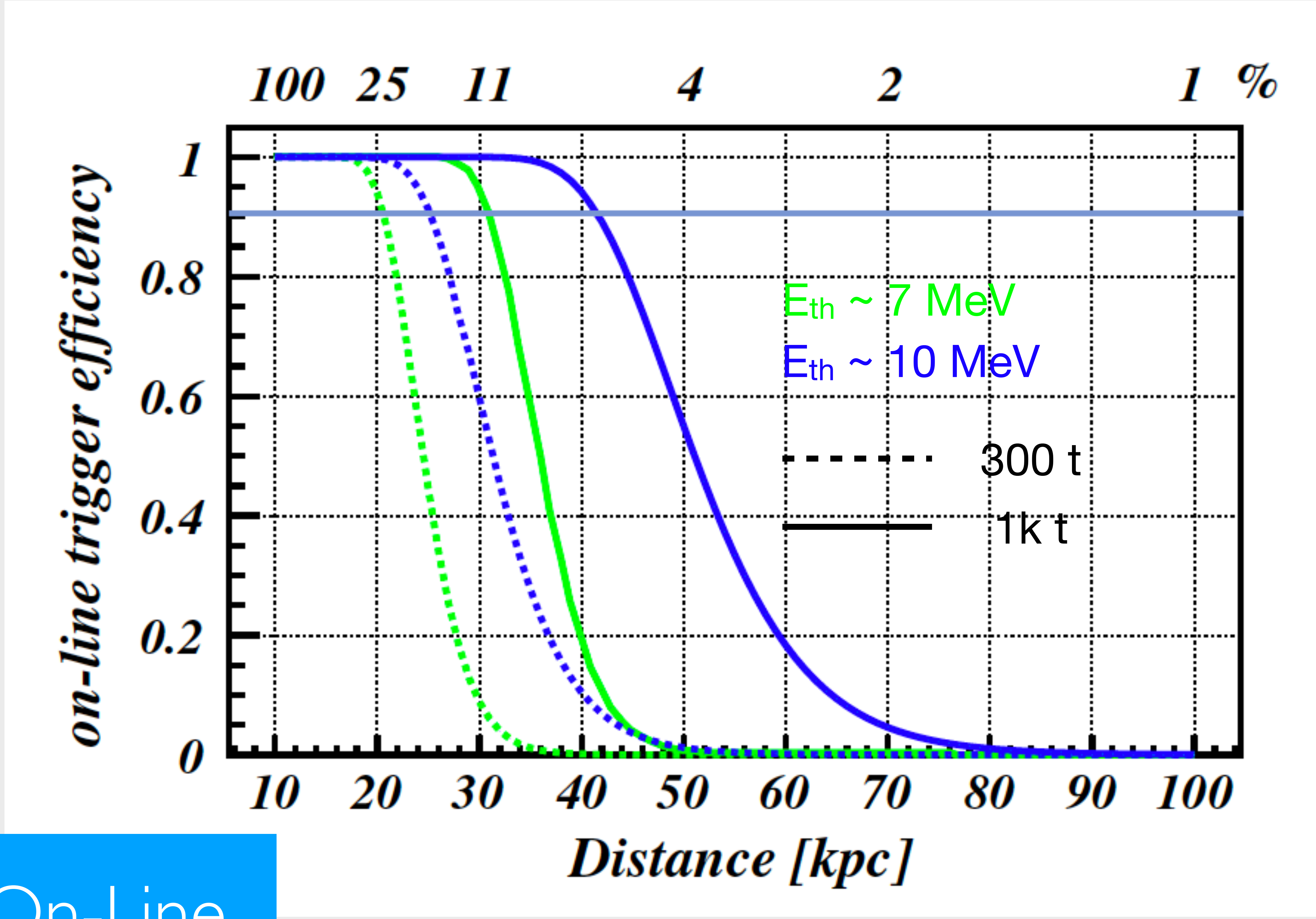
Neutrino interaction channels	Expected events
$\bar{\nu}_e$+p -> e^++n	***250***
ν_e+^{12}C -> ^{12}N+e^-	
$\bar{\nu}_e$+^{12}C -> ^{12}B+e^+	***15***
ν_i+^{12}C -> ν_i+^{12}C+γ	
ν_i+e^- -> ν_i+e^-	***10***
ν_e+^{56}Fe -> ^{56}Co+e^-	
$\bar{\nu}_e$+^{56}Fe -> ^{56}Mn+e^+	***25***
ν_i+^{56}Fe ->ν_i+ ^{56}Fe+γ	
Total	***300***

	ν Interaction Channel	E_ν Threshold	%
1	$\bar{\nu}_e + p \rightarrow e^+ + n$	(1.8 MeV)	(88%)
2	$\nu_e +^{12} C \rightarrow^{12} N + e^-$	(17.3 MeV)	(1.5%)
3	$\bar{\nu}_e +^{12} C \rightarrow^{12} B + e^+$	(14.4 MeV)	(1.0%)
4	$\nu_i +^{12} C \rightarrow \nu_i +^{12} C^* + \gamma$	(15.1 MeV)	(2.0%)
5	$\nu_i + e^- \rightarrow \nu_i + e^-$	(-)	(3.0%)
6	$\nu_e +^{56} Fe \rightarrow^{56} Co^* + e^-$	(10. MeV)	(3.0%)
7	$\bar{\nu}_e +^{56} Fe \rightarrow^{56} Mn + e^+$	(12.5 MeV)	(0.5%)
8	$\nu_i +^{56} Fe \rightarrow \nu_i +^{56} Fe^* + \gamma$	(15. MeV)	(2.0%)

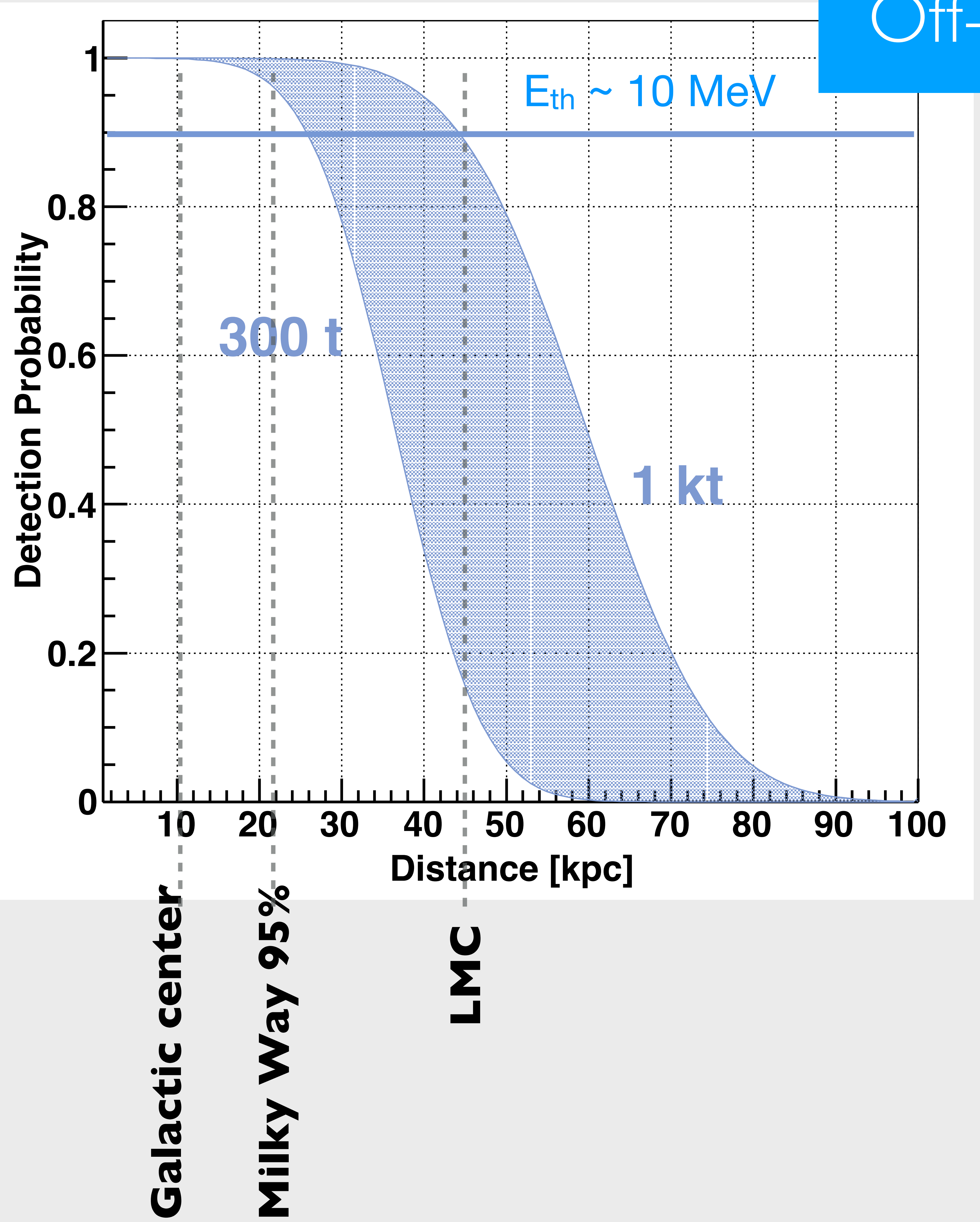
From model to model the number of IBD events may change a little but……
the overall picture do not change!

The LVD Sensitivity

Conservative: Only IBD channel without double signature



On-Line



- 10 MeV threshold is better
- n-tagging does not improve the sensitivity

Global LVD Results

Data set: 6/1992-2/2023 (last update)

Average Duty cycle: 95.5 %

Average Mass: 770 t

Exposure: 22.1 kt x year

Lifetime: 10673 days / 29.4 years

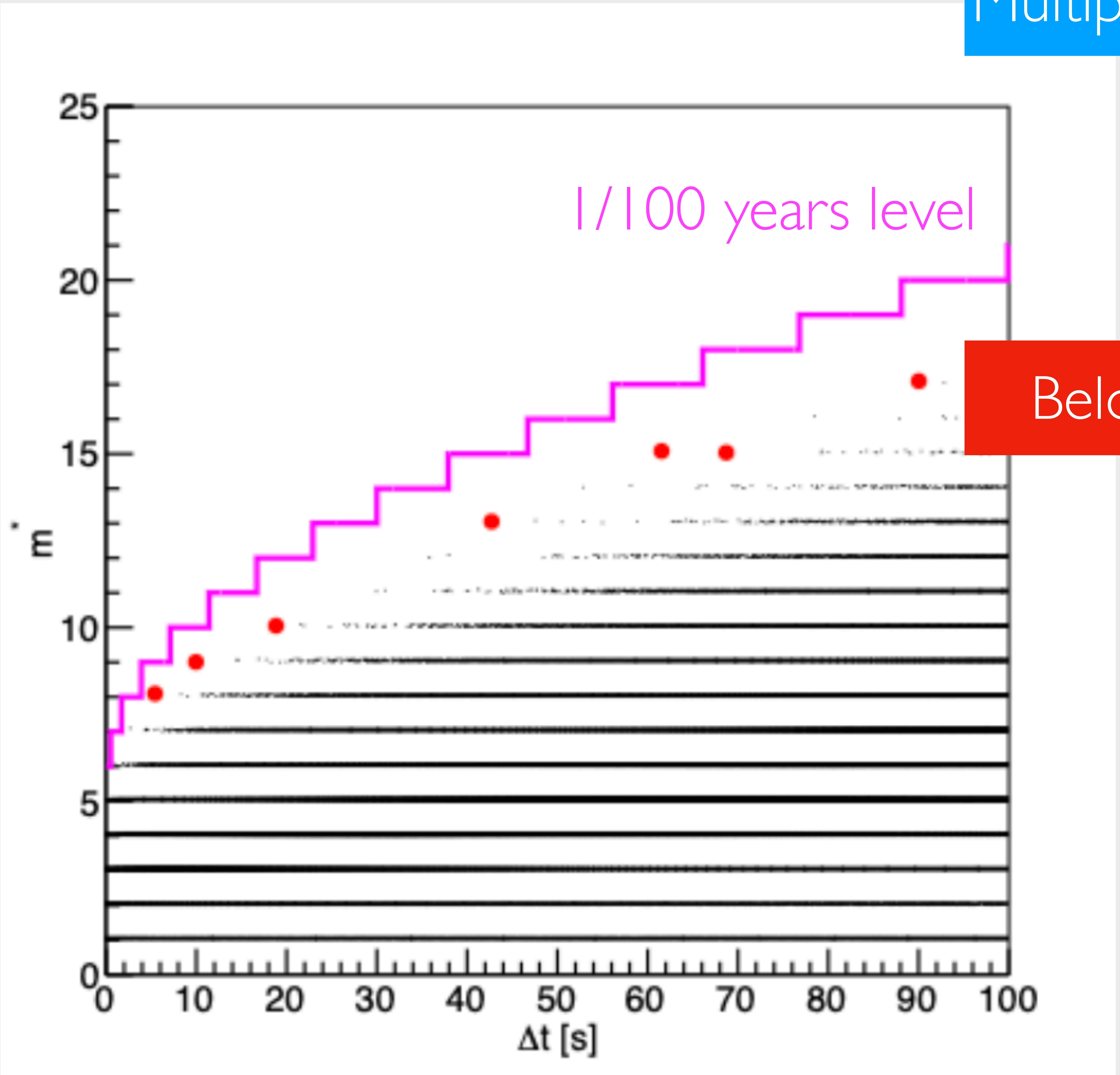
L1(10) Triggers: 19.7 Millions

N. of Clusters: 4.14 Millions

How do these clusters behave?

Cluster details I

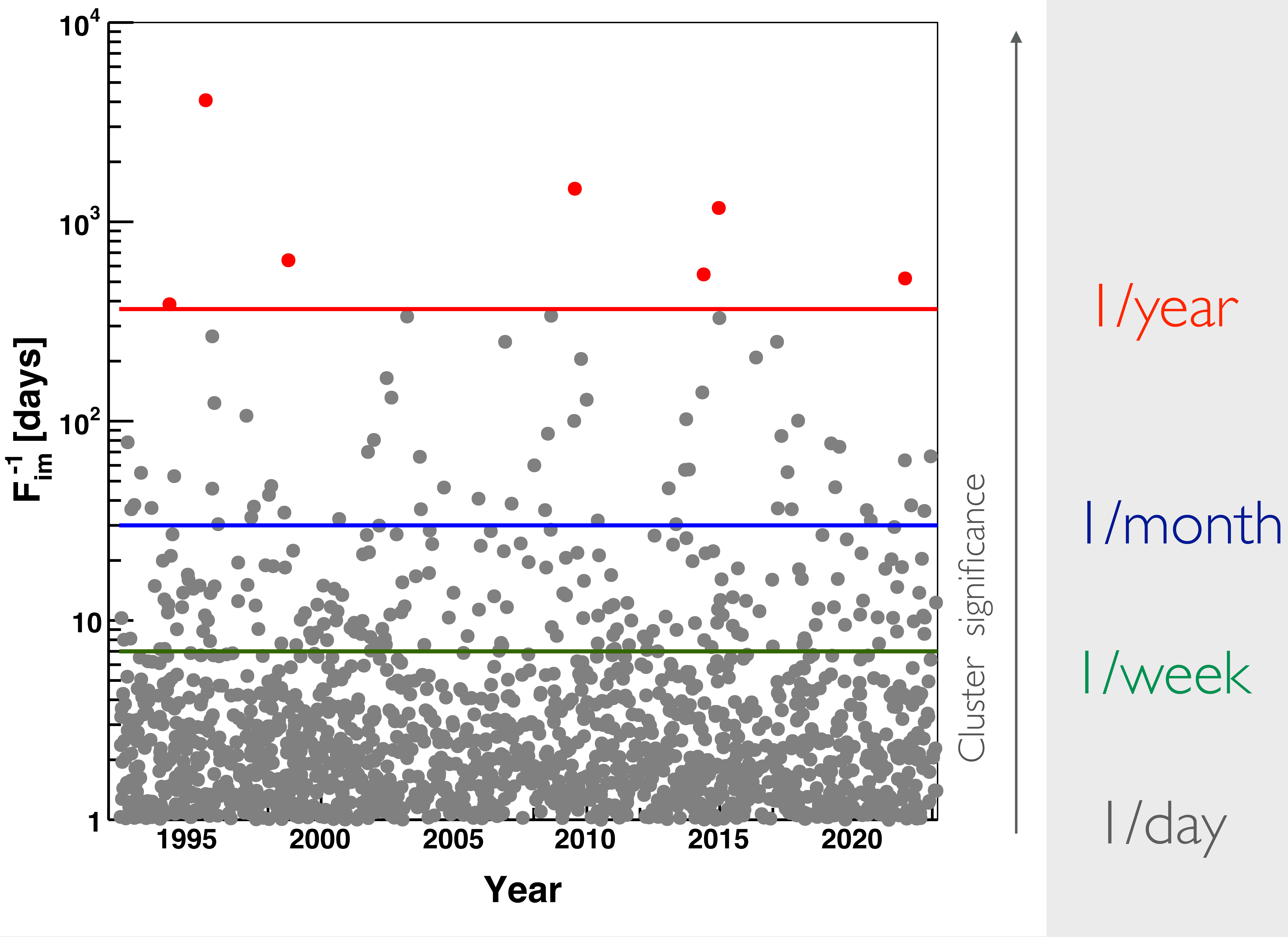
Multiplicity vs Δt



Below 1/year

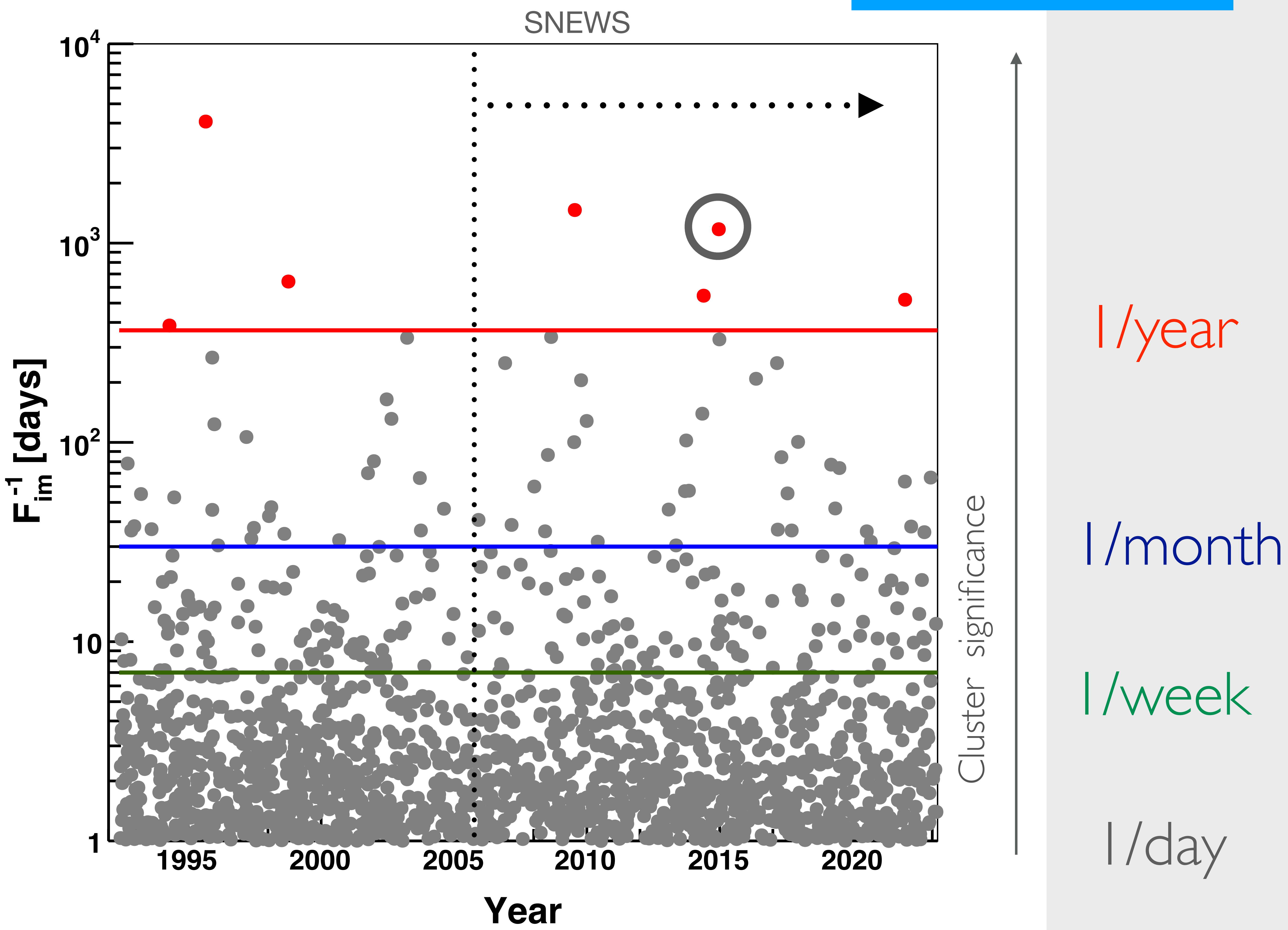
Cluster details II

Fim vs time



Cluster details II

Fim vs time



Clusters selected with the offline analysis are not necessarily sent as Alerts to SNEWS. In the common period 4 has F_{im}<1/y: one sent to SNEWS

Results 1992-2023

n.	UTC	$M_{act}[t]$	$f_{bk}[s^{-1}]$	$D_{90\%}[kpc]$	m	$\Delta t[s]$	$F^{-1}_{im}[years]$	$\bar{E}_{signal}[MeV]$	N_L
1	1994 16 April 10:40:49.263	346	$1.08 \cdot 10^{-2}$	29.5	7	18.88	1.06	26.5	2
2	1995 27 August 16:18:10.478	431	$1.85 \cdot 10^{-2}$	35.0	7	5.49	11.16	36.2	1
3	1998 7 October 15:41:41.775	552	$1.40 \cdot 10^{-2}$	30.6	12	90.05	1.76	32.2	3
4	2009 18 July 7:39:20.517	976	$2.40 \cdot 10^{-2}$	40.4	12	42.71	4.02	14.6	1
5	2014 25 May 3:54:14.555	959	$2.78 \cdot 10^{-2}$	36.8	14	61.56	1.49	22.6	4
6	2014 18 December 20:21:28.787	937	$2.33 \cdot 10^{-2}$	45.9	8	9.98	3.22	18.8	3
7	2021 23 December 00:39:00.279	863	$2.55 \cdot 10^{-2}$	38.1	14	68.75	1.42	19.0	4

Individually checked

Compatible with background fluctuation

No evidence of SN ν signals in LVD
Upper limit 0.08 event /year 90% c.l.

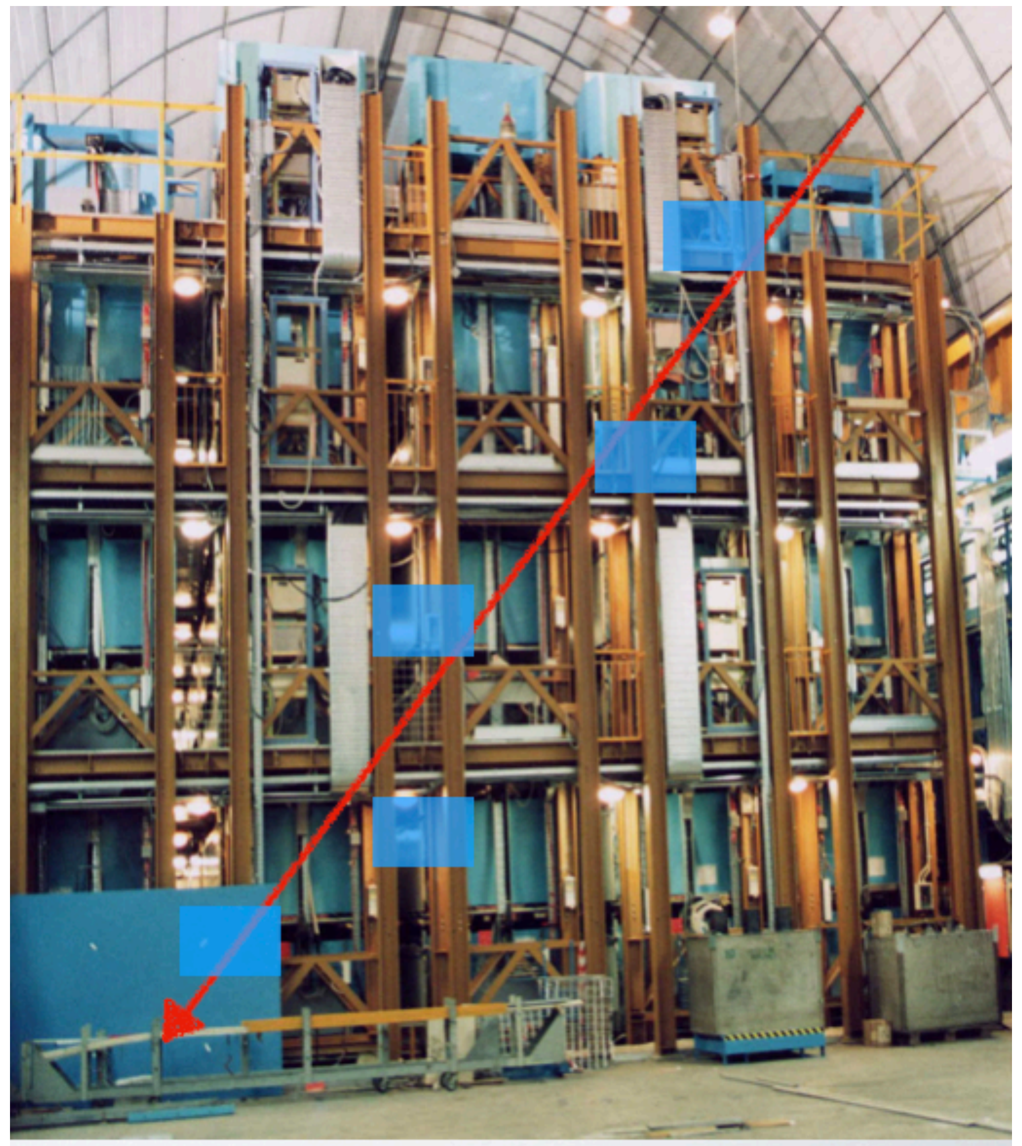
Muon Series Analysis

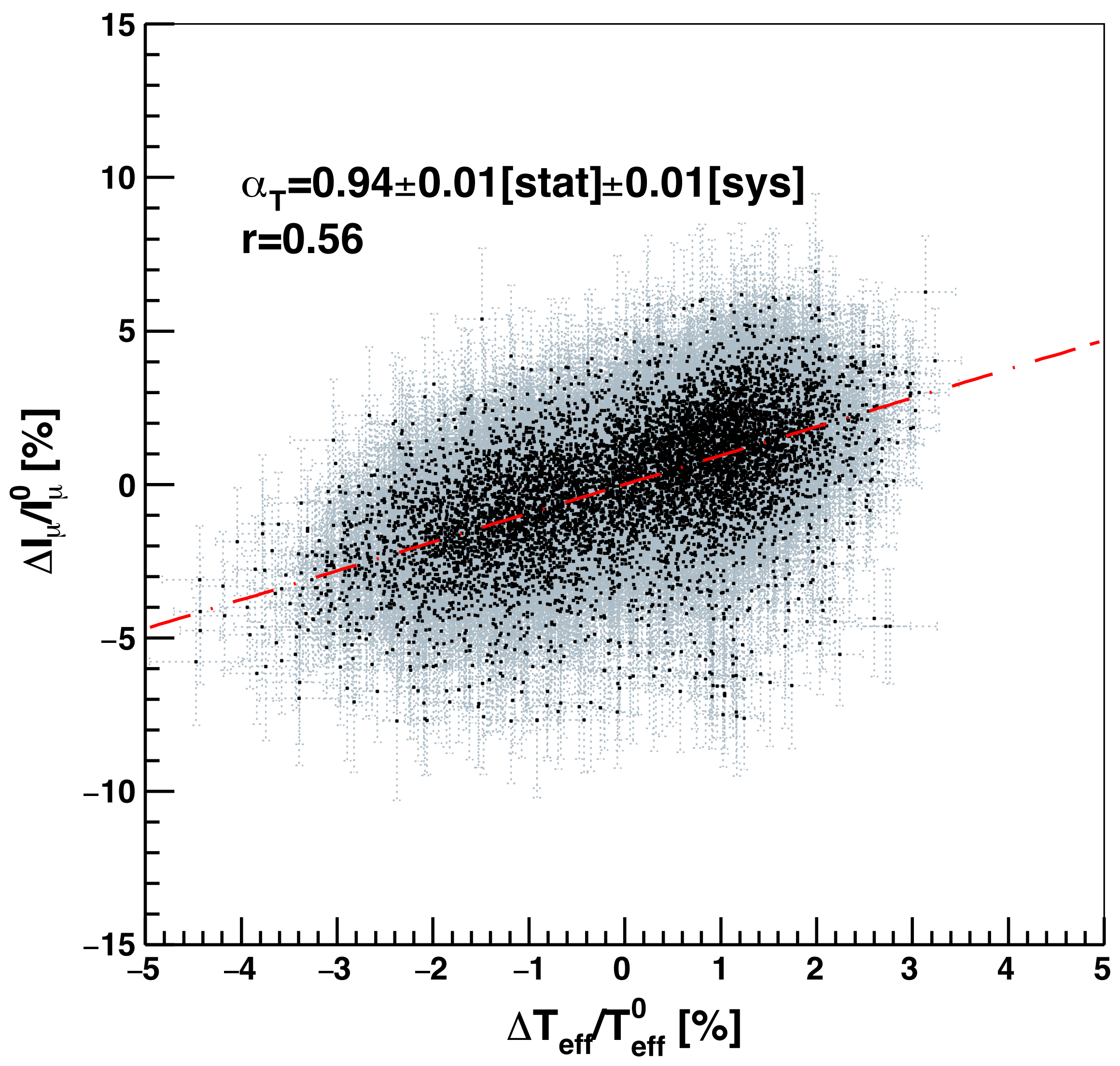
PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

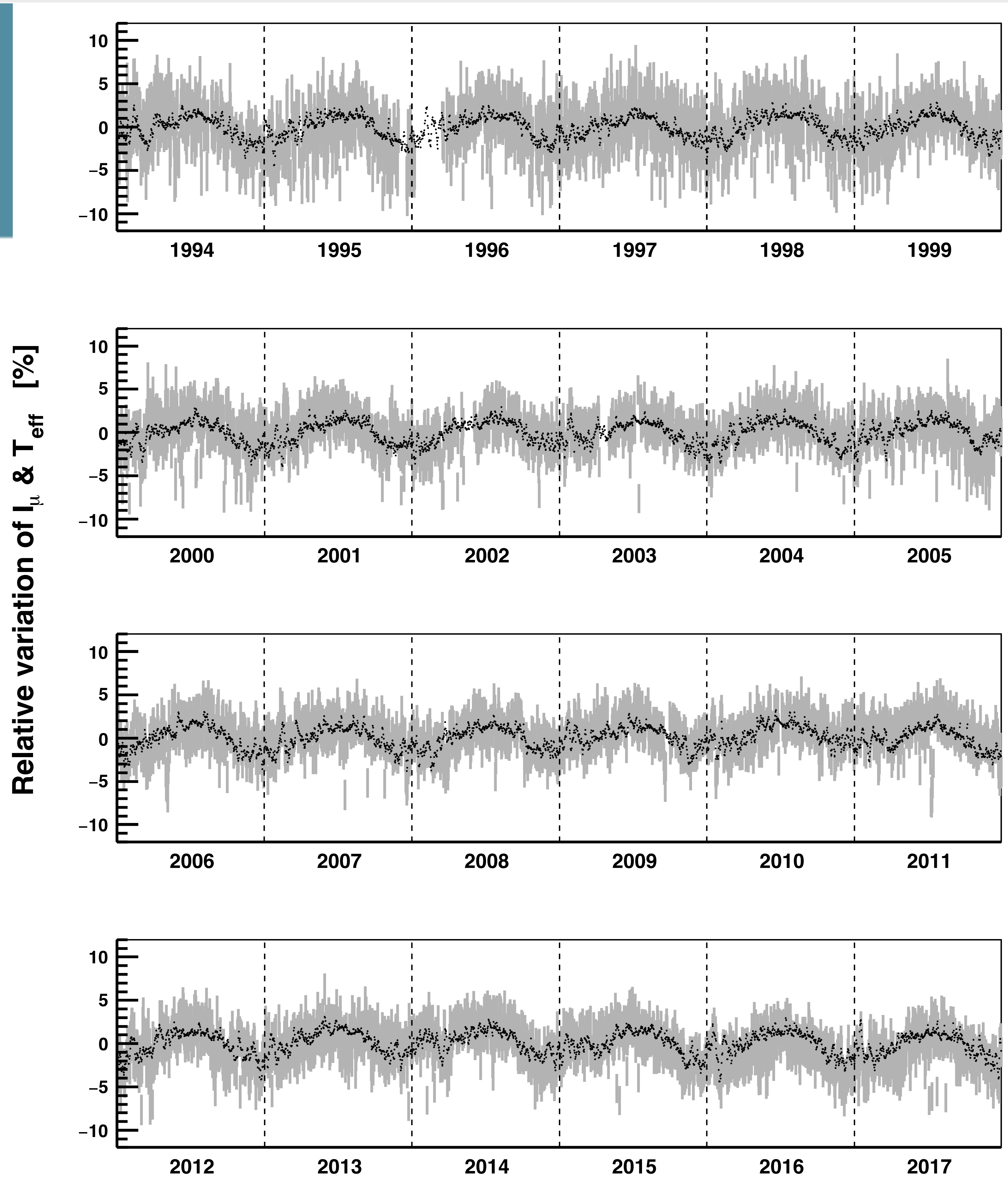
Highlights Recent Accepted Authors Referees Search Press About

Characterization of the varying flux of atmospheric muons measured with the Large Volume Detector for 24 years

N. Yu. Agafonova *et al.* (LVD Collaboration)
Phys. Rev. D **100**, 062002 – Published 19 September 2019







The longest μ time series

$$I^0_\mu = (3.35 \pm 0.0005^{stat} \pm 0.03^{sys}) \times 10^{-4} m^{-2} s^{-1}$$

PHYSICAL REVIEW RESEARCH **4**, 023226 (2022)

Exploration of the stratosphere with cosmic-ray muons detected underground

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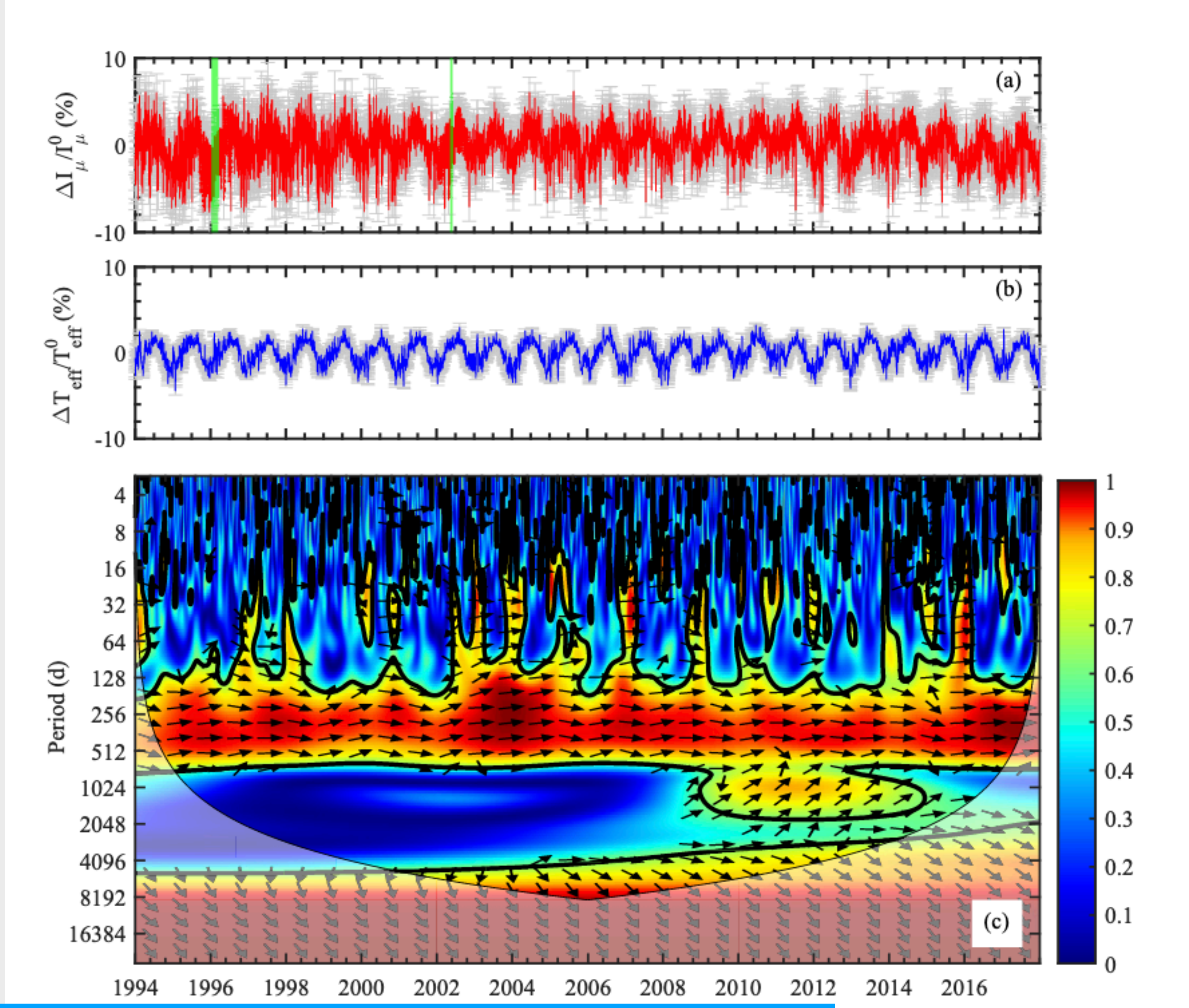
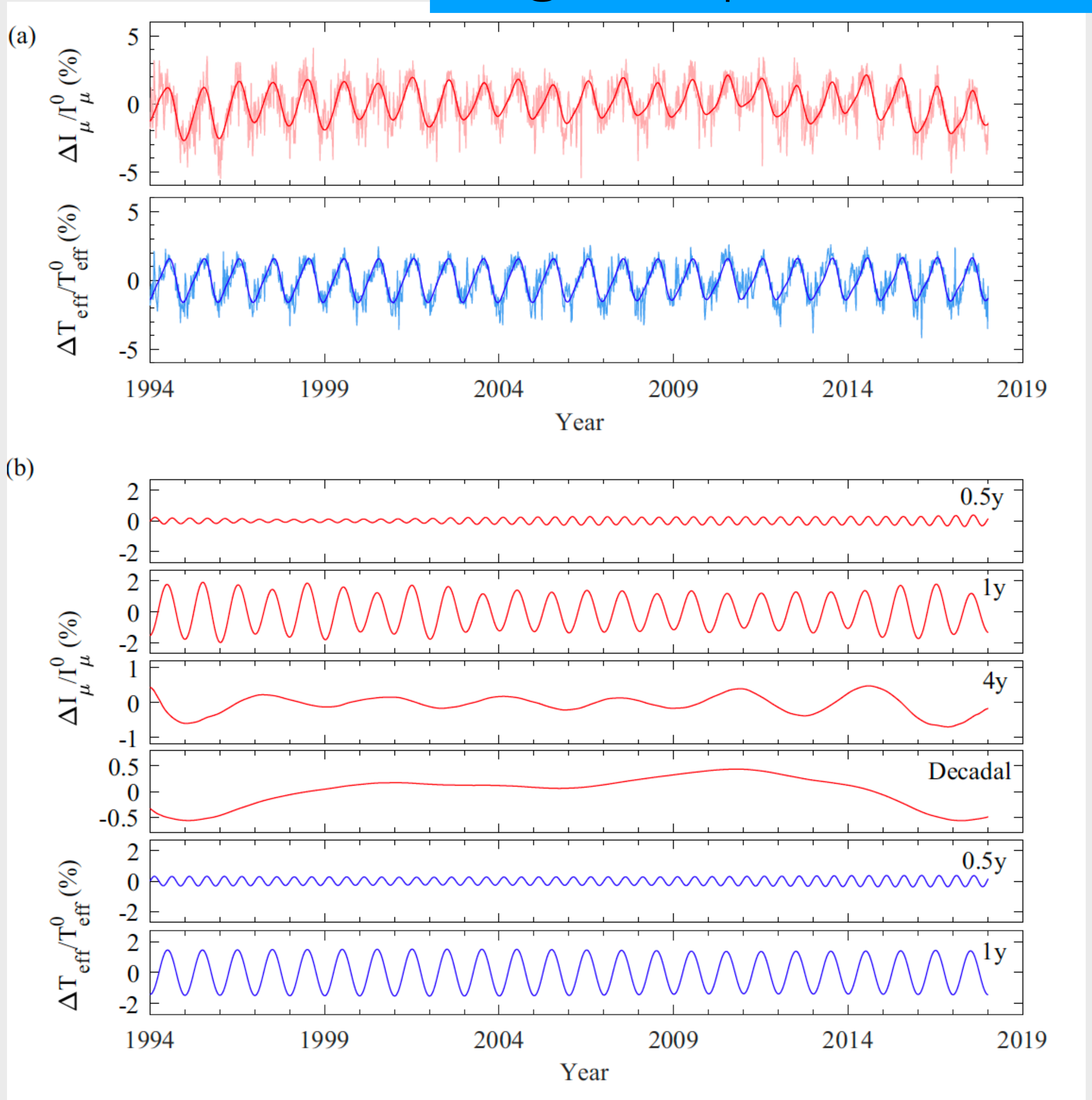
(LVD Collaboration)

Beyond the standard Fourier approach with advanced spectral-analysis methods



Continuous Wavelet Transform (CWT)

Singular Spectrum Analysis (SSA)



Conclusions

31 years data taking

Prompt alert to SNEWS since 2005

SN neutrinos: best upper limit
for the Milky Way survey

A summary paper in preparation

Some of the scientists who imagined, realised and contributed to the LVD experiment are not with us anymore. We are left with their memory and their teachings.