Large Area Phototubes for Next Generation Large Scale Astroparticle Physics Experiments

Bayarto Lubsandorzhiev

L.M. Balyasniy[4], S.A. Belyanchenko[3], L.B.Bezrukov[1], S. Dolinsky[5], R. Falkenstein[2], P. Grabmayr[2], Yu.N.Gordienko[4], G. Hallewell[7], J. Jochum[2], B.K. Lubsandorzhiev[1,2], N.B.Lubsandorzhiev[1], J. Nause[6], B. Nemeth, V.A. Poleshuk[1], R.V. Poleshchuk[1], V. Rangarajan, B.A. Shaibonov (Jr)[1]

[1] *Institute for Nuclear Research of RAS, Moscow, Russia*
[2] *Kepler Centre for Astro and Particle Physics, University of Tuebingen Tuebingen, Germany*
[3] *JSC "MELZ-FEU" , Moscow, Russia*
[4] *SC "SPU GEOFIZIKA-NV", Moscow, Russia*
[5] *GE Global Research, Niskayuna, NY, USA*
[6] *Cermet Inc., Atlanta, GA. USA*
[7] *CPPM, Marseille, France*

1st photoelectron multiplier
"Трубка Кубецкого" – "Kubetsky's tube"

Kubetsky Leonid Aleksandrovitch
1906 -1959

"Every big experiment should boost development of new experimental techniques which will pave the way for new, more sensitive experiments ….."

A.E.Chudakov

J.Learned, L.Bezrukov, A.Roberts et al formulated in 70-80s requirements for pmts for deep underwater and underground neutrino experiments.

DUMAND, BAIKAL

GRANDE,

IMB, Kamiokande

MILAGRO,

AMANDA, NESTOR,

ANTARES, NEMO,

ICECUBE, KM3NeT

Citius, Altius, Fortius

Faster, More Sensitive, Smarter

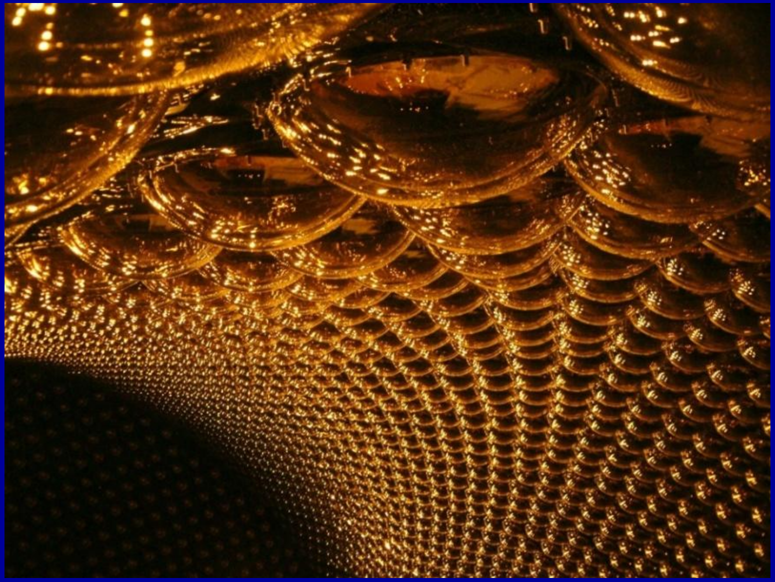
- High sensitivity to Cherenkov light - bialakali photocathode.
- Large sensitive area and 2π acceptance - hemispherical photocathode
- High time resolution (as low jitter as possible) - hemispherical photocathode
- Good SER (as good as possible) to suppress background due to K40.
- Low dark current - bialkali photocathode
- Fast response (~10 ns width or less)

First generation of large scale neutrino experiments (underground water Cherenkov arrays)

IMB

8” R1408

Kamiokande-I,II; Super-Kamiokande



20” R1449 Kamiokande I,II
20” R3600 Super-Kamiokande

- Detection of neutrino signal from SN1987A

- Discovery of neutrino oscillation

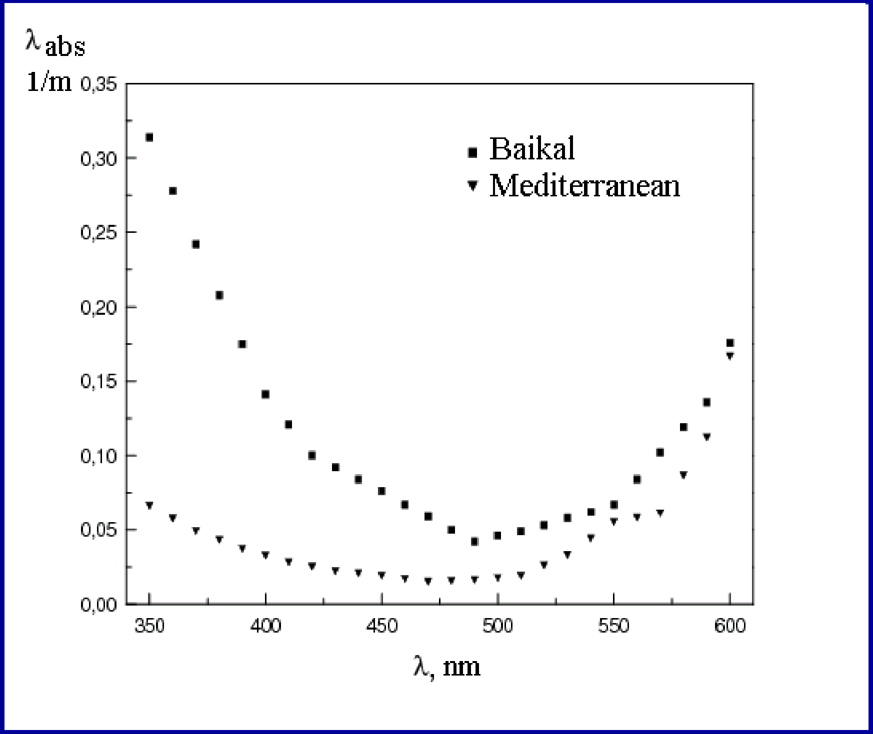
History of deep underwater neutrino telescopes spans more than 30 years.

For many years the Baikal Neutrino Telescope has been the only deep underwater neutrino telescope in the world.

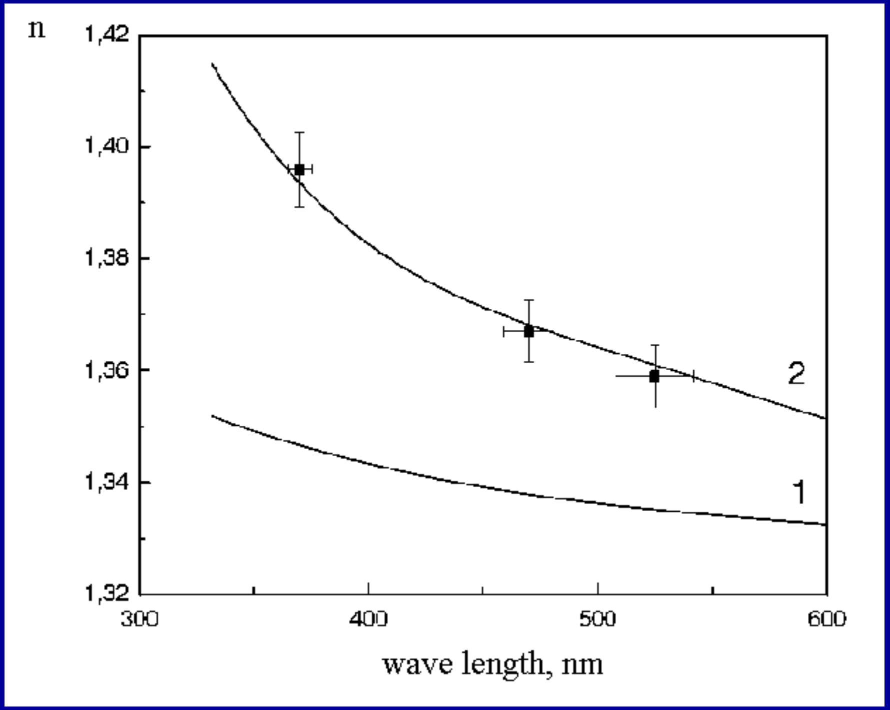
Now ANTARES joined the club

Influence of water parameters

Water transparency

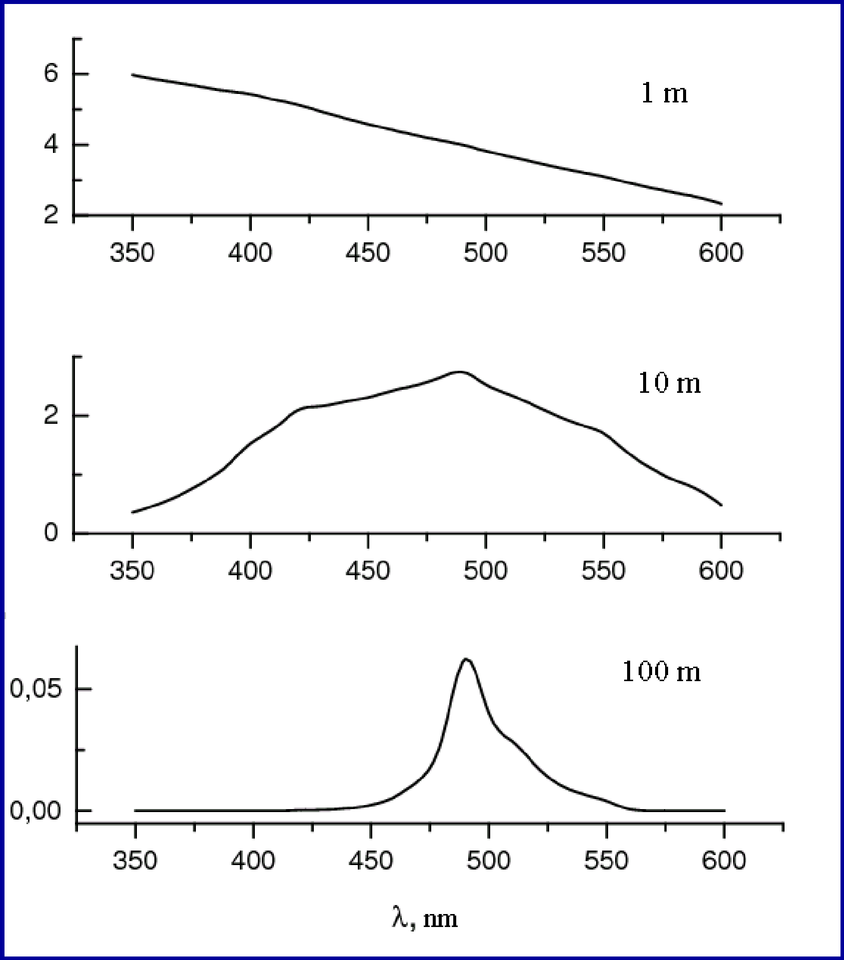


Light dispersion in deep Baikal water

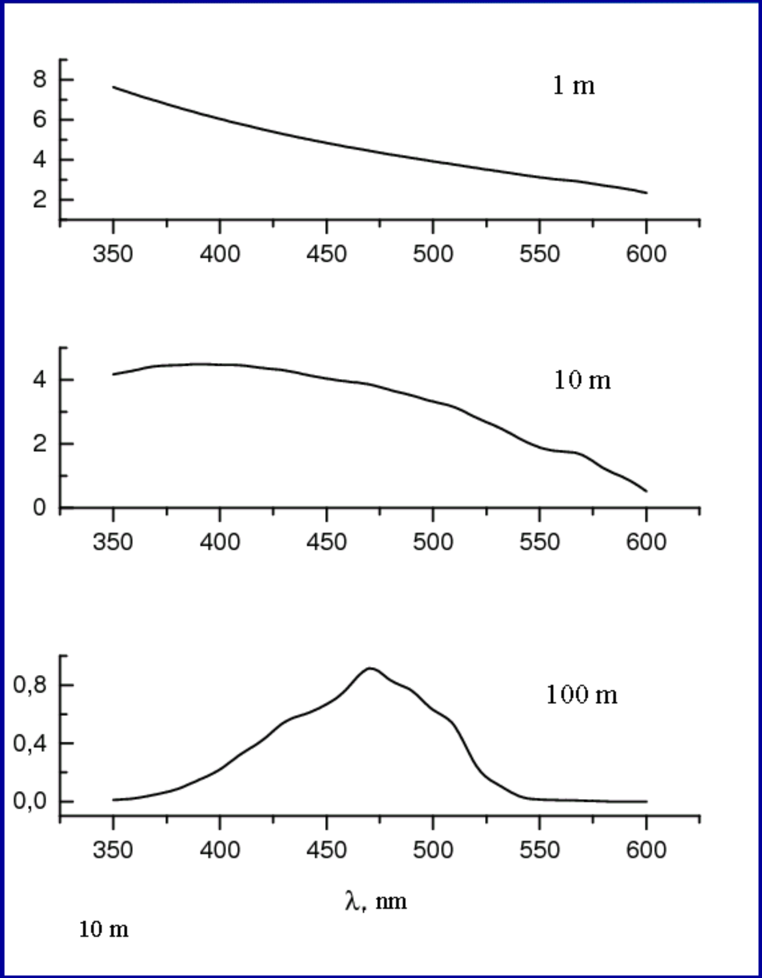


Transformation of Cherenkov light spectrum in water

Baikal



Mediterranean



Lubsandorzhiev, Pokhil 1997

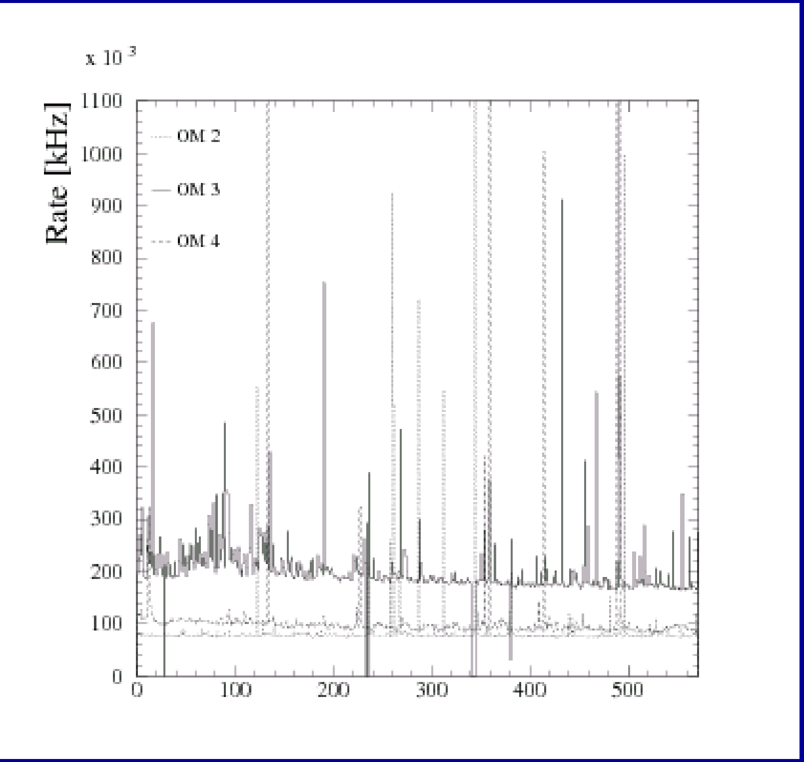
For Mediterranean:

Photodetectors with λ_{max} ~ 470-475 nm (Ultra/Hyper-Multialkali!)

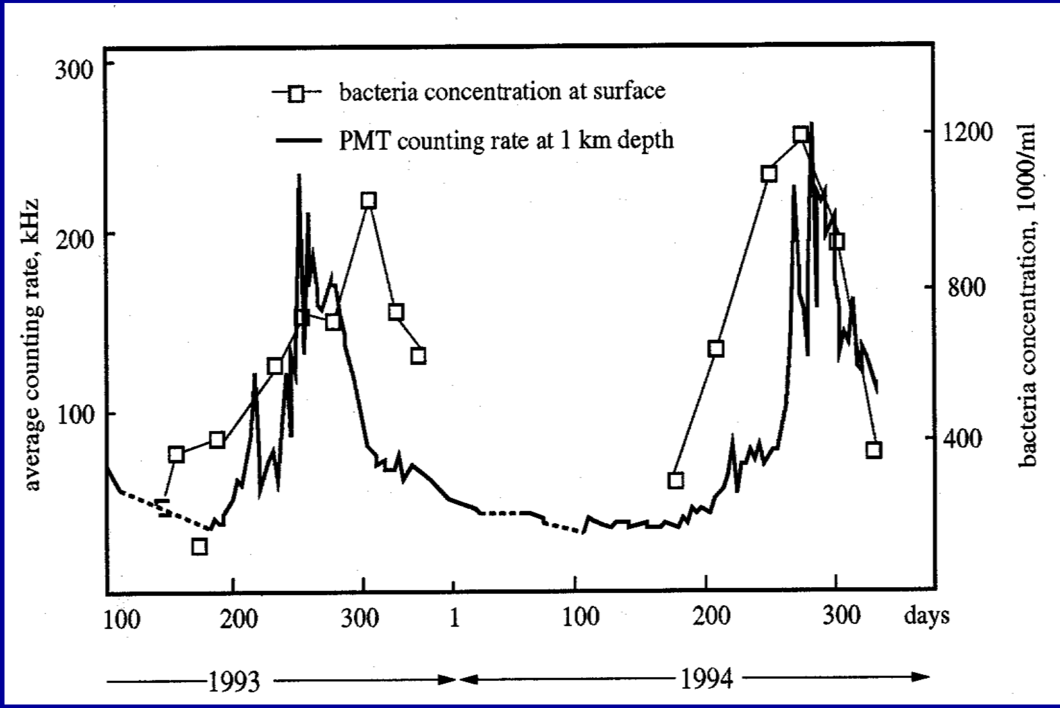
Lubsandorzhiev, Pokhil 1997

Light background in natural water - ocean, sea, lake

Pacific ocean, DUMAND



Lake Baikal, NT-36 and NT-72



36 OMs 72 OMs

QUASAR-370

Water parameters play crucial role

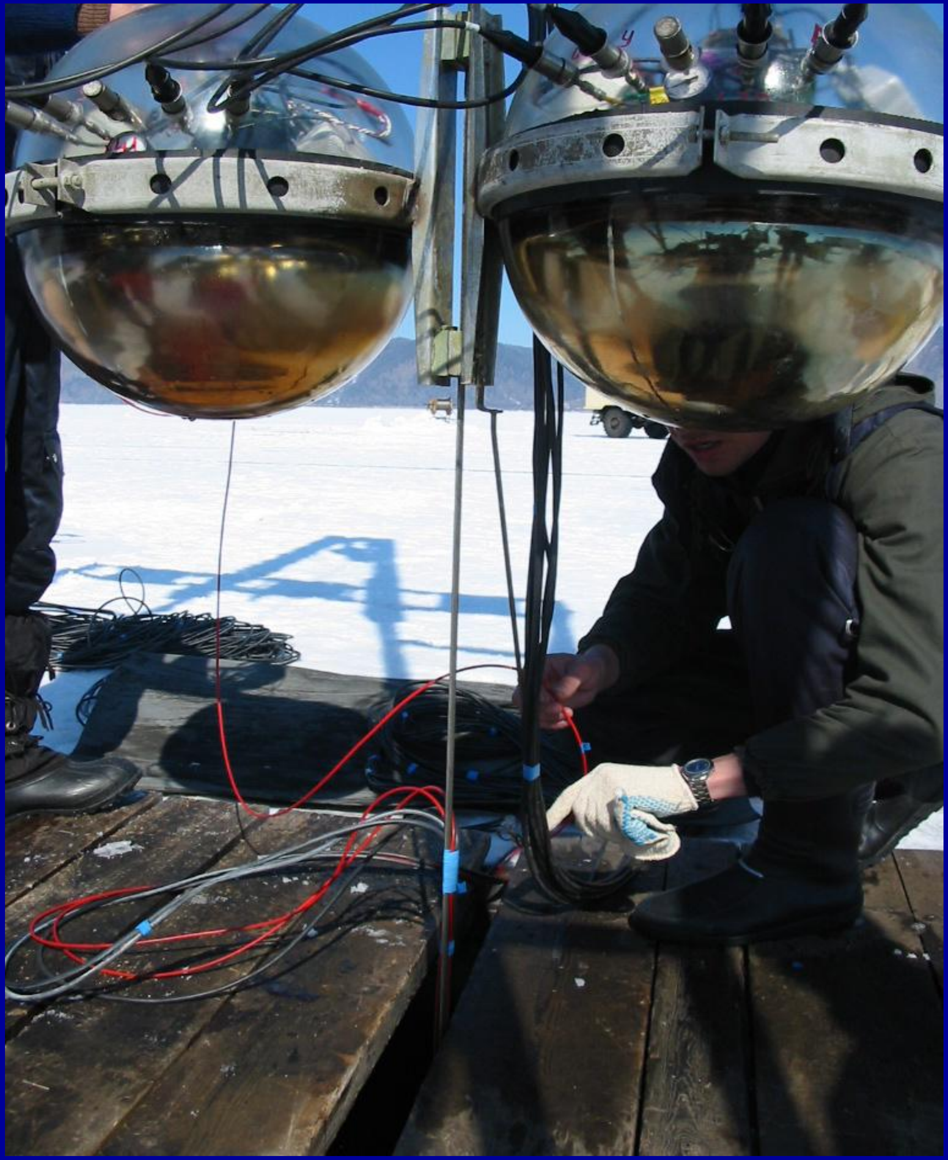
Light dispersion in water smears photons arrival times

e.g. 100 m - Δt(fwhm)~5ns for Mediterranean
PMT’s jitter of ~3 ns (fwhm) is enough

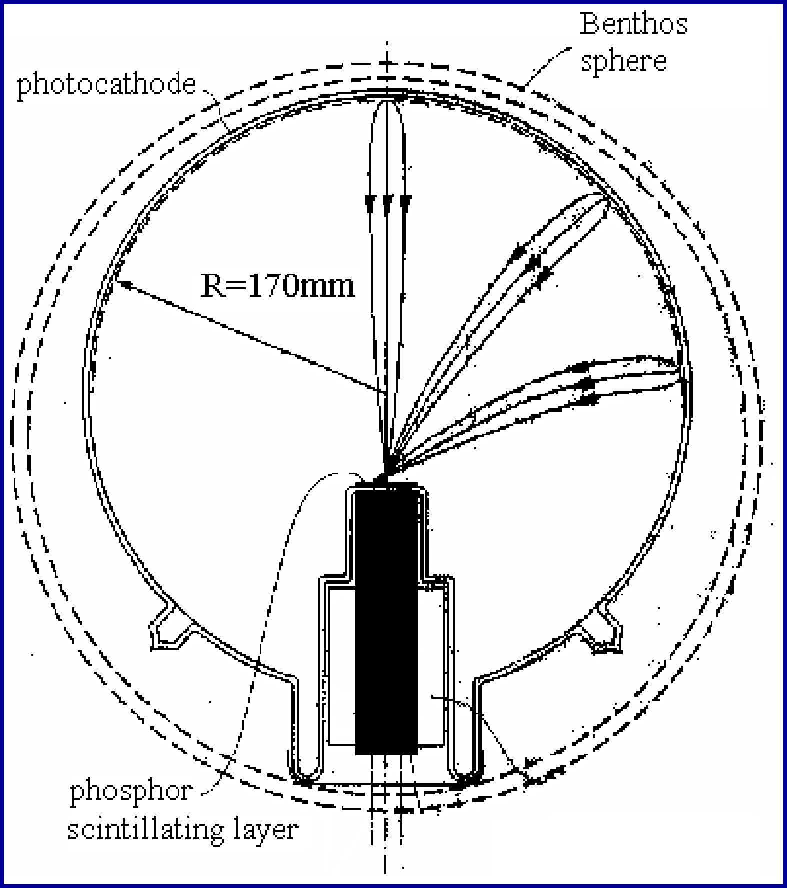
sensitivity in a wider range than conventional bialkali cathode (Ultra/Hyper Multialkali Cathode?)

Counting rate due to water luminescence dominates over PMT’s dark current

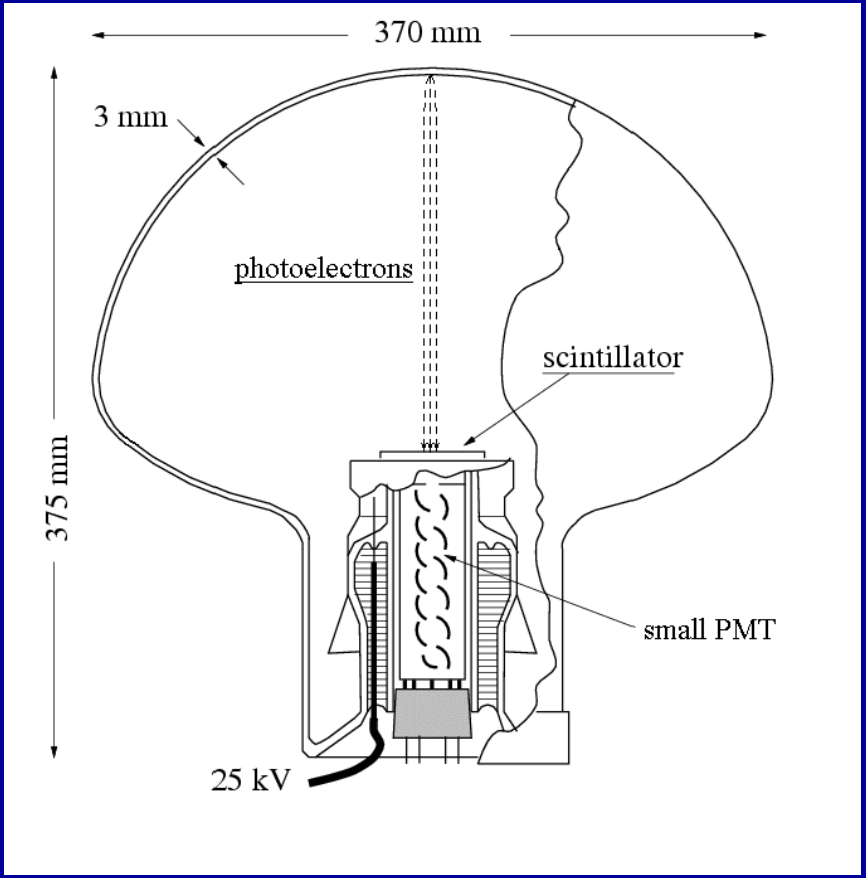
Deep underwater neutrino experiments



XP2600 PHILIPS/PHOTONIS



QUASAR-370 KATOD/INR

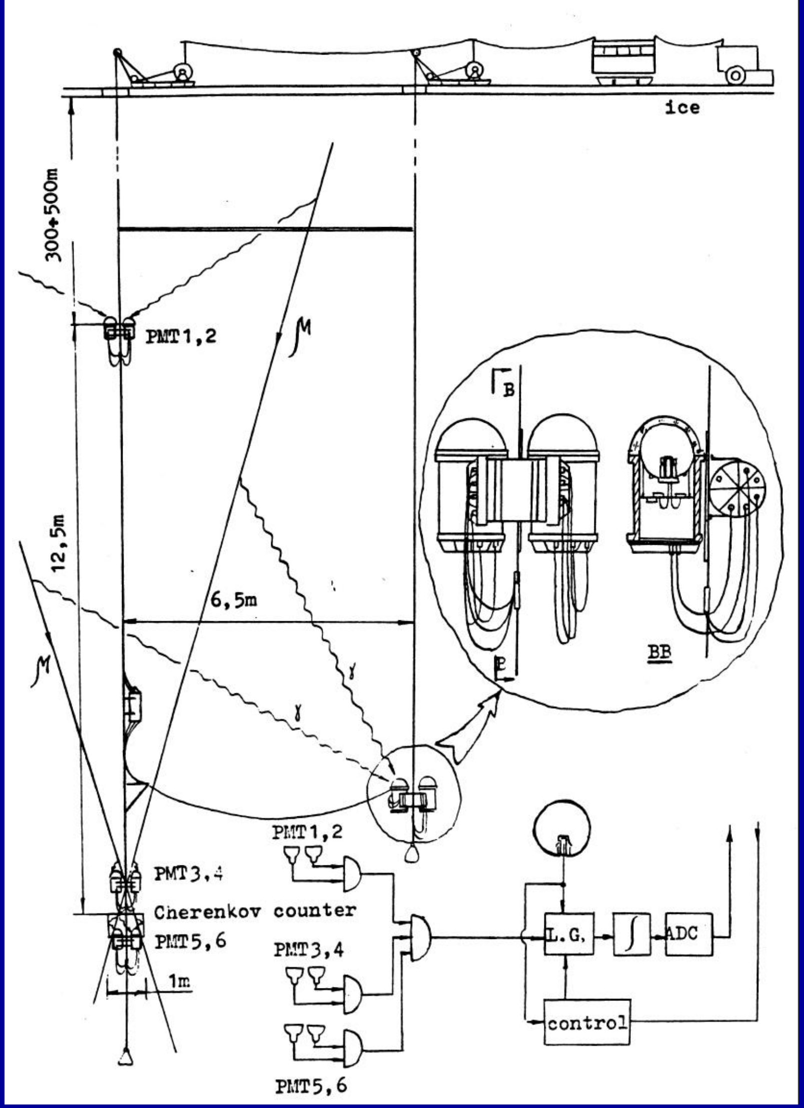


Record timing and excellent SER

"…the largest eye ever recorded, by the way, is a colossal 37 cm in diameter. The leviathan that could afford to carry such eyes around is a giant squid with 10-metre tentacles.. "

Richard Dawkins.
Climbing Mount Improbable. 1997

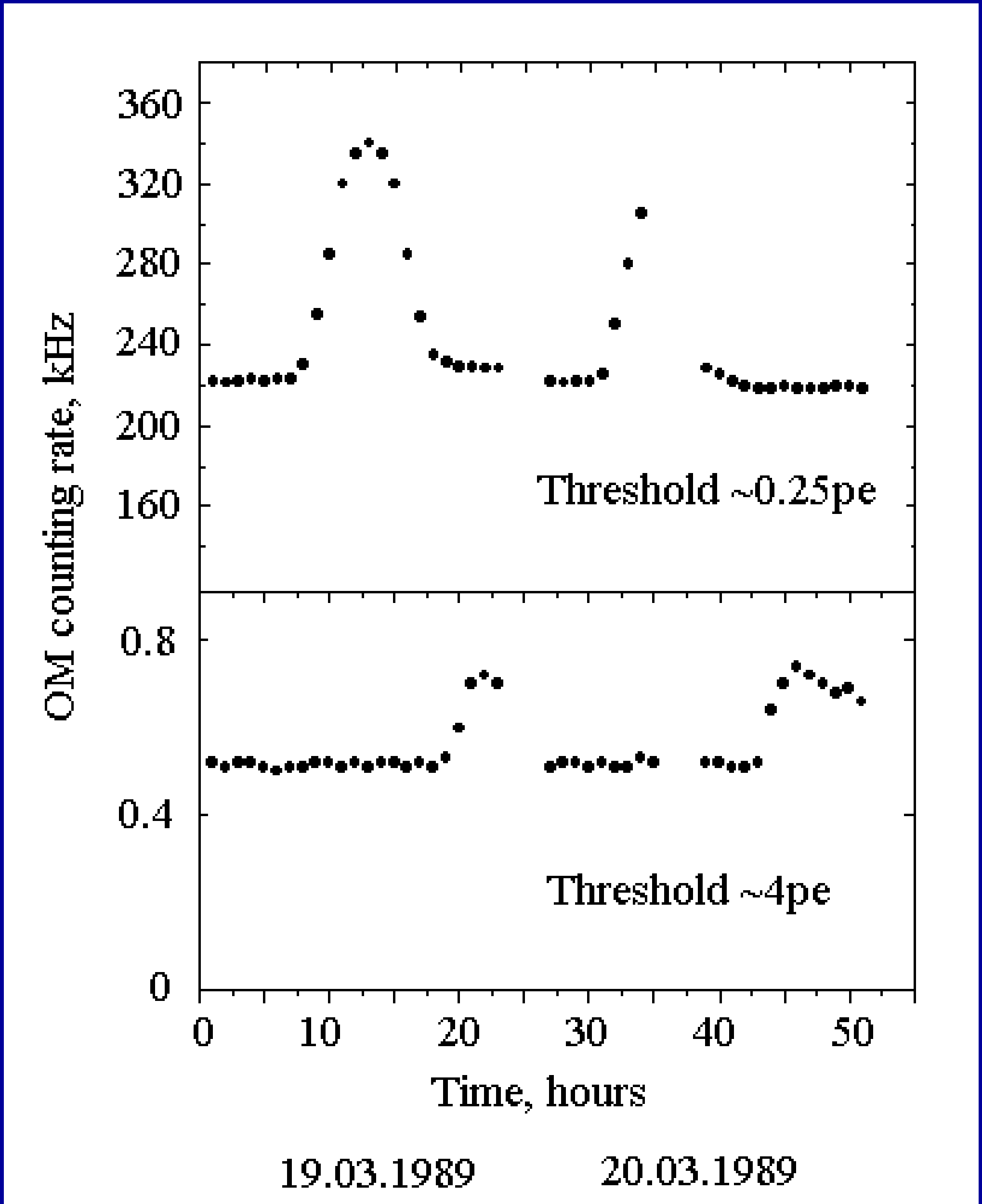
- Proof of principle of high energy neutrino detection
- Discovery of fresh water luminescence
- Discovery of fresh water bioluminescent microflashes
- Anomaly low light absorption of deep ice



1987-1989 tests of first large area hybrid phototubes at Lake Baikal

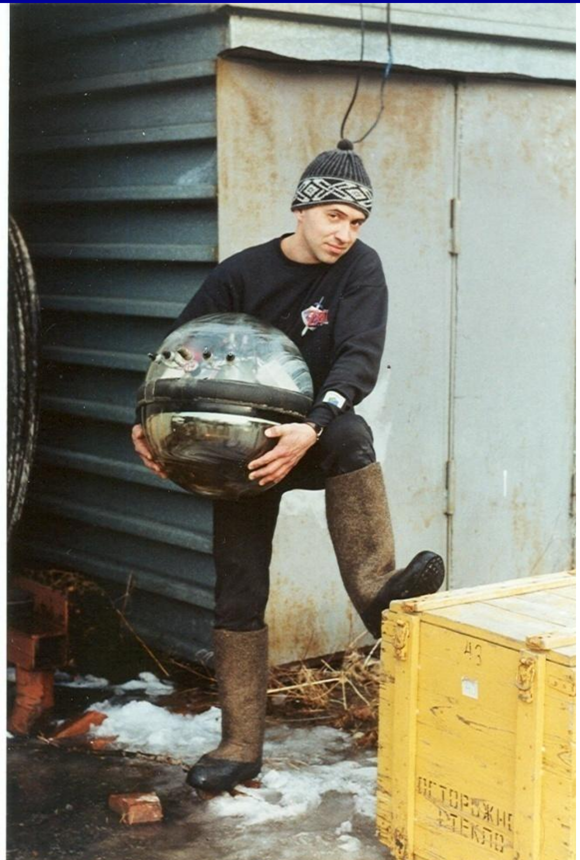
Multiphoton pulses from some tiny spieces of the lake biota were discovered at the depth of 400-500 m.
There is a very good correlation with their daily migration.

This phenomenon was discovered only owing to the fact that afterpulses in hybrid phototubes are substantially suppressed in comparison with conventional PMTs!



1987

Lake Baikal



1994

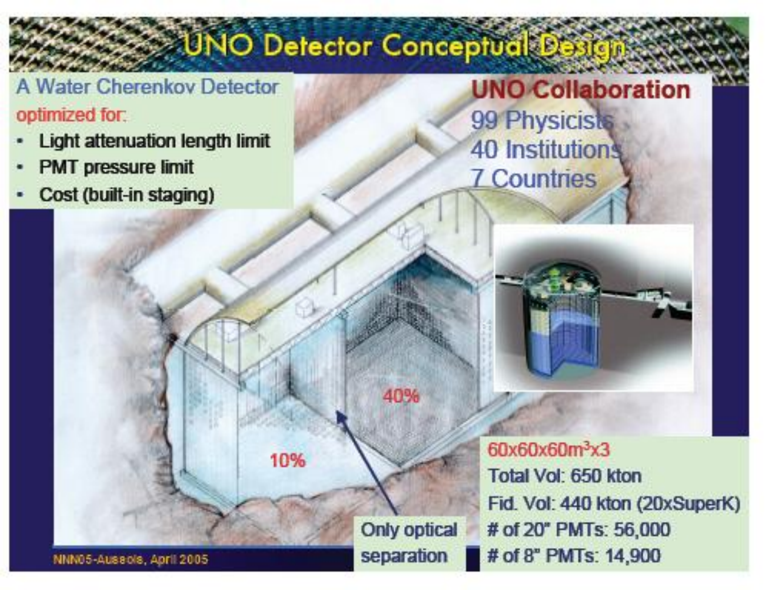
Lake Baikal

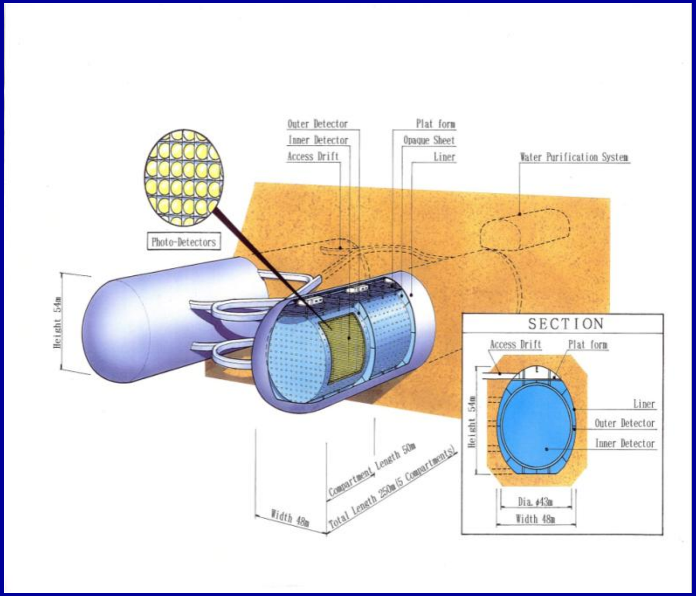
1998

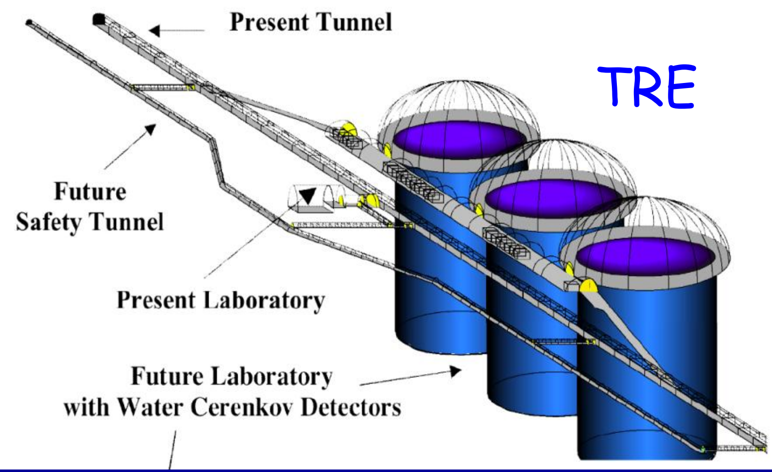
Deutsches Museum, Bonn

Next generation neutrino experiments

Water Cherenkov experiments



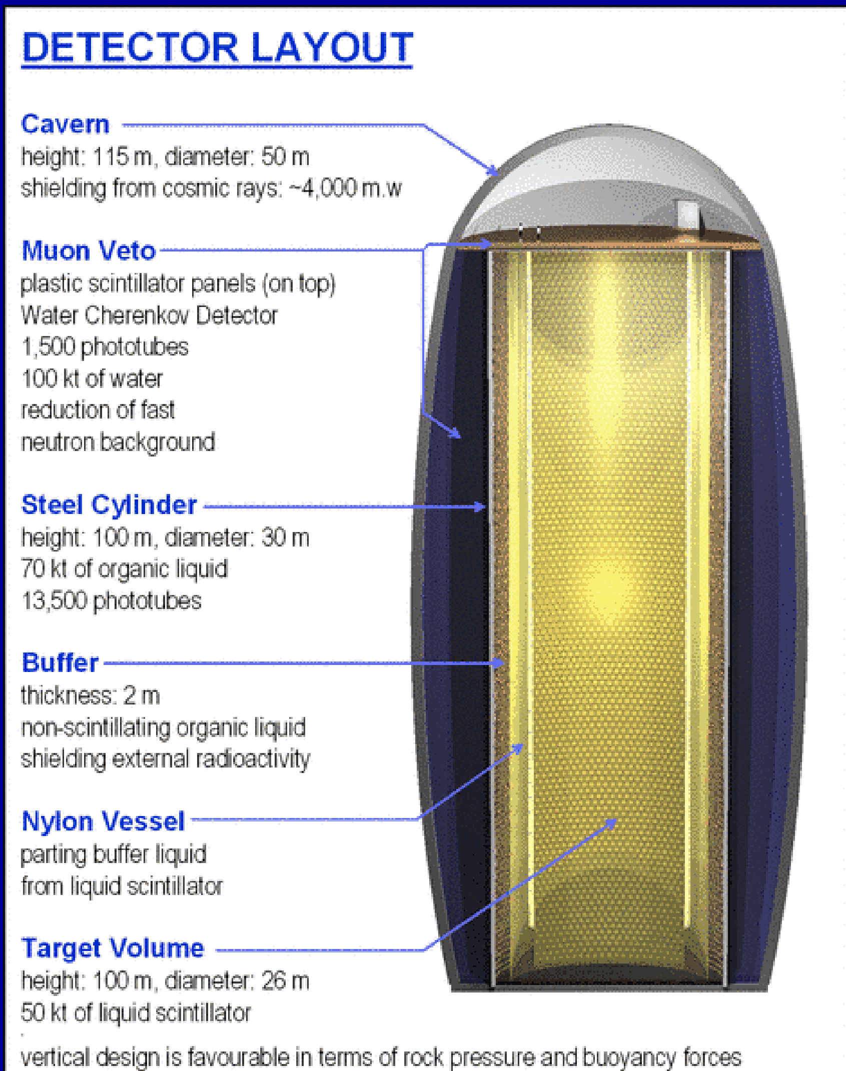


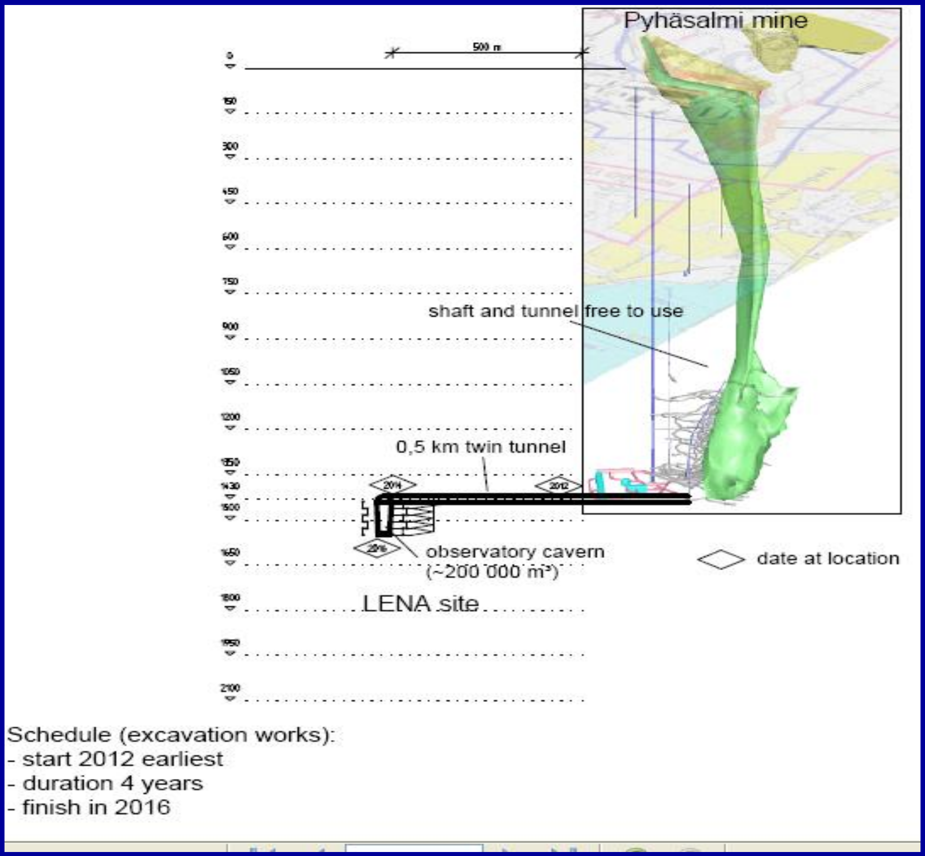


UNO, DUE, TRE

UNO: 80 000 20" PMTs
DUE: ~200 000 20" PMTs
TRE: ~200 000 20"PMTs

Liquid scintillator experiment LENA





Challenge to the development of large sensitive area photodetectors

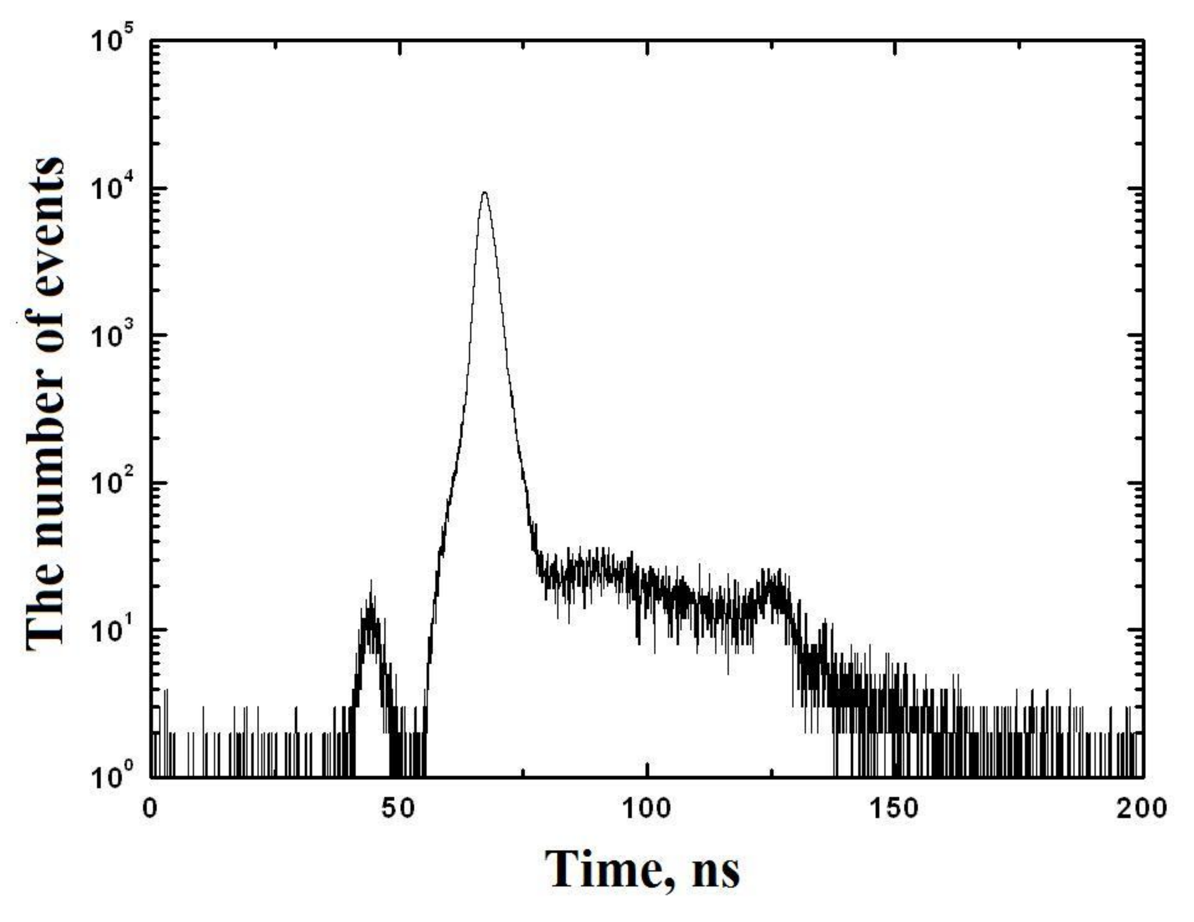
Conventional PMTs or Hybrid Tubes?

Disadvantages of classical PMTs

- Poor collection and effective quantum efficiencies
- Poor time resolution?
- prepulses
- late pulses (*Bezrukov*, *Lubsandorzhiev 1983*)
- afterpulses
- sensitivity to terrestrial magnetic field
- larger PMT size - larger dynode system (Dph/Dd1), practically impossible to provide 2π acceptance (*Lubsandorzhiev*, *Pokhil 1990-91*)

Photoelectron backscattering in PMTs

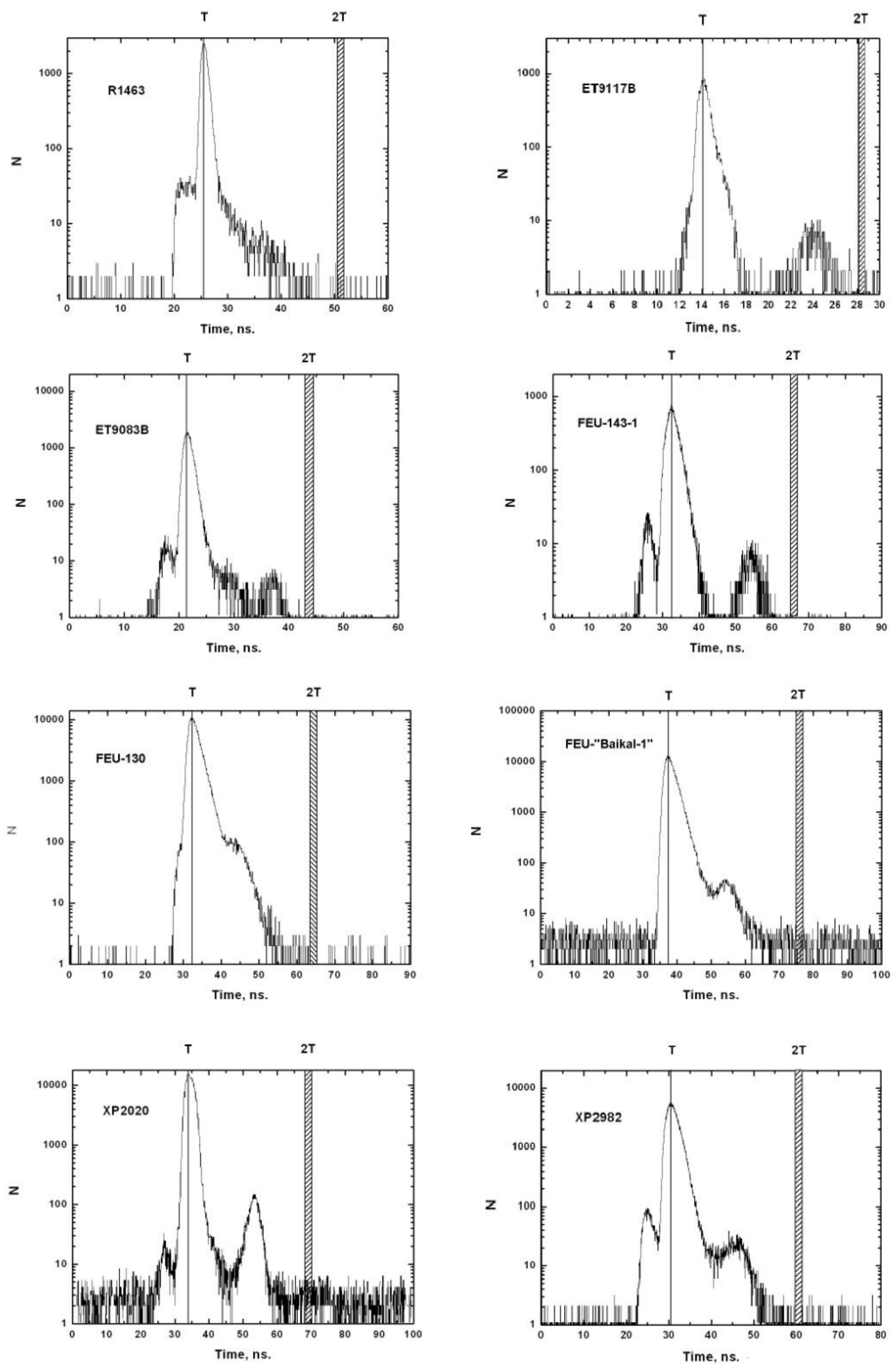
8” ET9350KB



Jitter ~ 2.5-3 ns (FWHM)

Prepulses - ~1%

Late pulses - 4-5%



Photoelectron backscattering – general inherent phenomena of classical vacuum PMTs

Closely connected with Effective Quantum Efficiency (Absolute sensitivity)
Lubsandorzhiev, Vasiliev 1997.

Measurements of fluorescence absolute light yield with <5% precision

Photoelectron detection efficiency - <3% ?????!!!!!!

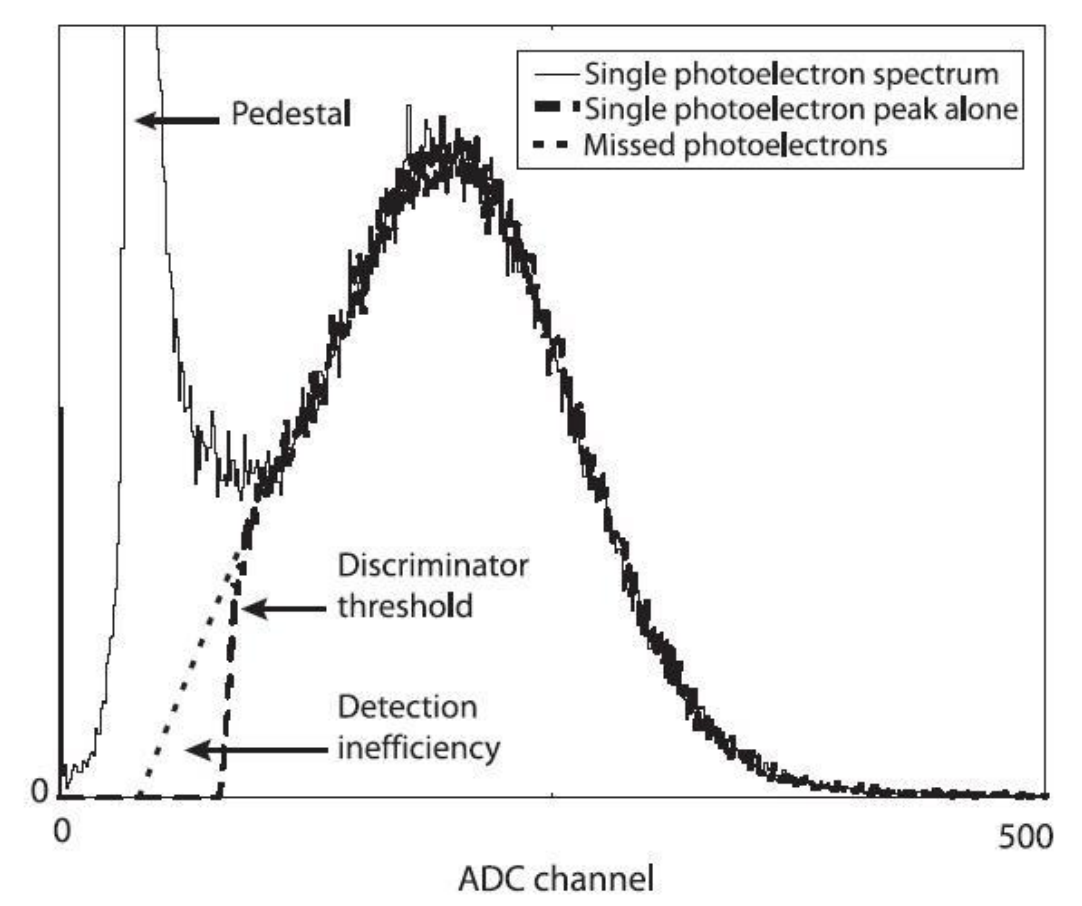
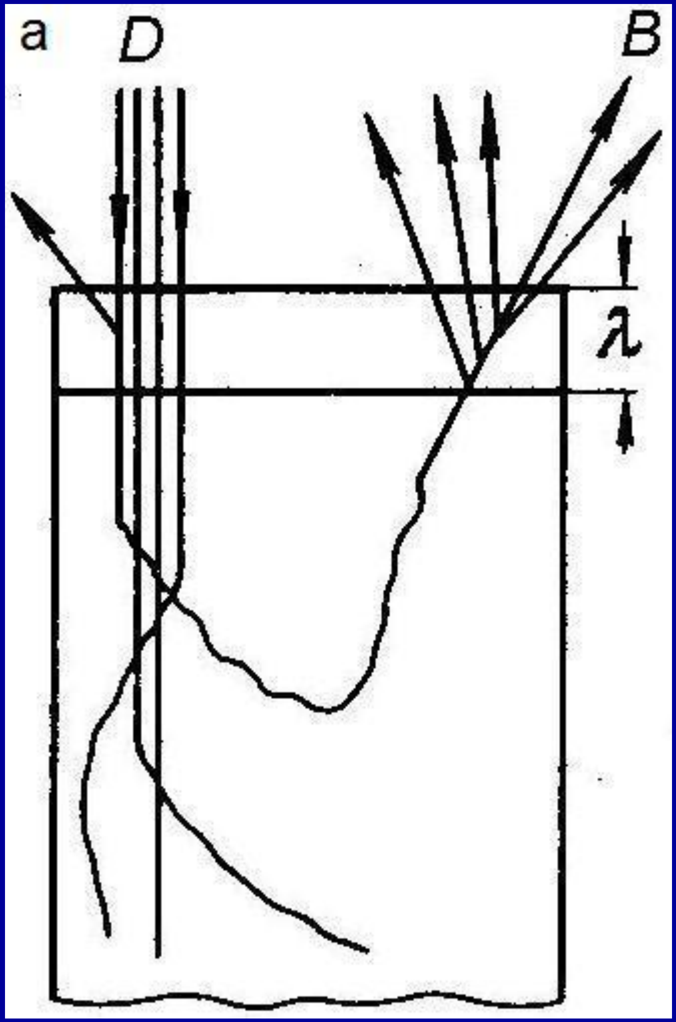


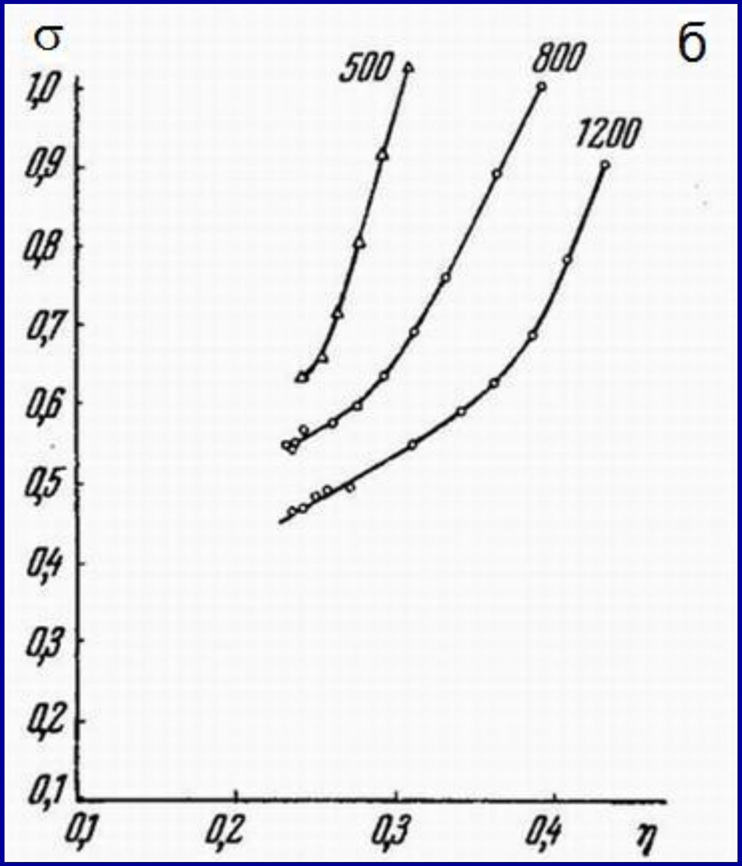
Fig. 8. Single photoelectron spectrum, with and without the pedestal.

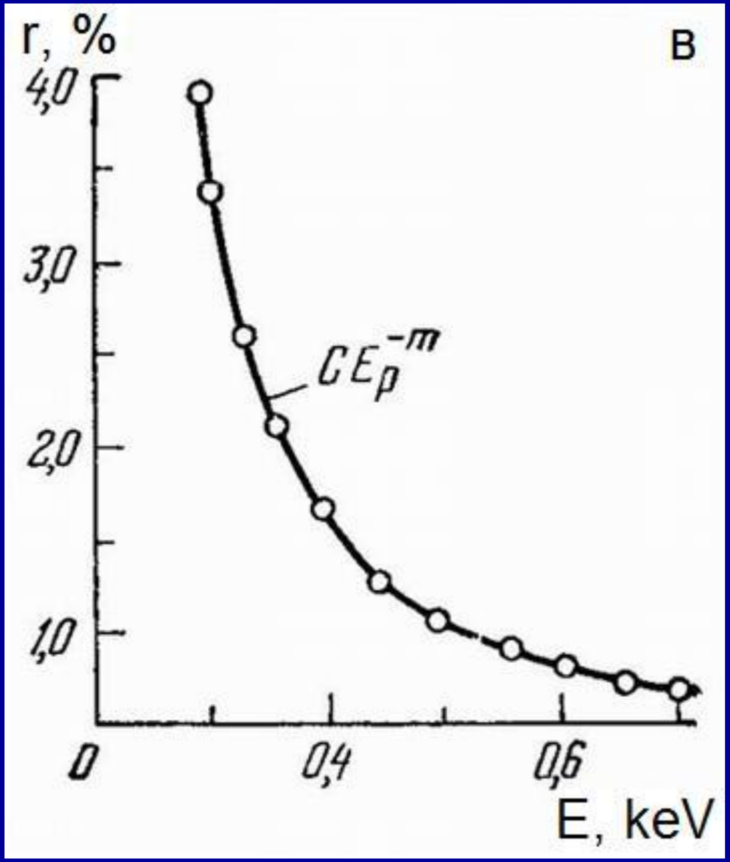
G. Lefeuvre et al. / Nuclear Instruments and Methods in Physics Research A 578 (2007) 78–87

Backscattering



Secondary electrons are produced by backscattered electrons



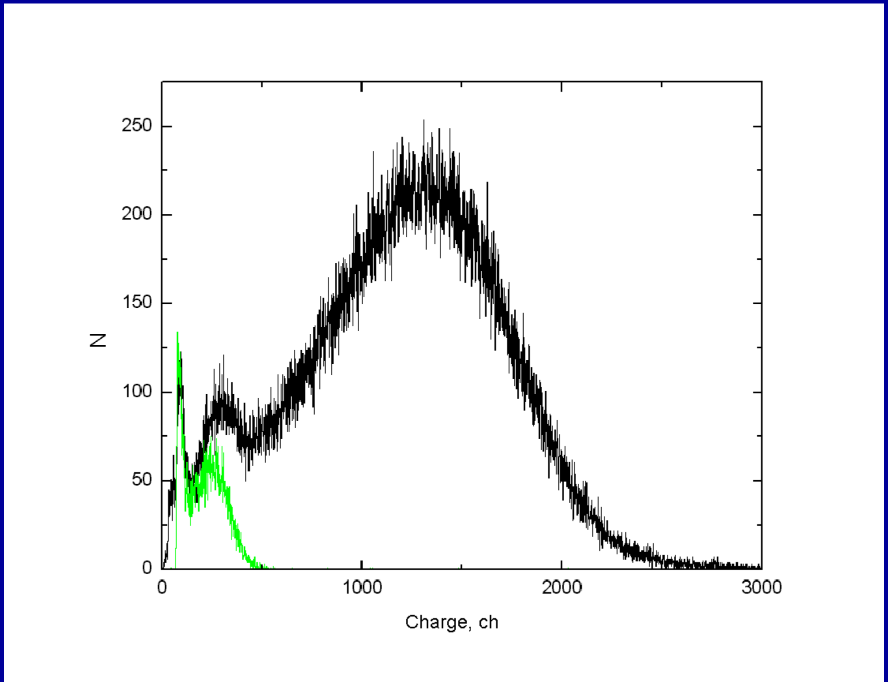


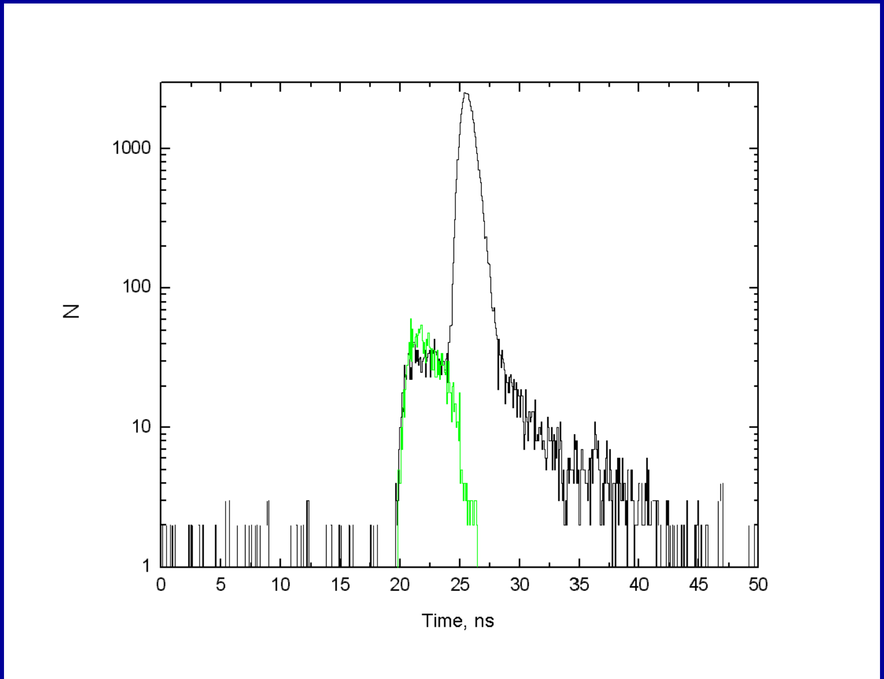
σ- secondary emission coeficient

η- backscatering probability (elastic+inel)

r – elastic bckacattering coef.

Studies of Hamamatsu R1463 (1/2’’) at a low threshold

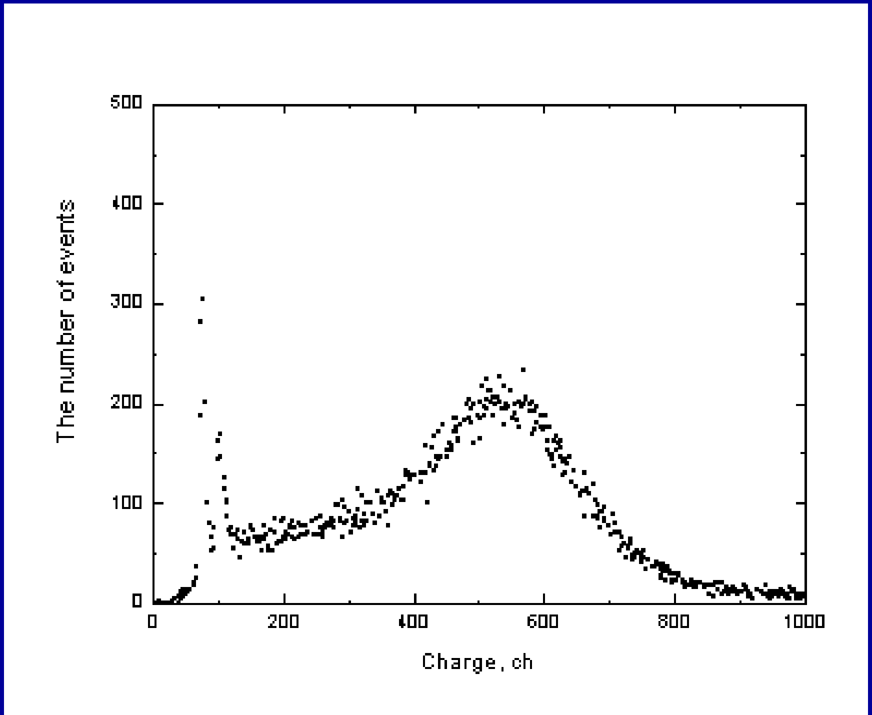


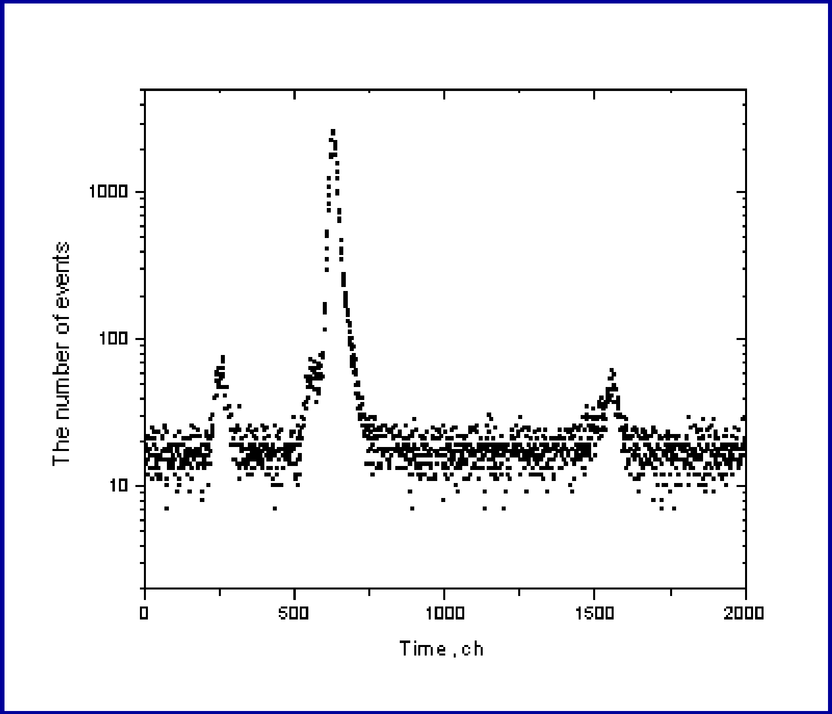


- Threshold - ~ 0.005 pe!
- Green - spectra measured with cathode camera switched off, i.e. cathode and 1 dynode are short circuited

Big hemispherical PMTs at low thresholds

Hamamatsu R8055 (13”)

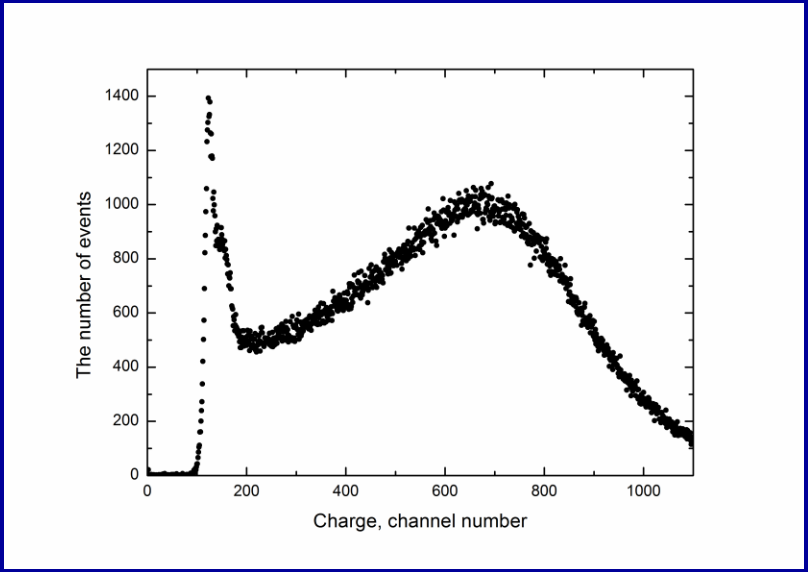


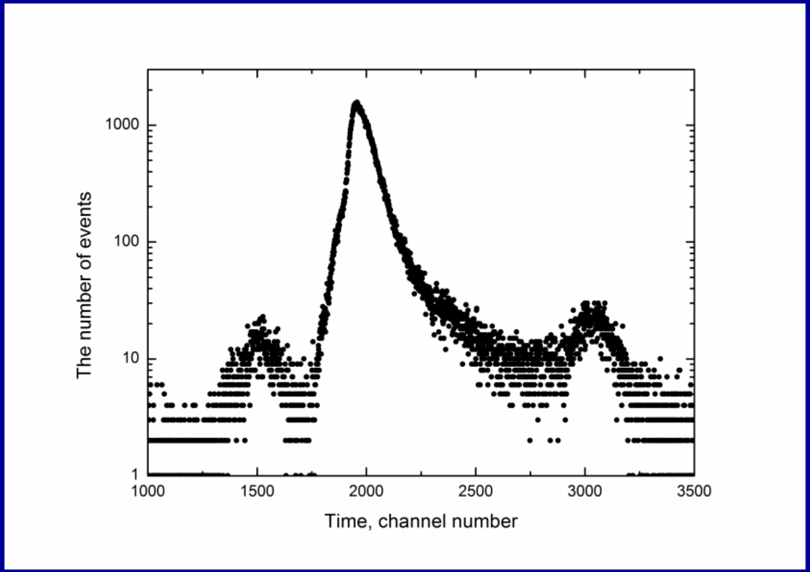


SER ~70% (fwhm)
0.005 pe threshold!

Jitter ~ 1.8 ns (fwhm)

Photonis XP1807 (12”)

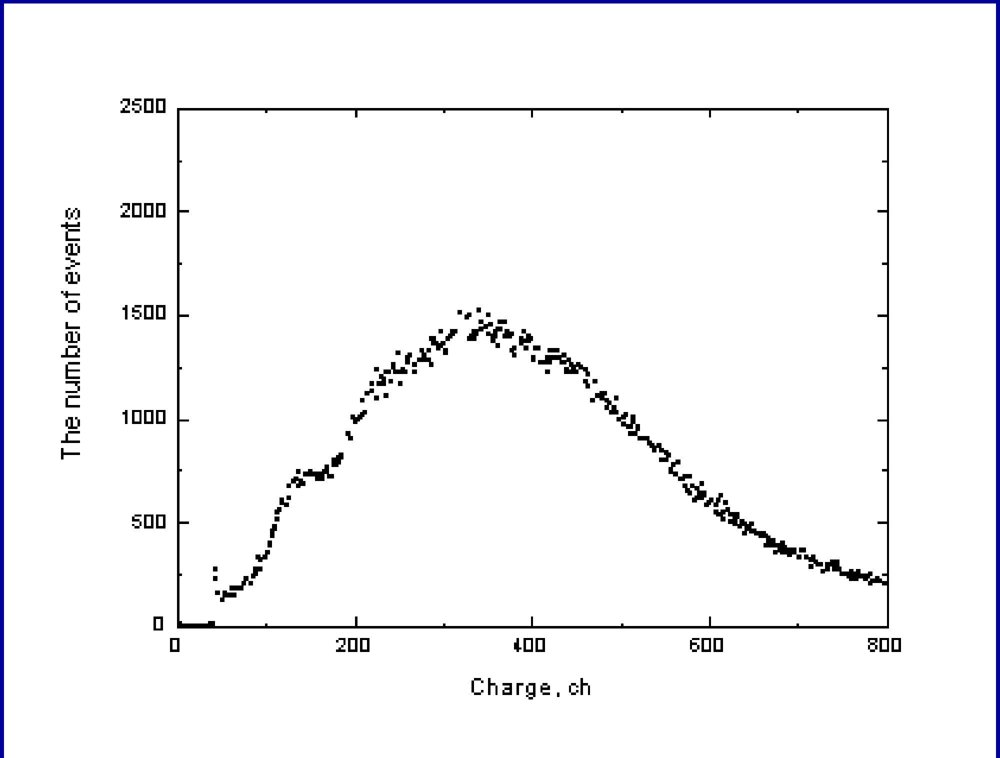




Threshold ~0.005 pe!!!

Jitter ~ 7.5 ns (FWHM)

R8055



$\sigma \sim 35$

strong nonpoissonian behaviour!

Point like illumination at the pole of the PMT's photocathode

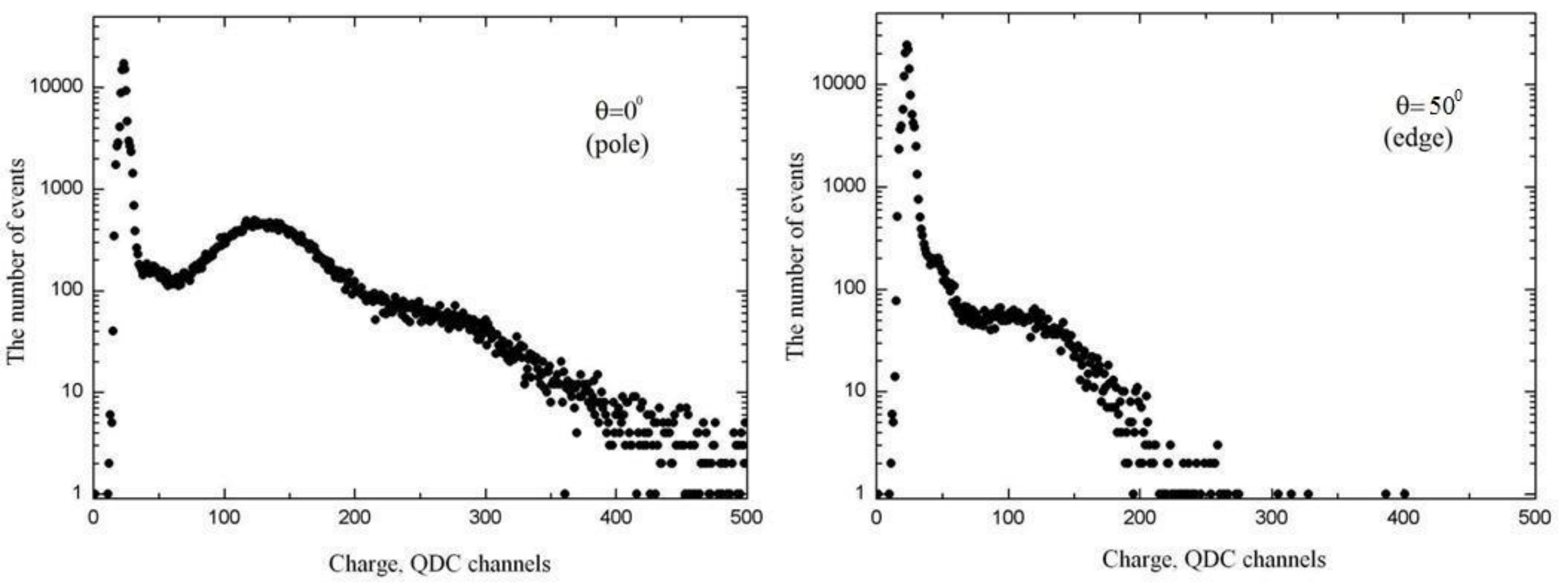
Afterpulses - ~20%
heavy caesiation?

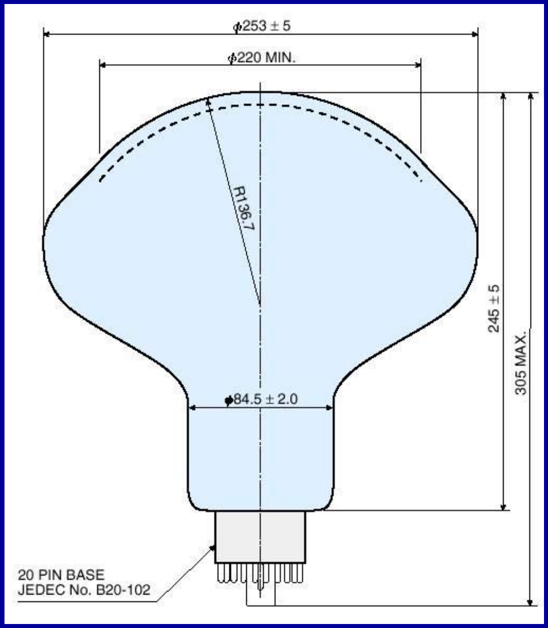
New parameter to evaluate PMT's quality - its ability to work at low thresholds.

Impressive improvements of conventional PMTs perfomance!

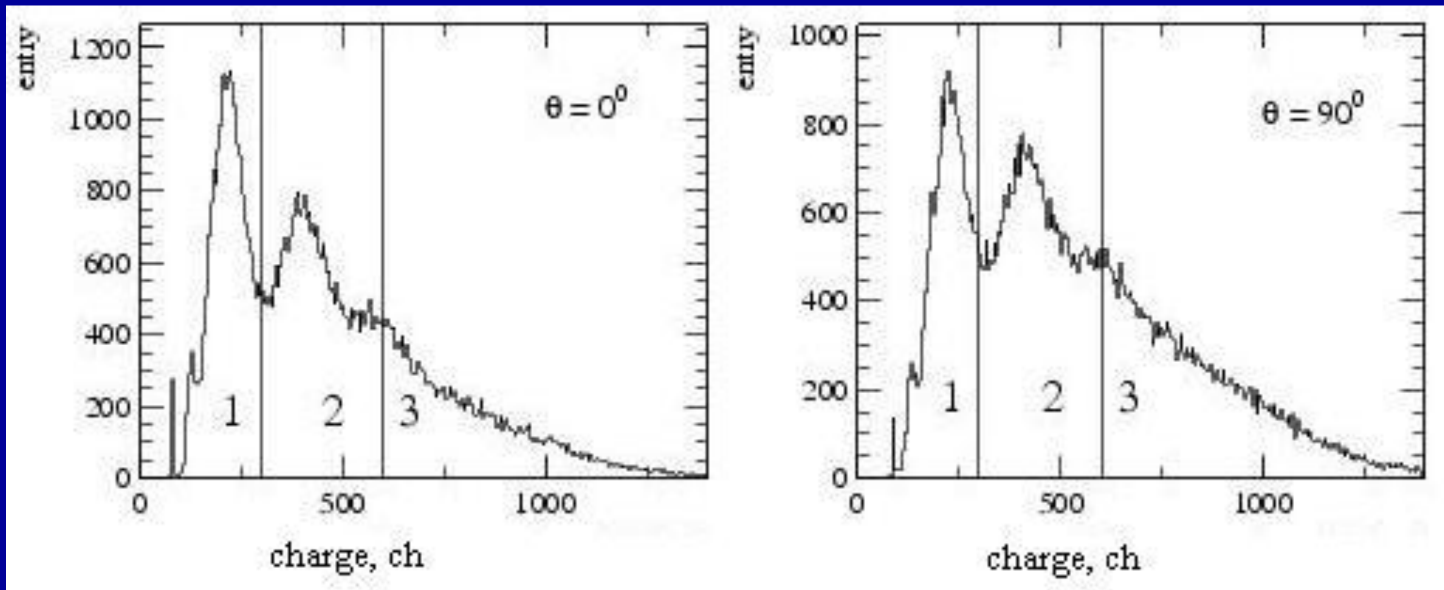
13" R8055 Hamamatsu and 12" XP1807 Photonis

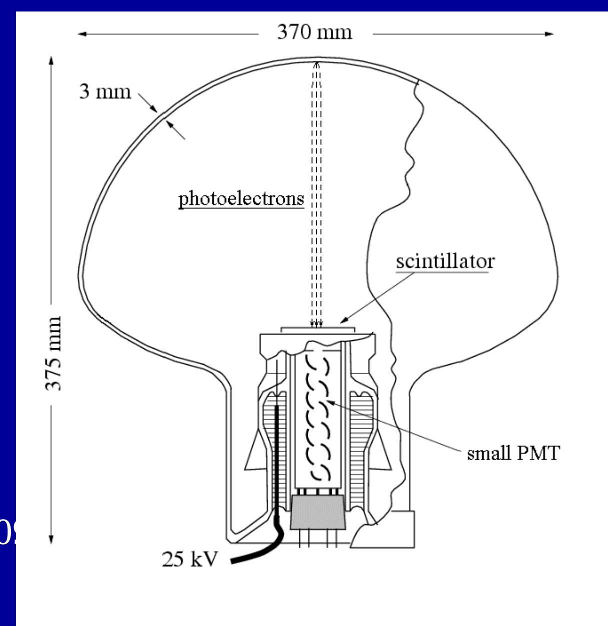
R7081 10” Hamamatsu



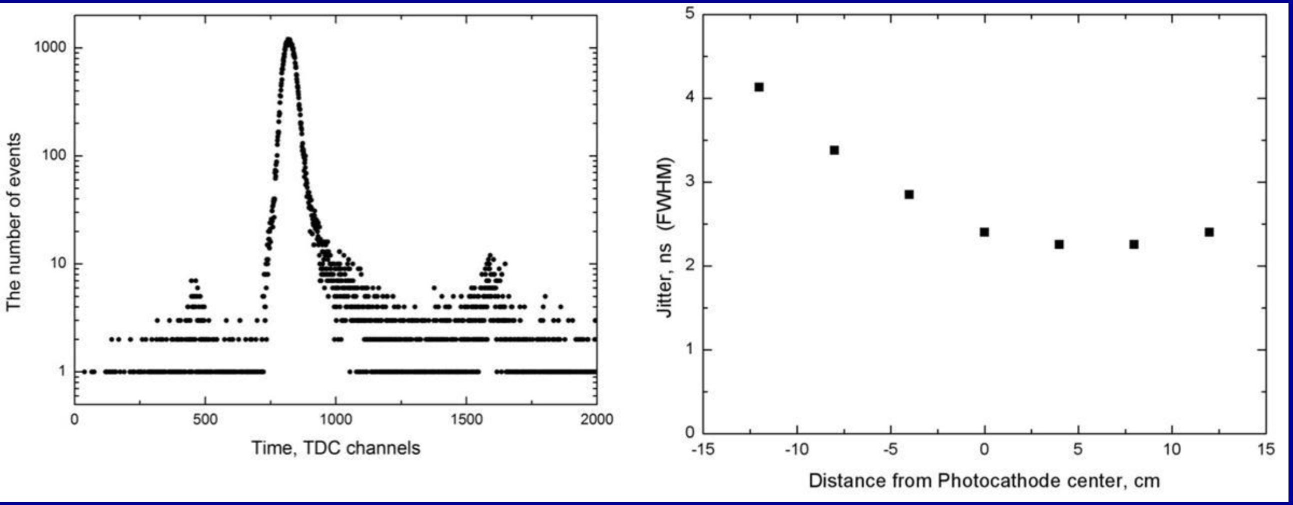


QUASAR-370Y

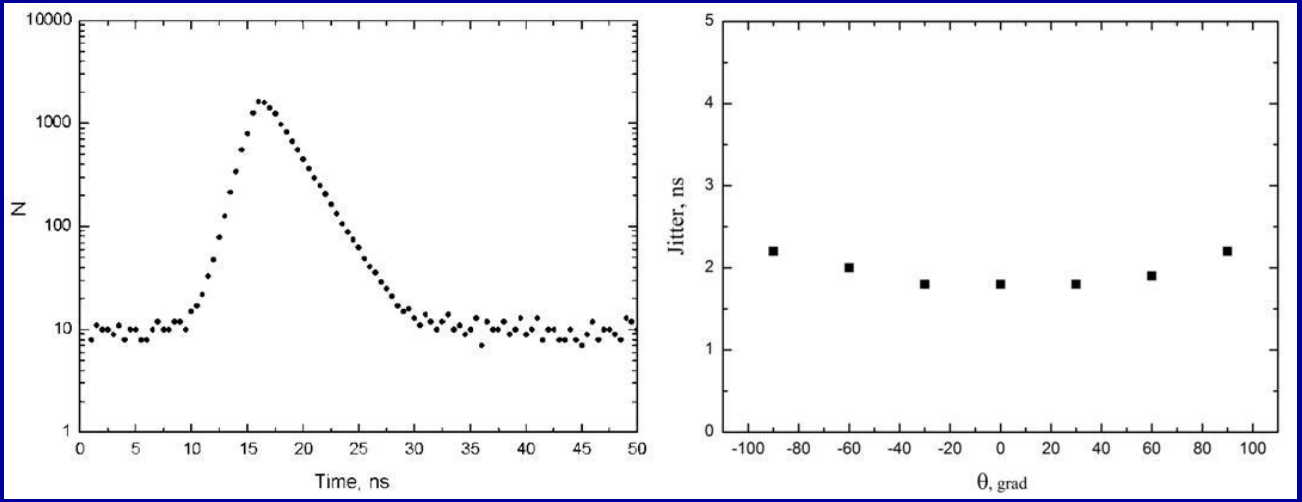

entry
1200
1000
800
600
400
200
0
0
500
1000
θ = 0⁰
1
2
3
charge, ch
entry
1000
800
600
400
200
0
0
500
1000
θ = 90⁰
1
2
3
charge, ch


370 mm
3 mm
photoelectrons
scintillator
375 mm
small PMT
25 kV

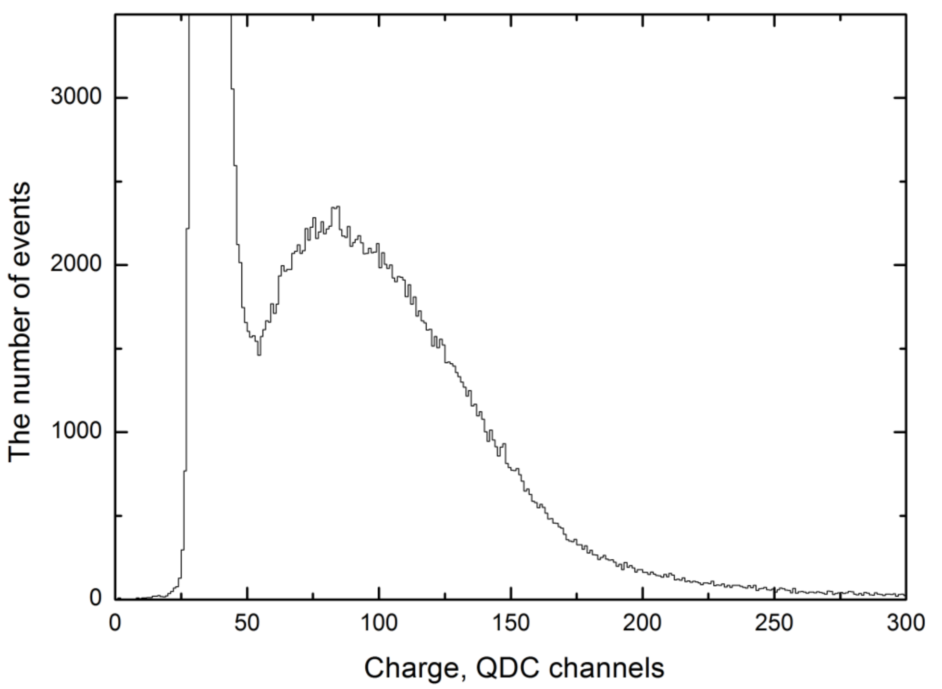
R7081

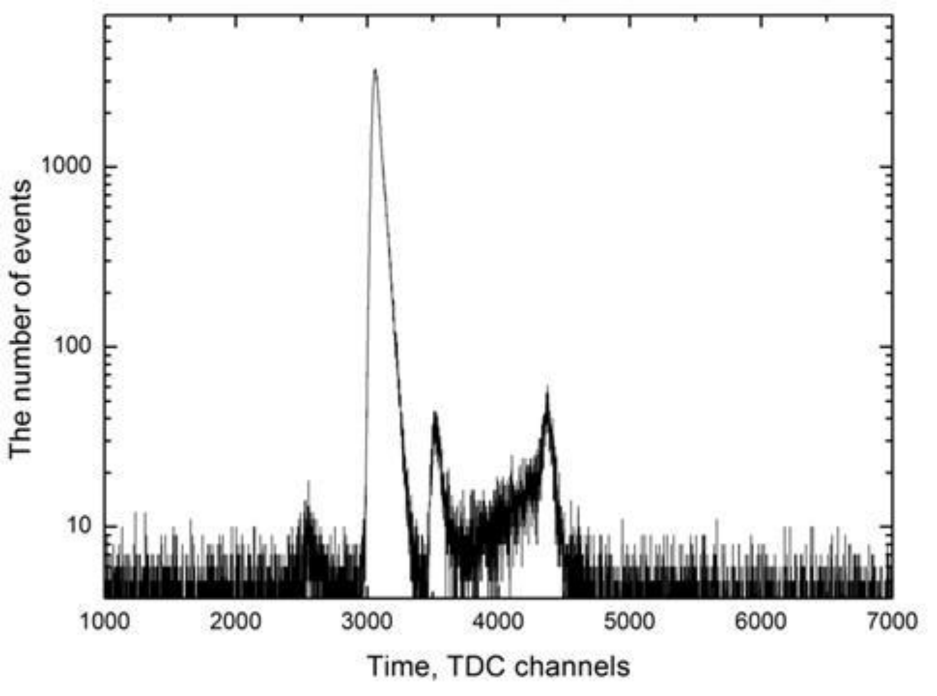


QUASAR-370Y



R3600-06 0,5 m cathode





Jitter - ~4,7 ns (FWHM); QE~23% at 400 nm

8-9 kHz noise (>0.1 pe)

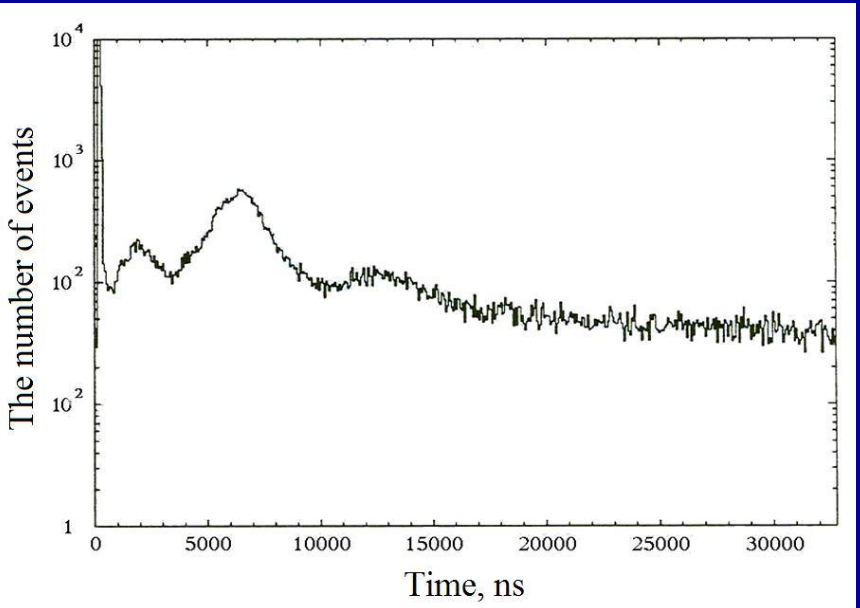
3 counts/cm^2 (20°C)!!!

<1 counts/cm^2 (0 °C)!!!

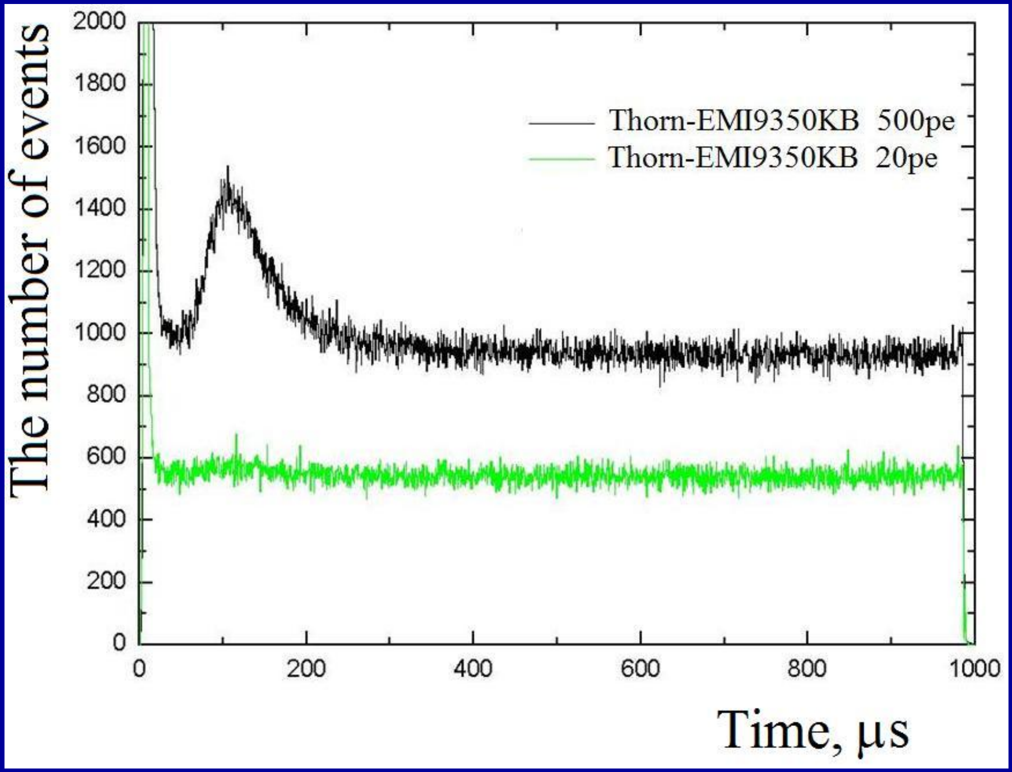
Afterpulses

Fast afterpulses – 300 ns; Long afterpulses – 300-15 μs

Long AP - 15 μs range



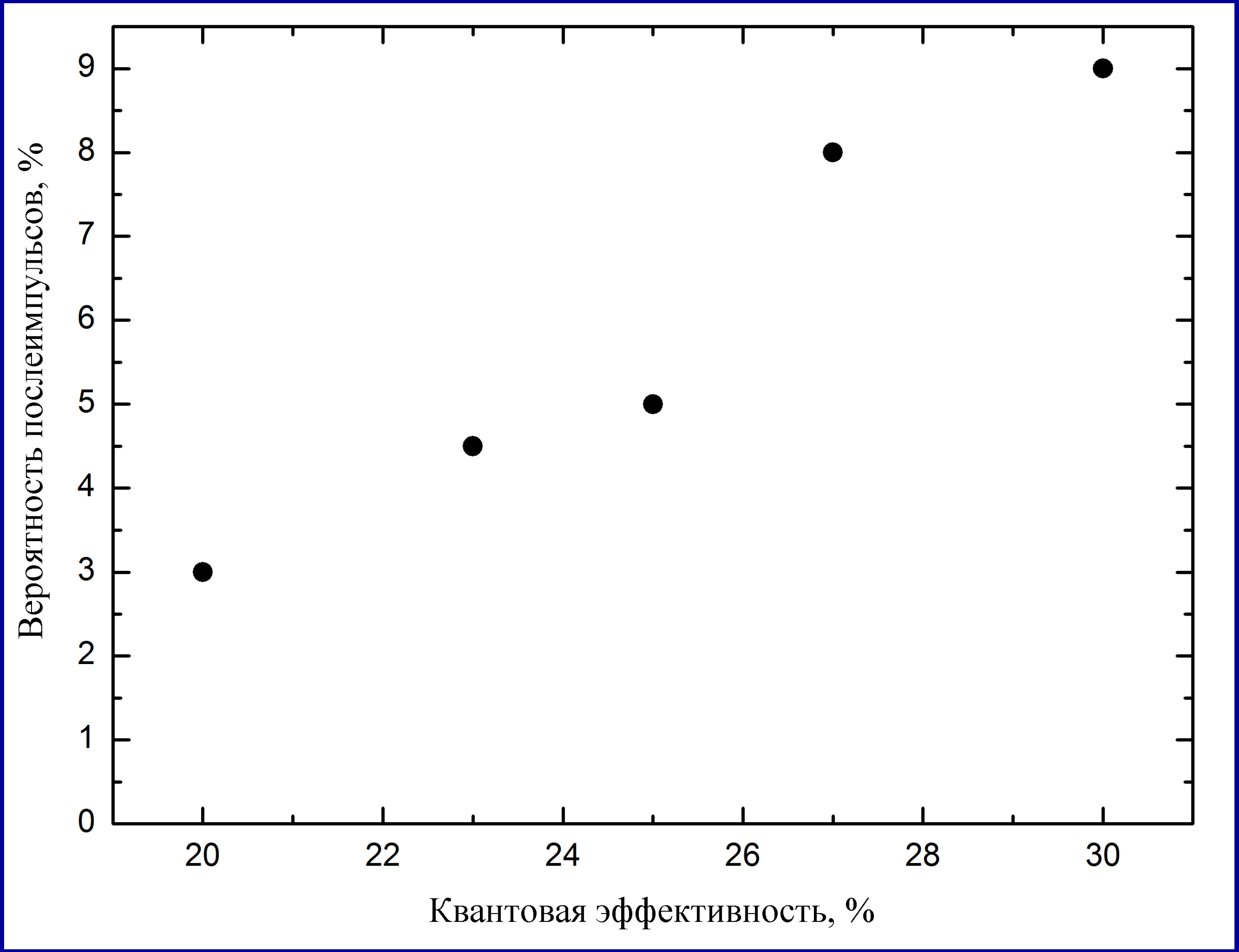
Extremely long AP 70-240 μs range!!!



Observed only in two samples of 8” PMTs (EMI and Photonis)

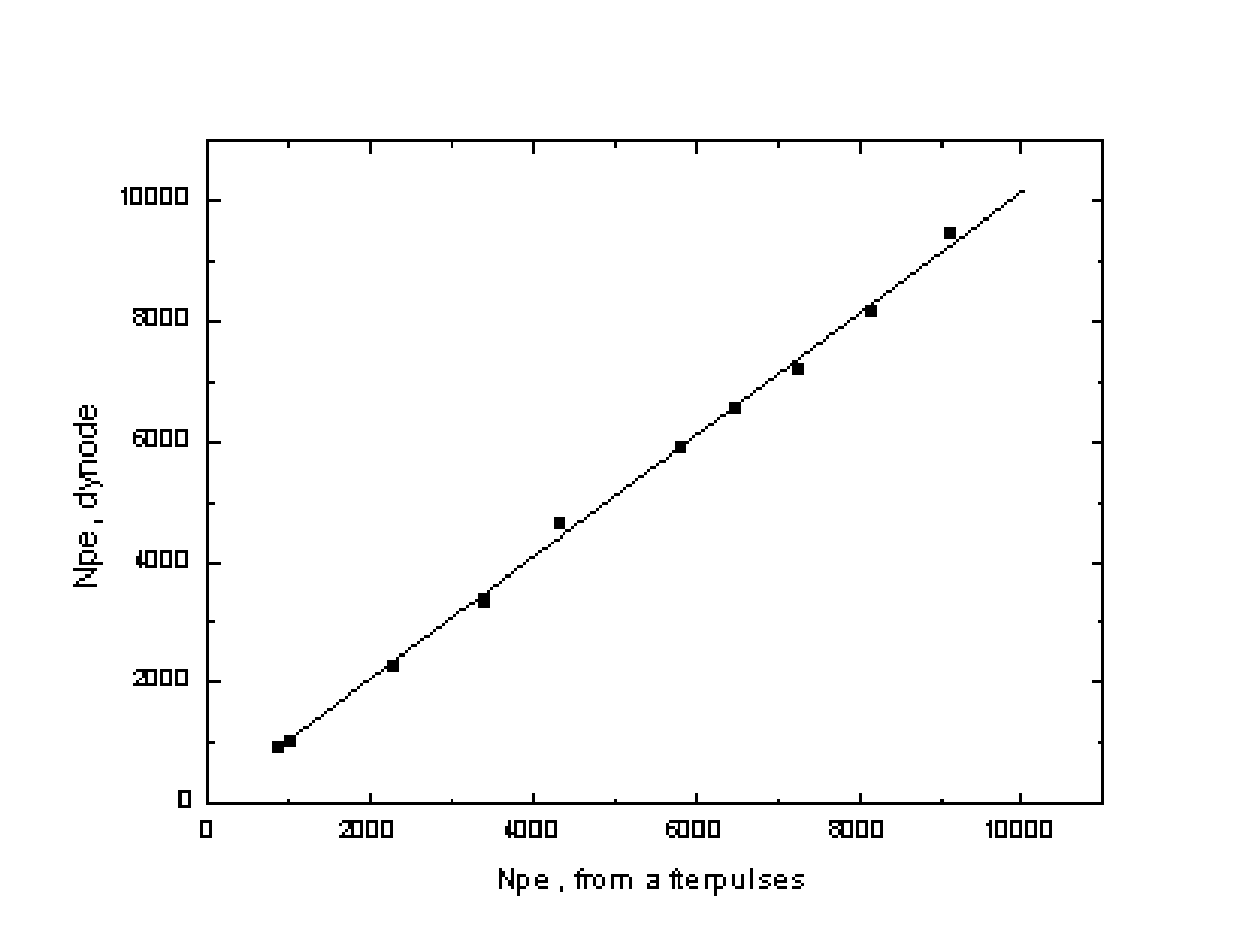
Lubsandorzhiev, Poleshchuk, Vasiliev 2005

Sensitivity – Afterpulses rate correlation



Lubsandorzhiev, Shaibonov, Vasiliev 2004
Dornic et al. 2005

Afterpulses rate – evaluation of N_{pe}



Lubsandorzhiev, Poleshchuk 2005

Hybrid phototubes with luminescent screen

A.E.Chudakov 1959 - hybrid tube with luminescent screen

Van Aller al, S-O. Flyckt et al. 1981 - prototypes of «smart tube»

Van Aller, S-O. Flyckt et al. 1981-1986 - XP2600

L.Bezrukov, B.Lubsandorzhiev et al. 1985-1986 - Quasar-300 and Quasar-350 tubes

L.Bezrukov, B.Lubsandorzhiev et al. 1987 - Tests of XP2600 and Quasar -300 tubes in Lake Baikal

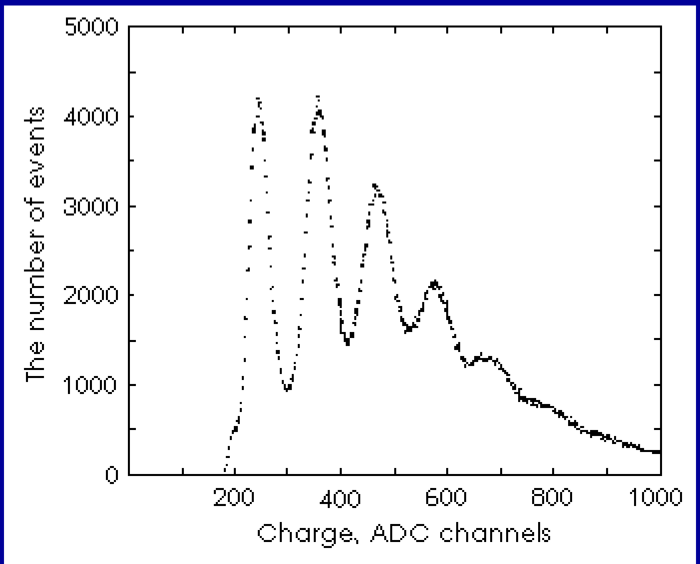
L.Bezrukov, B.Lubsandorzhiev et al. 1990 - Quasar-370 tube.

Hybrid phototube with luminescent screen

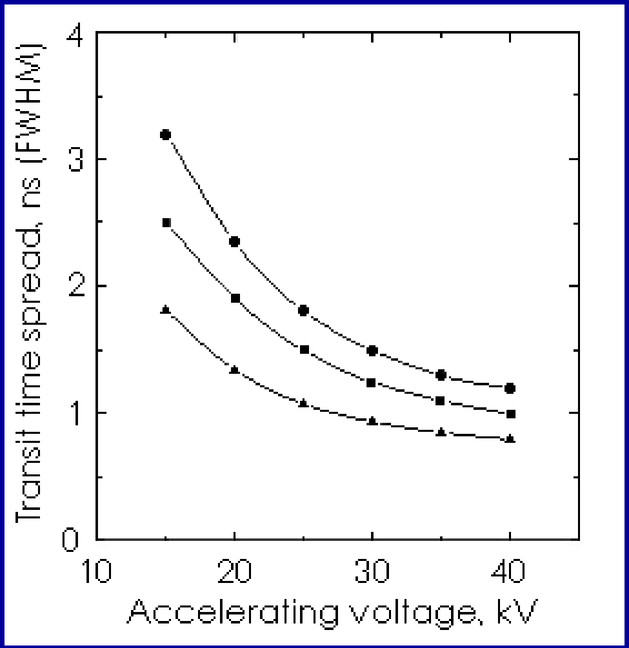
- Why luminescent screen?
- Luminescent screen - thin layer of scintillator (monocrystal or phosphor) covered by aluminum foil

- Light amplifier + small conventional type PMT

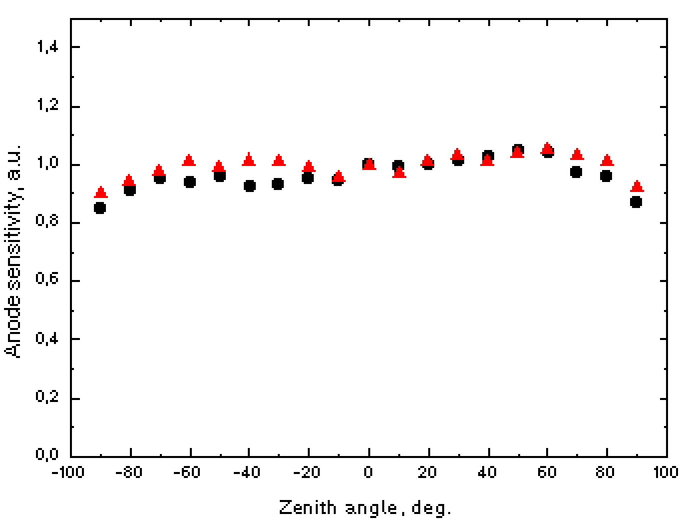
QUASAR-370



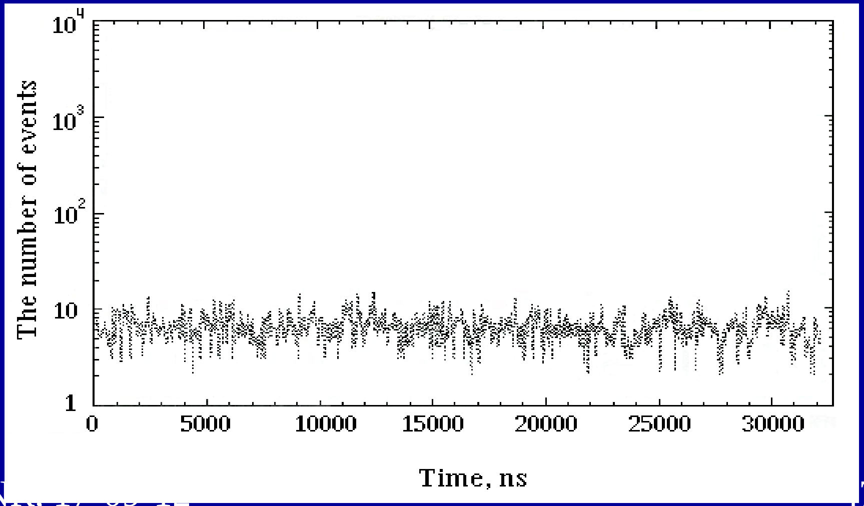
The number of events
Charge, ADC channels
0
1000
2000
3000
4000
5000
200
400
600
800
1000



Transit time spread, ns (FWHM)
Accelerating voltage, kV
0
1
2
3
4
10
20
30
40

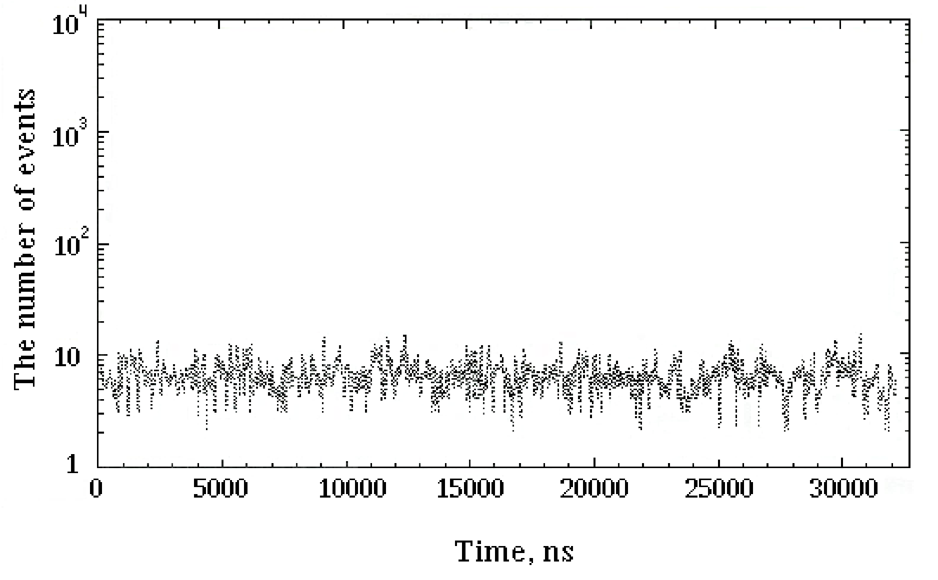


Anode sensitivity, a.u.
Zenith angle, deg.
0,0
0,2
0,4
0,6
0,8
1,0
1,2
1,4
-100
-80
-60
-40
-20
0
20
40
60
80
100

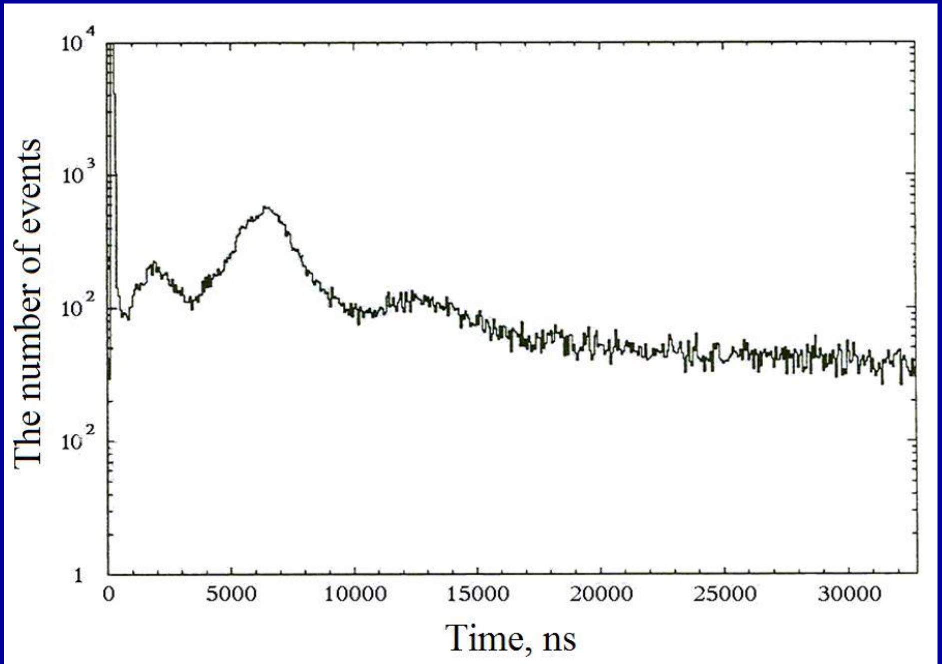


The number of events
Time, ns
1
10
10^2
10^3
10^4
0
5000
10000
15000
20000
25000
30000

Quasar-370 afterpulses - <1%

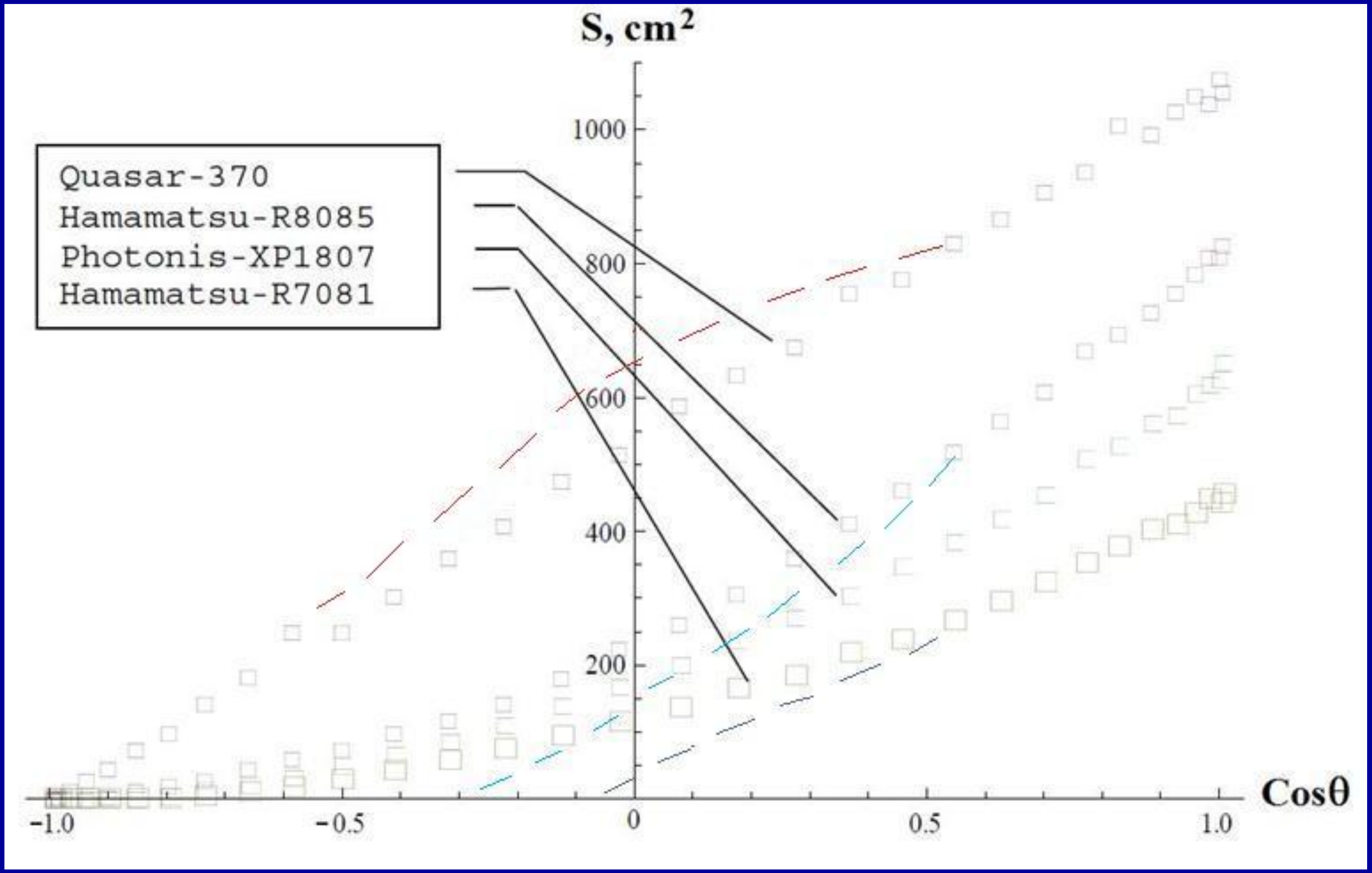


QUASAR-370



EMI9350KB

S_{geom} vs θ



S, cm2
1000
800
600
400
200
Quasar-370
Hamamatsu-R8085
Photonis-XP1807
Hamamatsu-R7081
-1.0
-0.5
0
0.5
1.0
Cosθ

QUASAR-370 modifications

QUASAR-370 modifications	Scintillator	SER(FWHM) %	TTS(FWHM) ns
QUASAR-370YSO	YSO (ph&mc)	70-80	1.8-2.2
QUASAR-370GSO	GSO (ph)	80-90	2.2-2.7
QUASAR-370YG	YSO+GSO (ph)	90	2.7-3.0
QUASAR-370LPO	LPO (mc)	70-80	1.8-2.2
QUASAR-370SBO	SBO (ph)	40-60	1.3-1.5
QUASAR-370YAP	YAP (mc)	40-60	1.3-1.5
QUASAR-370LSO	LSO (mc)	35	1

ph – phosphor; mc - monocrystal

Quasar-370 phototube has excellent time and very good single electron resolutions

- no prepulses
- no late pulses in TTS
- low level of afterpulses
- ~100% effective collection effiency
- 1 ns TTS (FWHM)
- very good SER (competitive to HPD)
- immunity to terrestrial magnetic field

  $>2\pi$ sensitivity

Effective QE

↕

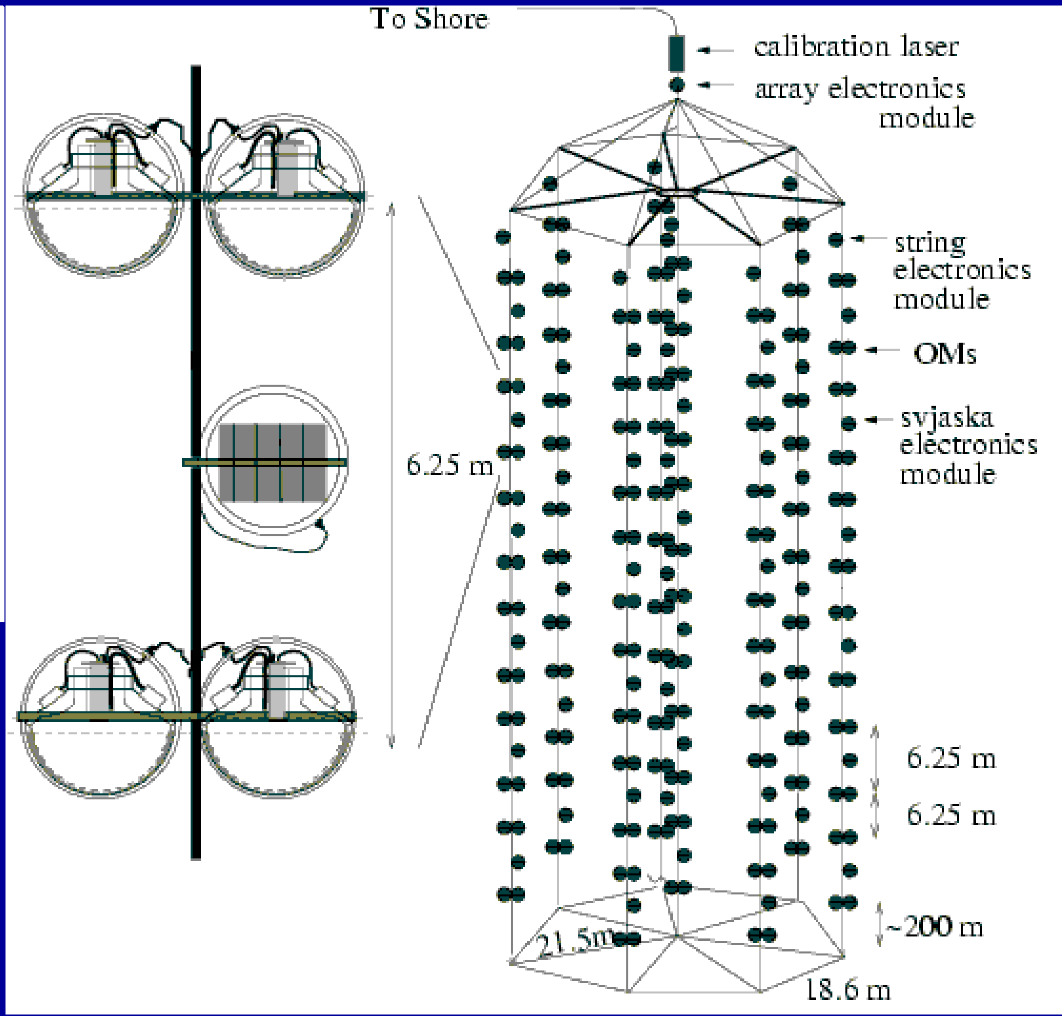
Collection efficiency

↕

Phototelectron backscattering

Afterpulses

QUASAR-370 in the Lake Baikal Neutrino Experiment



226 QUASAR-370 phototubes is operating in the Lake Baikal

many tubes have been operating since 1993

QUASARs on the lake Baikal ice

SMECA detector - Surface Mobile Eas Cherenkov Array

5 QUASAR-370G phototubes

Studies of the lake Baikal neutrino telescope angular resolution

SMECA joint operation with NT-200:
angular resolution of NT-200 - σ~4-5°

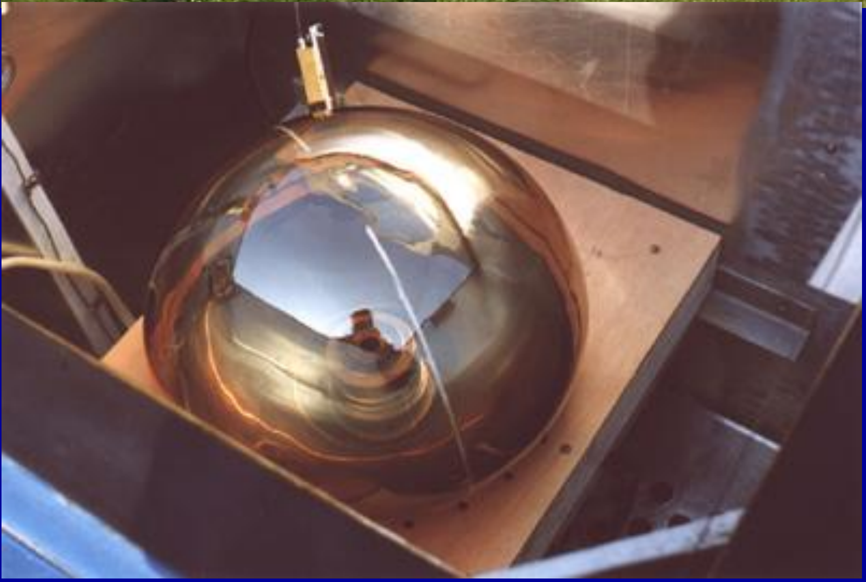
QUASARs in EAS-TOP EAS experiment in Campo Imperatore - QUEST detector (QUasars in Eas-Top)

5 QUASAR-370G phototubes in QUEST detector in frame of EAS-TOP experiment

So far the most precise studies of EAS Cherenkov light lateral distribution and primary cosmic rays absolute intensity around the “knee” ($\sim 3\times 10^{15}$ eV)

Many tanks to E.Lorenz for help with QUASAR-370G tubes for this detector

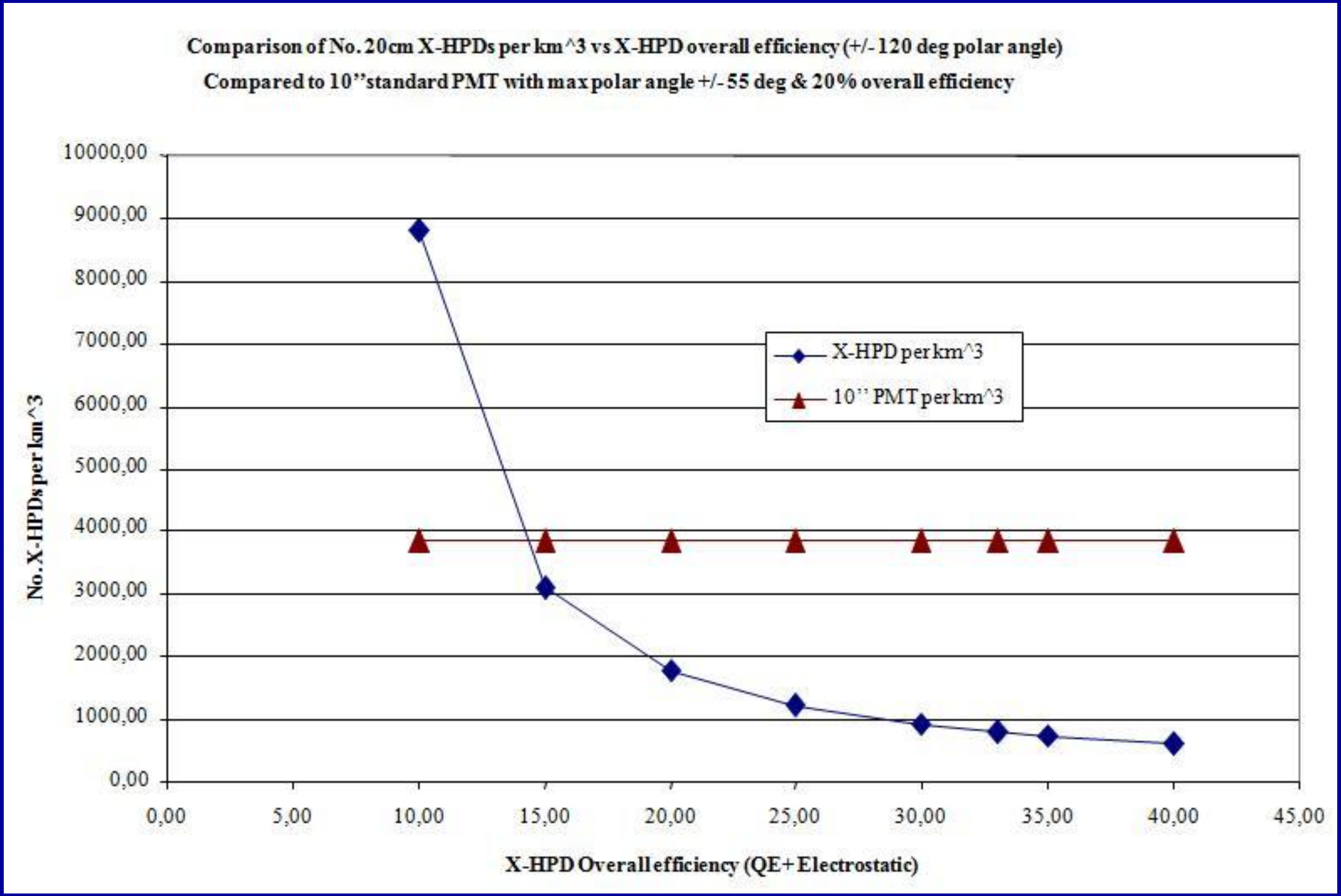
TUNKA EAS Cherenkov experiment in the Tunka Valley



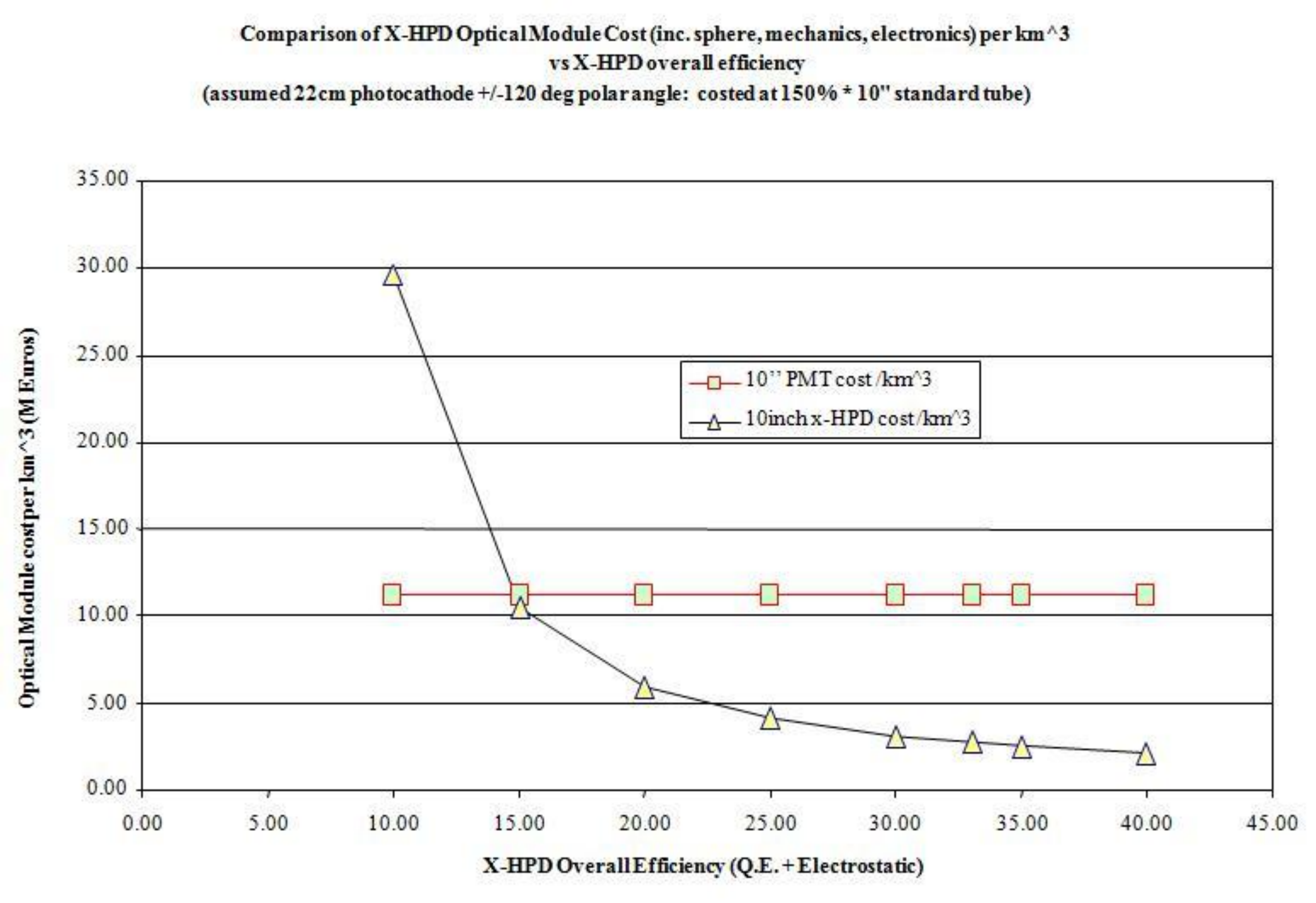
25 QUASAR-370G phototubes is currently operating.
Studies of primary cosmic rays energy spectrum and chemical composition around the «knee» region
The TUNKA experiment has been operating since 1993

Successful operations of several astroparticle physics experiments (BAIKAL, TUNKA, SMECA, QUEST) prove the phototube's high performances, high reliability and robustness.

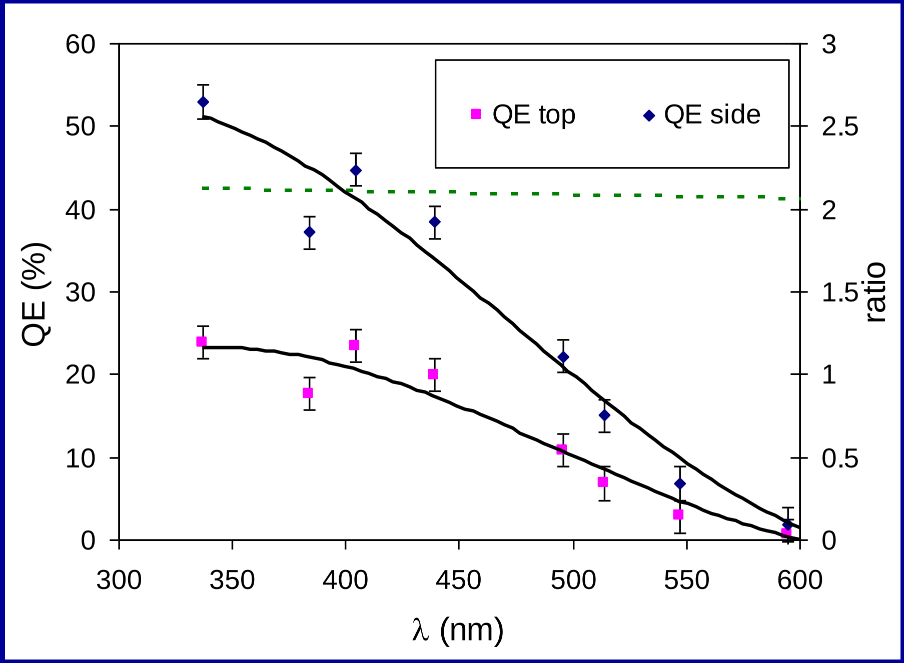
A number of modifications of the Quasar-370 phototube have been developed with different scintillators in its luminescent screen: YSO, YAP, SBO, LSO, LPO etc.



G. Hallewell, B.Lubsandorzhiev

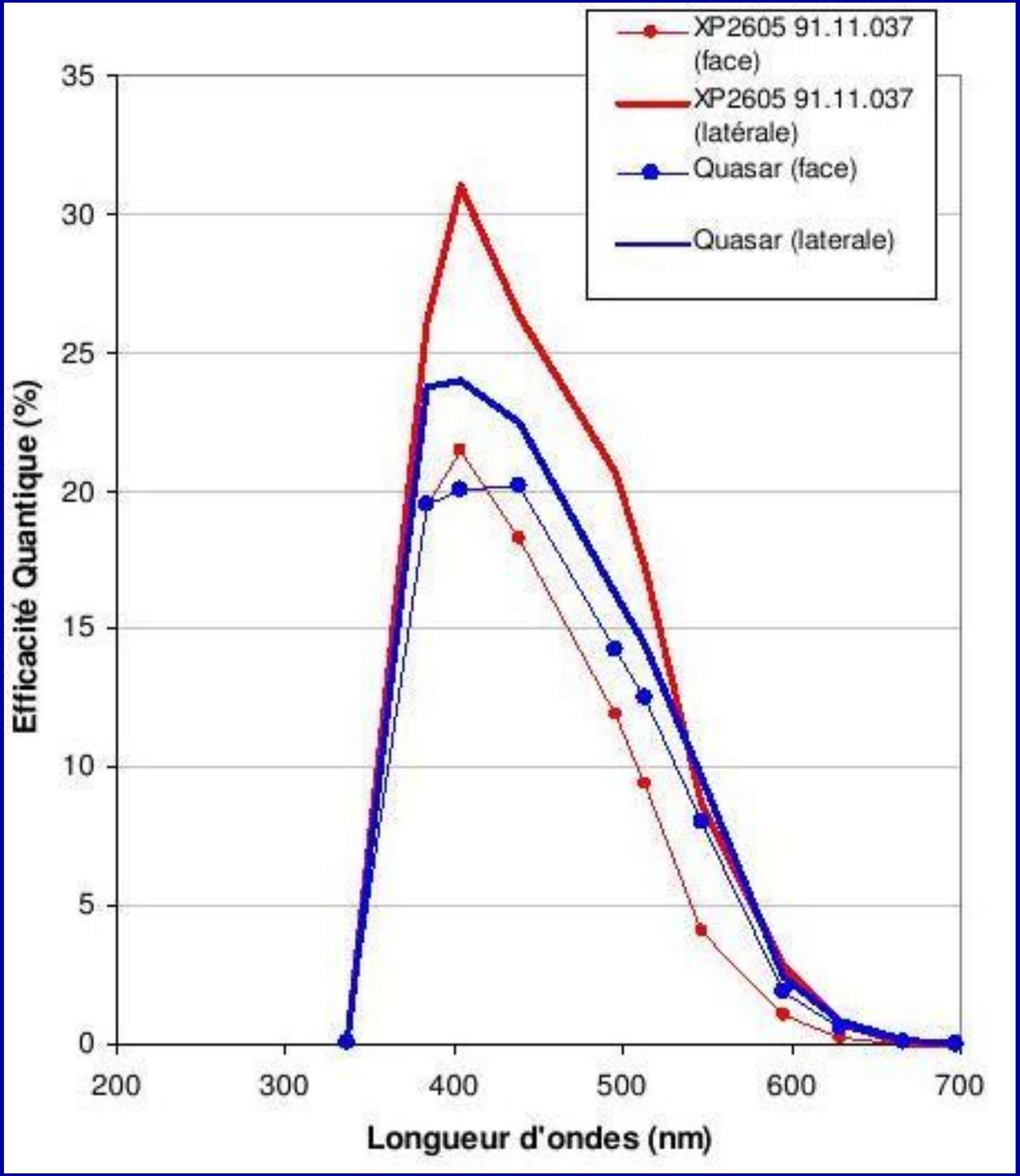


G. Hallewell, B.Lubsandorzhiev



A.Braem et al. NIMA 570 (2007) 467
Photonis measurements.
>50% QE due to double hitting!!!

1987-1991
XP2600 - 30-50% effect
Quasar-370 - 10-25%



XP2600 - ~50% effect

Quasar-370Y - ~ 20%

Hybrid tubes have record timing and excellent SER

BUT

There is one substantial drawback --- slow time response due to scintillator light emission kinetics

Solution ---- fast high efficiency scintillators

Requirements for scintillators:

- high light yield
- fast emission kinetics
- vacuum compatibility
- compatibility with phocathode manufacturing procedure: high temperature, aggressive chemical environment etc.

Scintillators have to be:

Inorganic

Nonhygroscopic

Time resolution of hybrid phototubes and scintillator parameters

$W(t) \sim \exp(-(G/\tau)t)$

G - the first stage amplification factor

$G = n_{p.e.} / N_{p.e.}$

$n_{p.e.}$ - # of p.e. detected by small PMT; $N_{p.e.}$ - # of p.e. on the phototube cathode

$G \sim Y(E_e)$

Y - scintillator light yield

τ - scintillator decay time

Scintillator should have Y/τ as high as possible

Figure of merits - F

$$F_1 = (Y/\tau)\times a$$

$$F_2 = (Y/\tau)\times a\times b$$

Y - light yield, τ - decay time,

a - detectibility by small PMT or SiPM

b - compatibility with photocathode manufacturing

	YSO	YAP	SBO	LSO	LS	Bril350	Bril380
F_1	1	1.3	1.3	1.8	4*	4.6	6.4
F_2	1	1.3	1.3	1.8	4*	0?	0?

* - using a photodetector with A3B5 photocathode

ZnO:Ga

F1 = F2 = 250!

Challenge:

- the material should be extremelly pure
- problems with monocrystal growth but phosphor will be O'K for luminescent screen

ZnO:Ga

Luckey D., 1968 NIM
Light yield = NaI(Tl); Decay time - 0.4 ns!

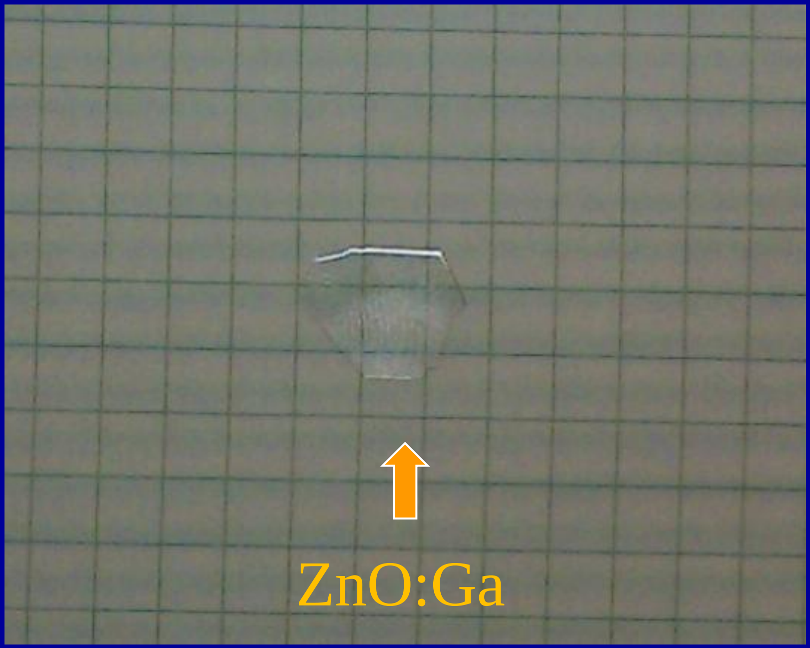
W.Moses. NIMA (LBNL-50252)
Light yield - 15000 γ/MeV; Decay time - 0.4 ns.

Hypothetical hybrid tube with ZnO:Ga and high QE fast small PMT would be a fantastic photodetector with <1ns jitter (FWHM) and <1ns anode pulse width!

"ZnO:Ga – ideal scintillator for hybrid tubes"

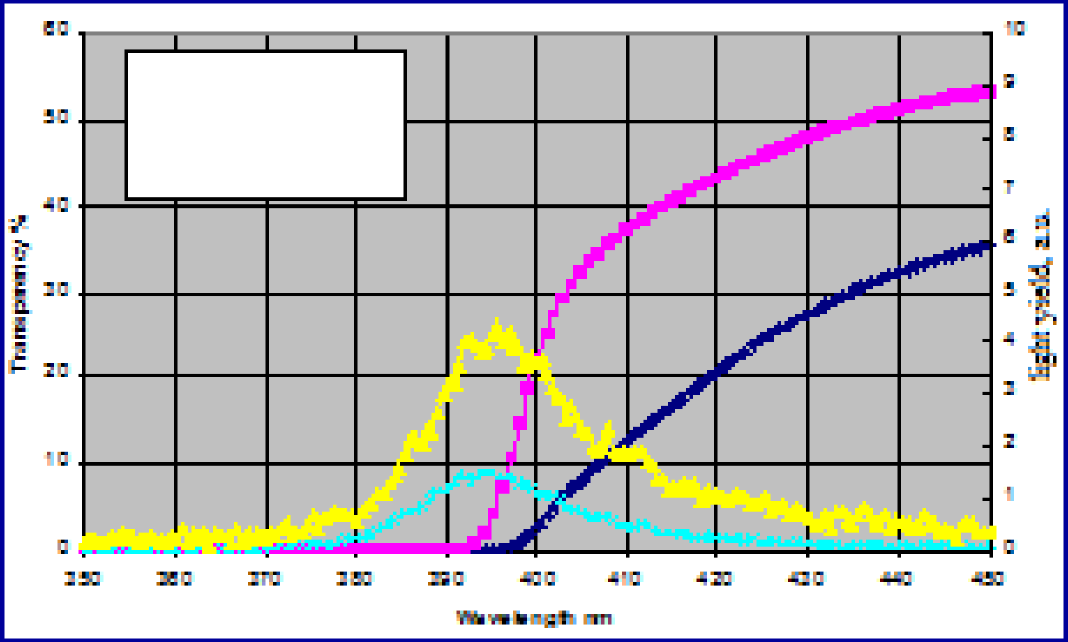
B.Lubsandorzhiev and B.Combettes TNS 2008

ZnO:Ga crystals from Cermet Inc. Atlanta, GA, USA



~300 μ thickness

~1cm^2 area



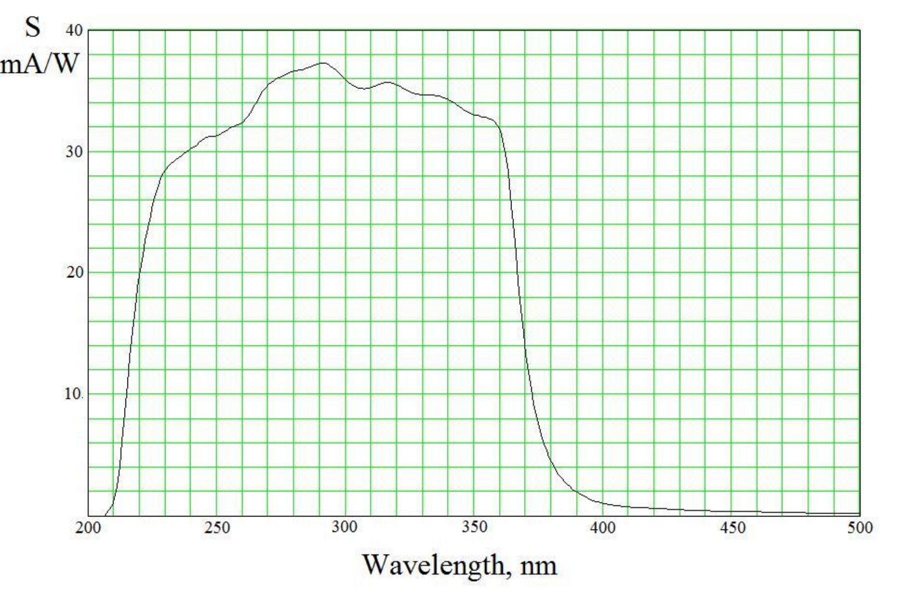
λ_{max} ~ 390 nm

Light yield ~ 1200 γ/MeV

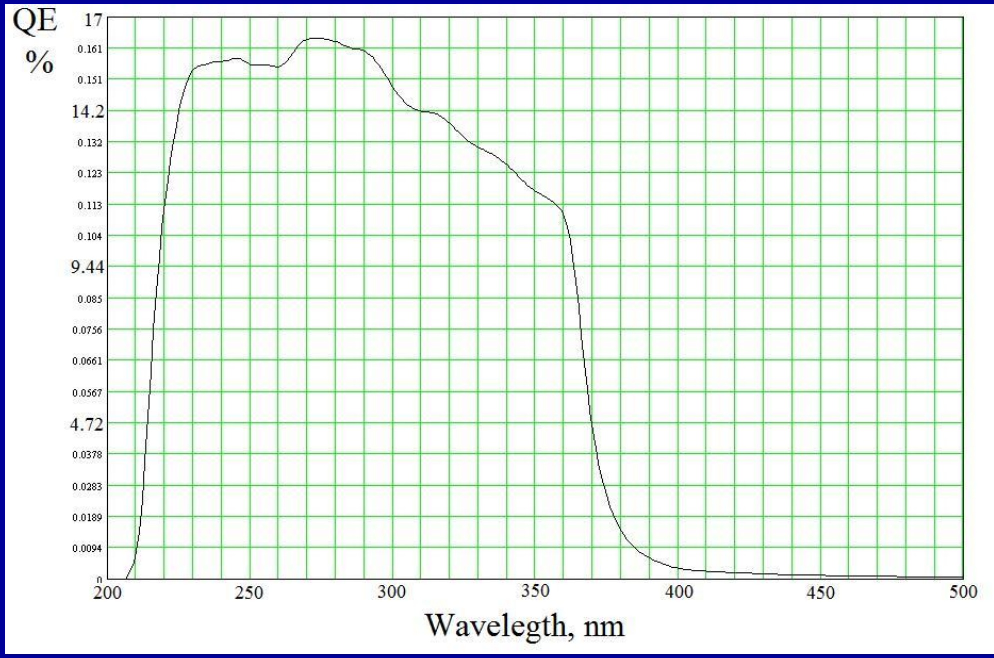
Pilot sample of HPD with ZnO:Ga crystal based on image intensifier

B.Lubsandorzhiev, L.Balyasny, S.Belyanchenko et al. 2011.

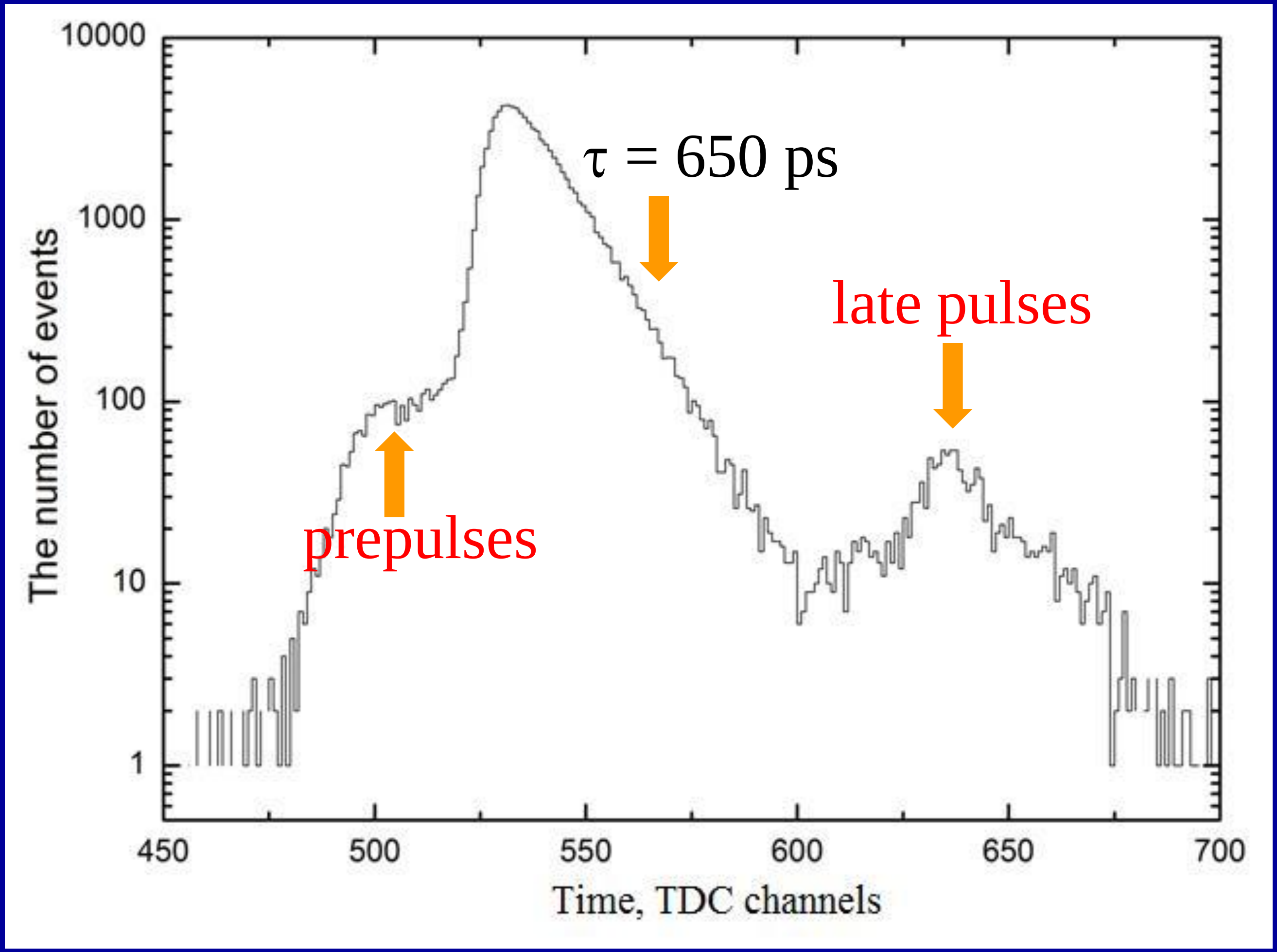
Pilot sample's GaN photocathode sensitivity



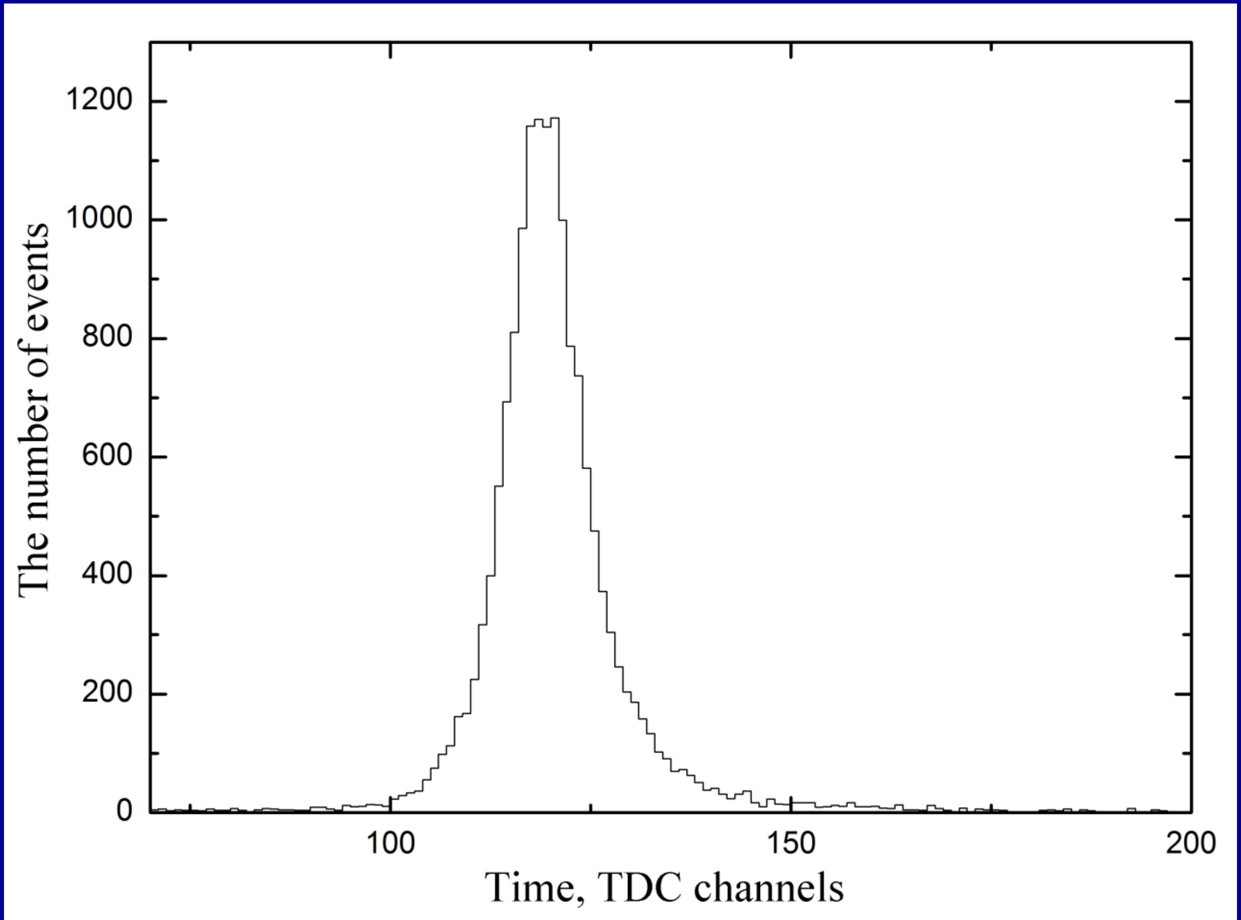
QE ~ 17%



τ~ 650 ps, light yield ~ 1200 γ/MeV

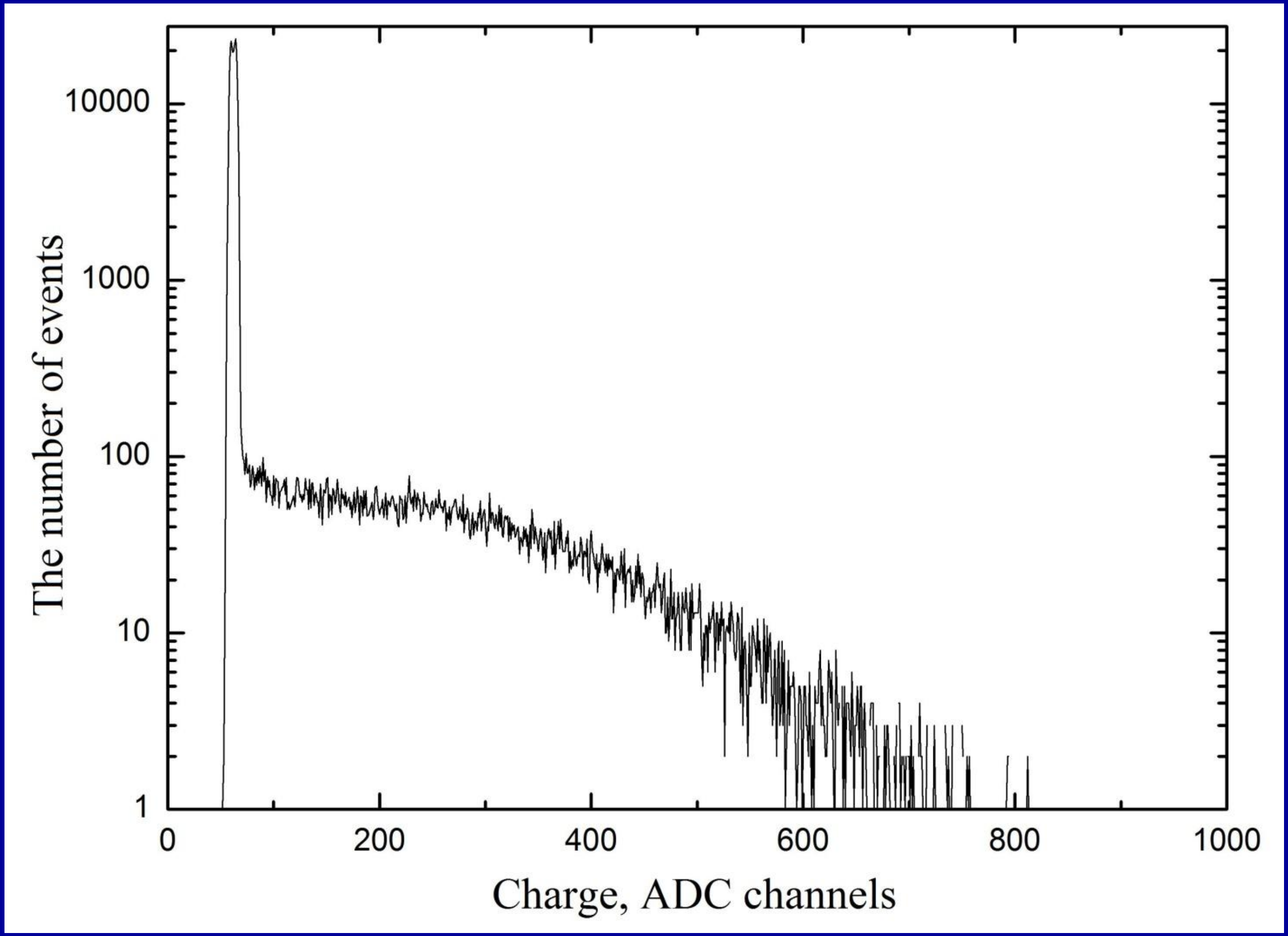


Jitter (TTS)



Δt_{hpd} ~ 750 ps (FWHM); Δt_{LED} ~ 700 ps

Single electron response



Practically no single pe peak

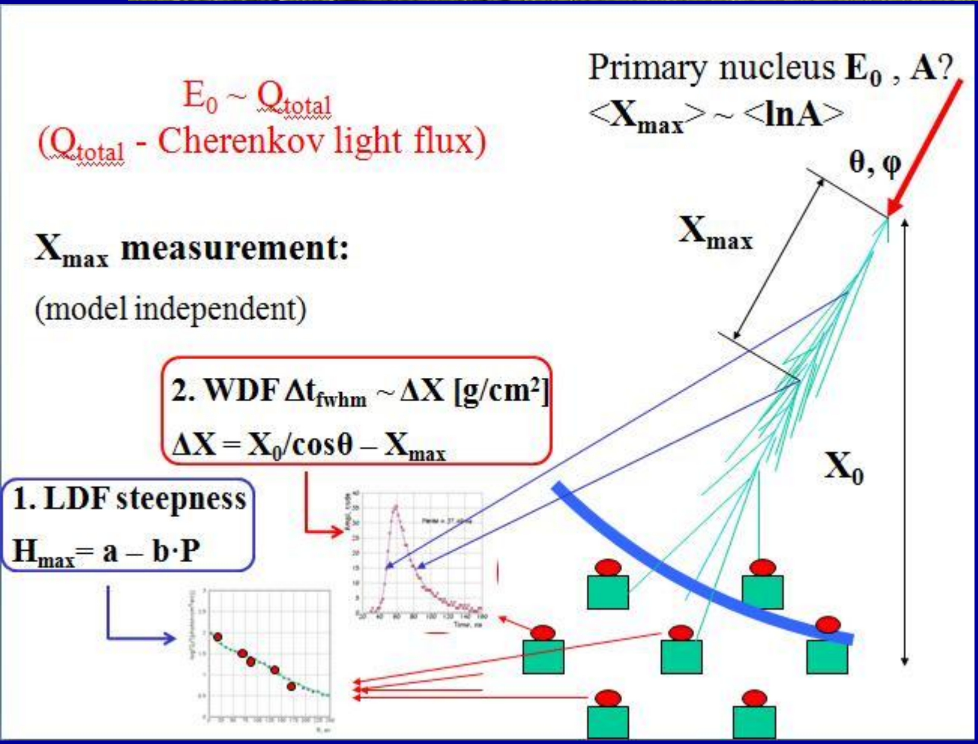
There is at least one application for which hybrid tubes equipped with the ZnO:Ga crystals with the light yield even at present level are very interesting

↓

Wide angle EAS Cherenkov Arrays

(TUNKA, SCORE, LHAASO, Auger-Next etc)

TUNKA EAS Cherenkov experiment



Primary cosmic rays studies in the energy range of 10^{15}-10^{18} eV

Width of EAS Cherenkov signals is sensitive to the mass composition of primary cosmic rays

No need to operate in 1 pe mode (threshold ≥ 100 pe)

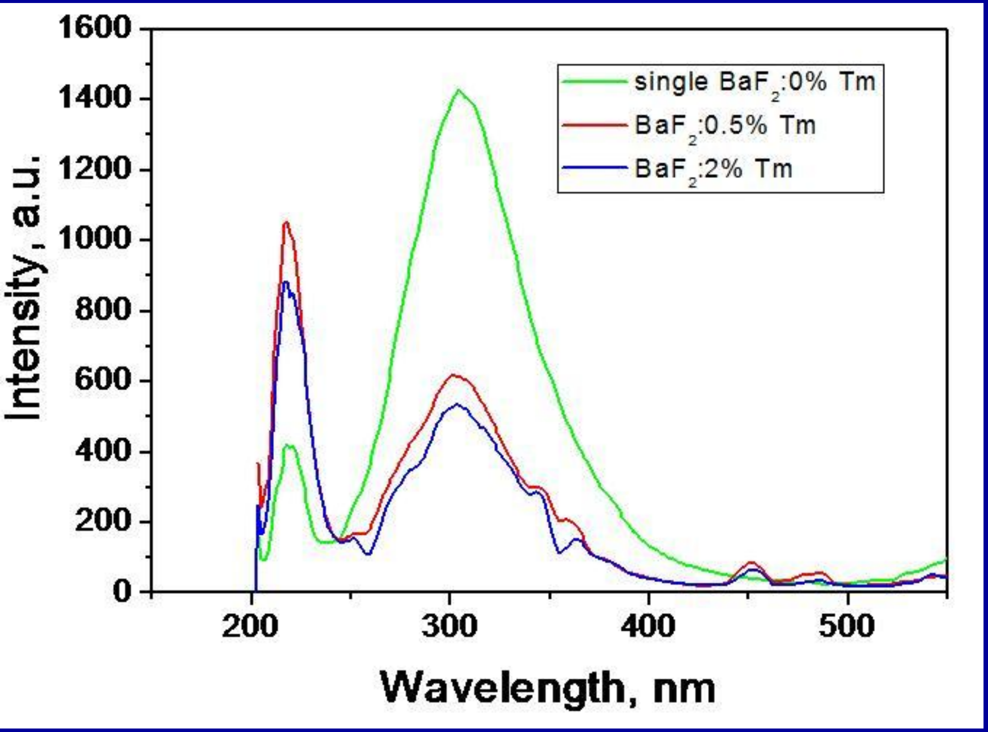
D.M.Seliverstov et al.

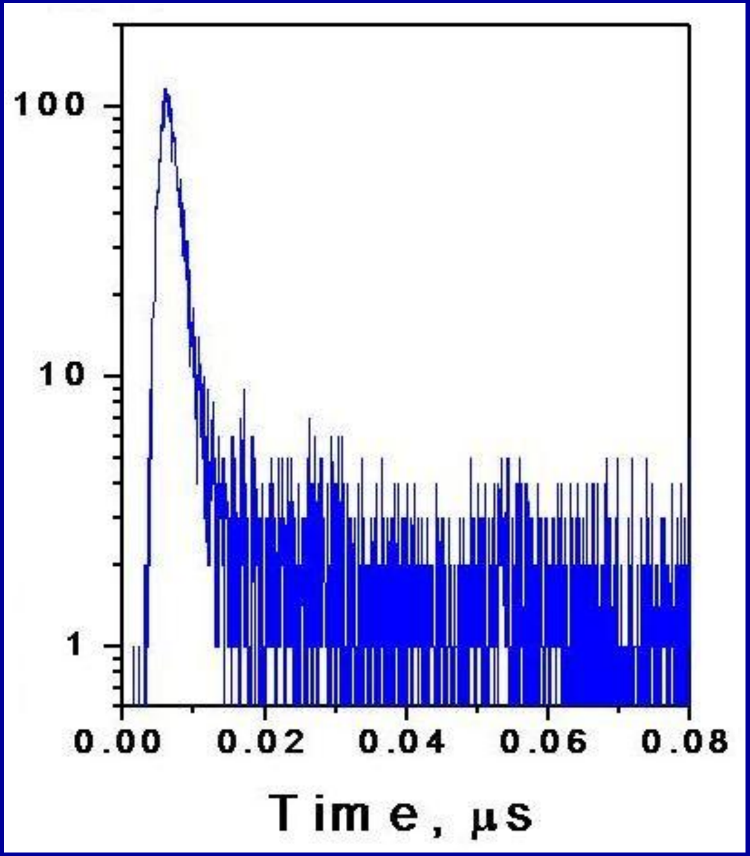
BaF_2:Tm - $\tau \sim 0.9$ ns; slow component is suppressed!
Light yield – 4000-6000 γ/MeV

N.Surin et al.

Metal-organic scintillators – a few ns decay time;
light yield – ~10 000 γ/MeV
Vacuum compatible!
Temperature?

BaF_2:Tm

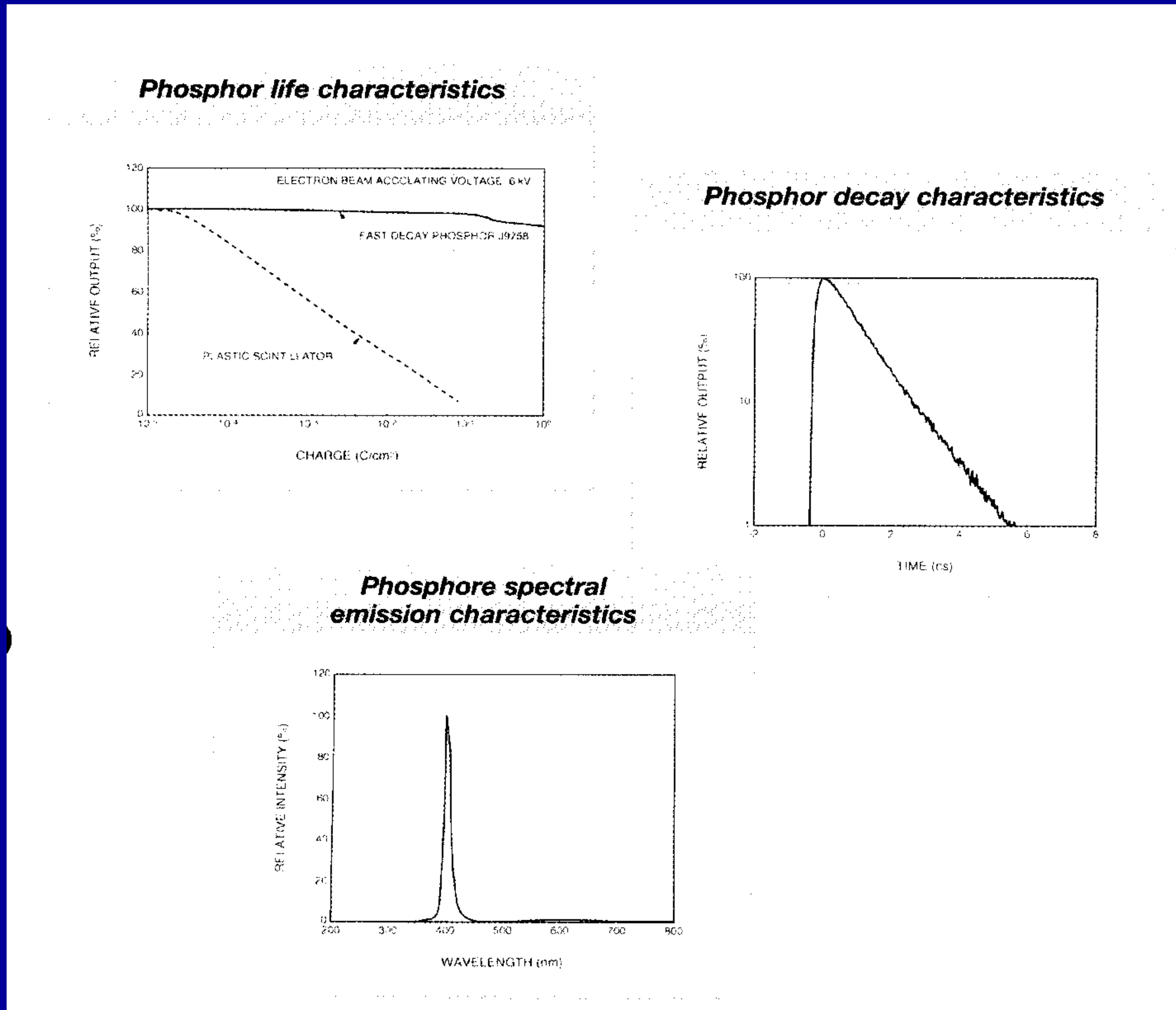




LY ~ 4000 γ/MeV

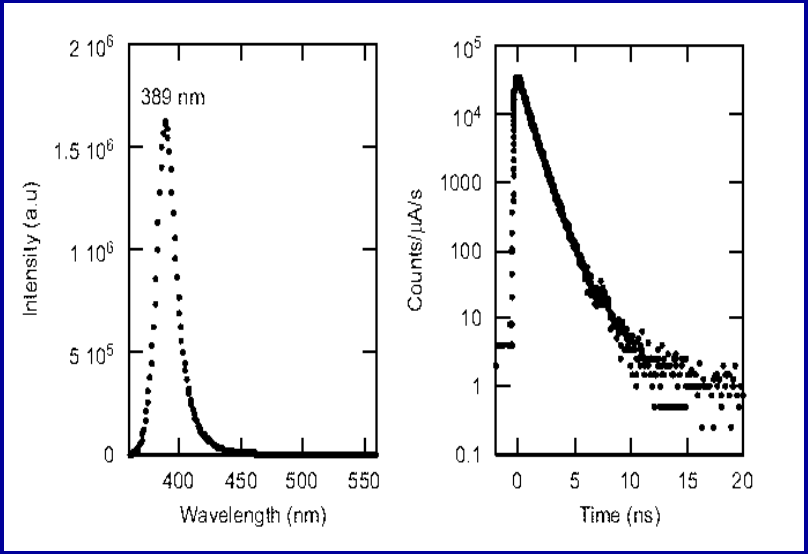
τ ~ 0.9 ns

Hamamatsu J9758 phosphor, τ~1ns, Y ~3 Y(YAP)

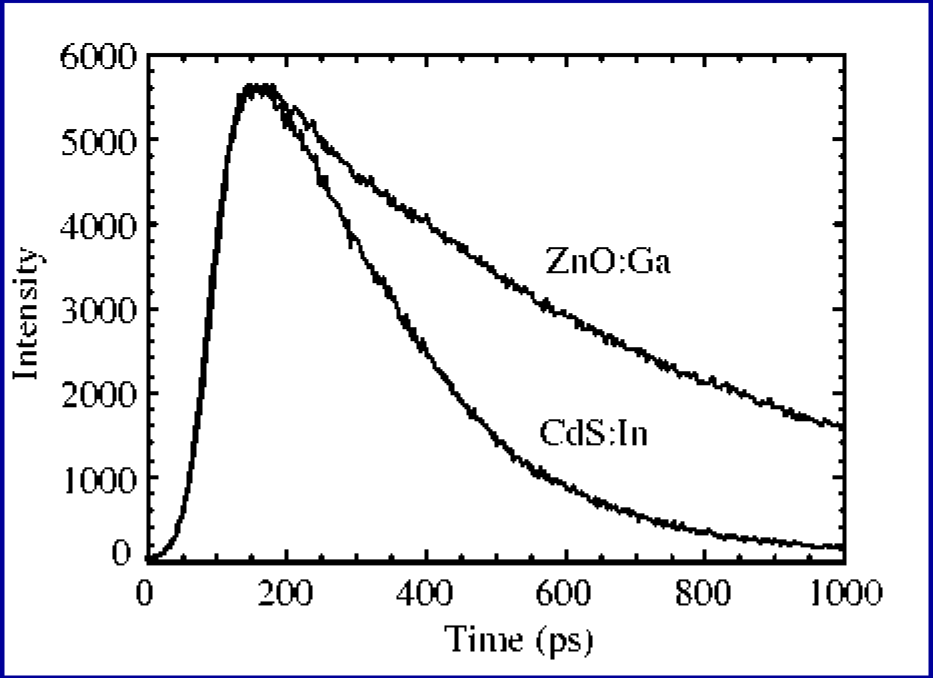


InGaN or GaN scintillators?!

Expected to be very fast and very effective!



Light yield - 15000 photons/MeV
Decay time - 0.4 ns!



E.D.Bourret-Courchesne et al. NIMA

W.Moses. NIMA (LBNL-50252)

- Luminescent screen (new scintillators, not only crystals but phosphors too!)
- HV compound (like foam p-urethane)
- HV power supply
- HV connectors (no connectors, HV fully integrated into phototubes optical preamplifier, only low DC voltage input!? (like Hamamatsu's small PMT modules)
- Photocathode
- We need 21st century technology

What is the ideal photodetector for the next generation neutrino telescopes?

Spherical (up to 50 cm dia) with $>2\pi$ angular acceptance

High sensitivity in a wider region than conventional bialkali cathode

High effective quantum efficiency - good SER

Time resolution - better than ~3 ns (fwhm)

no prepulses, low level of late pulses and afterpulses

The only way to fulfill all such requirements is a new generation of Hybrid Phototubes with luminescent screen

Quasar-370 and XP2600 are very close to the ideal photodetector

Anyway they are very good prototypes of the ideal photodetector for the next generation of neutrino telescopes and/or other giant neutrino projects like LENA, Hyper-Kamiokande, etc.

There are two good options for large are photodetectors for next generation astroparticle physics experiments –
Classical vacuum PMTs and Hybrid Phototubes.

Good news are coming for hybrid phototubes develeopment:
new fast high efficiency scintillators.

ZnO:Ga is a very promising scintillator for hybrid phototubes with luminescent screens.

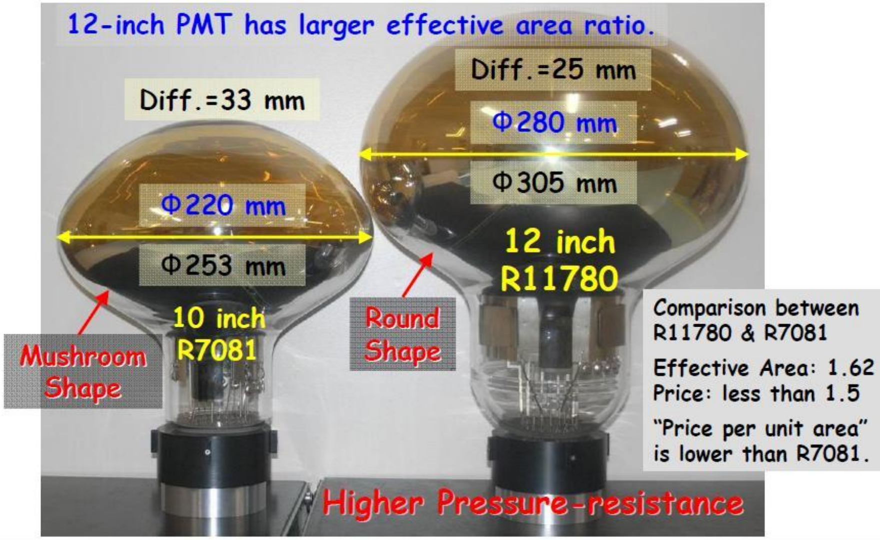
It is necessary to increase the light yield of the crystals.

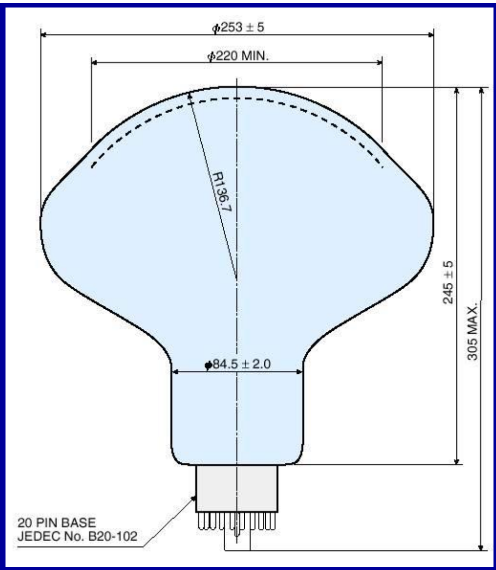
Search for new fast scintillator materials of high efficiency should be continued. Fast “new” BaF2 and metal-organic scintillators are promising.

New 12” Hamamatsu PMT

Comparison of Dimension between R11780 (12”) and R7081 (10”)

HAMAMATSU





Comparison of Characteristics

HAMAMATSU

Items	R11780 12-inch PMT	R7081 10-inch PMT
Diameter	305 mm	253 mm
Effective Area	280 mm min.	220 mm min.
Effective Area Ratio	84.3%	74.6%
Tube Length	385 mm	300 mm
Dynodes	LF/10-stage	LF/10-stage
GAIN	1.0E+07 at2000V	1.0E+07 at 1500V
T.T.S. (FWHM)	2.7 ns	2.9(3.4) ns
P/V Ratio	3.0	2.5(2.8)
Dark Counts	10,000 cps	7,000 cps

ET Enterprises electron tubes

Large diameter pmt range

Parameter	9372	9350	9352	9354	9357	*D784*
Diameter (in)	5	8	8	8	8	11
No. of stages	6	14	6	12	12	12
Typical operating gain	10^7	10^8	10^4	10^7	10^7	10^7
Typical QE% at peak	28	30	30	30	18	30
Surface area (cm^2)	160	425	425	425	425	*800*
Typical dark cps at 20C	1500	4000	-	4000	4000	*8000*
Typical SER ratio	1.5	1.5	-	2	2	*2*
Typical 1e TTJ fwhm(ns)	2.7	8	-	2.7	2.7	*3*
Minimum Temperature	-30C	-30C	-30C	-30C	-196C	*-30C*
Weight (grams)	380	700	700	700	700	*2000*

LIGHT11 – 01Nov2011

ADIT Electron Tubes

New ET 11” PMT

under development

ET Enterprises electron tubes

Large diameter hemispherical pmts

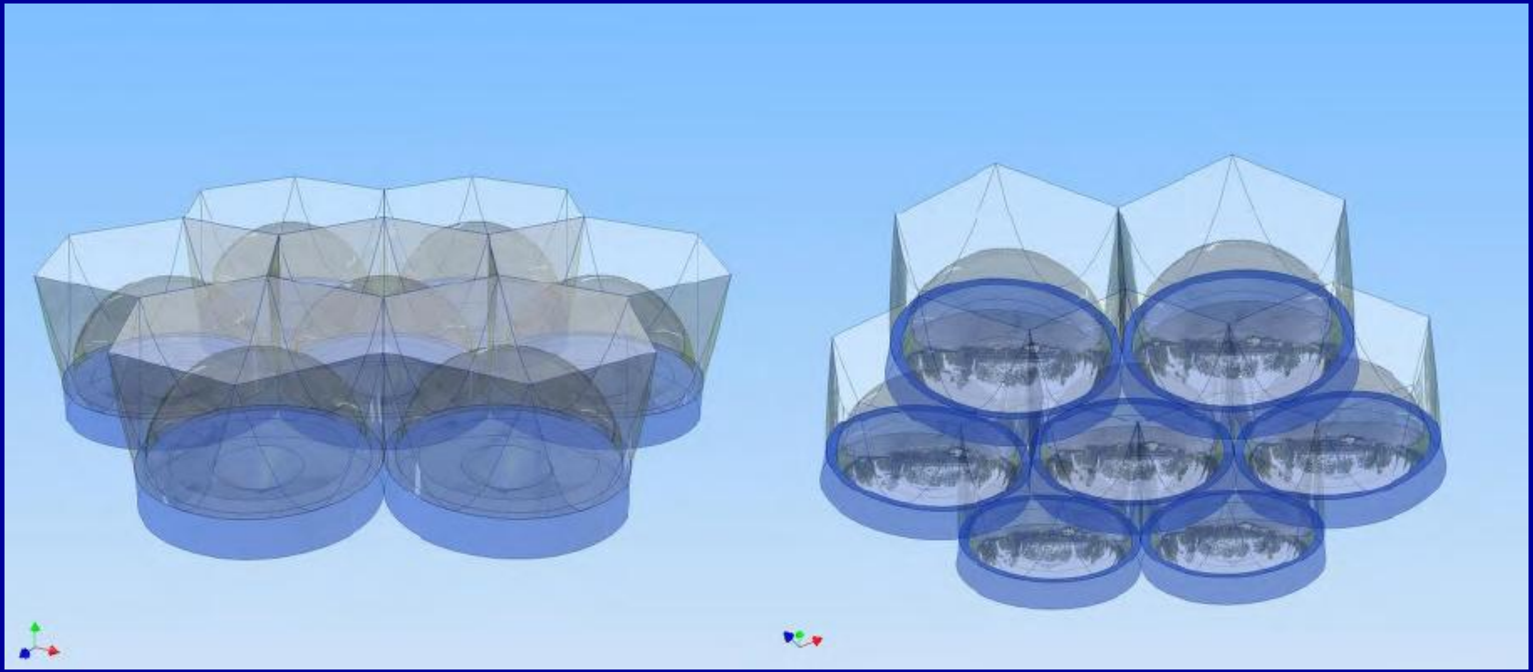
Design specifications:

- External water pressure of 11 bar
- Long life in pure water
- Glass with low content of radioactive isotopes
- Design for good photoelectron collection
- Design for good timing (TTJ)

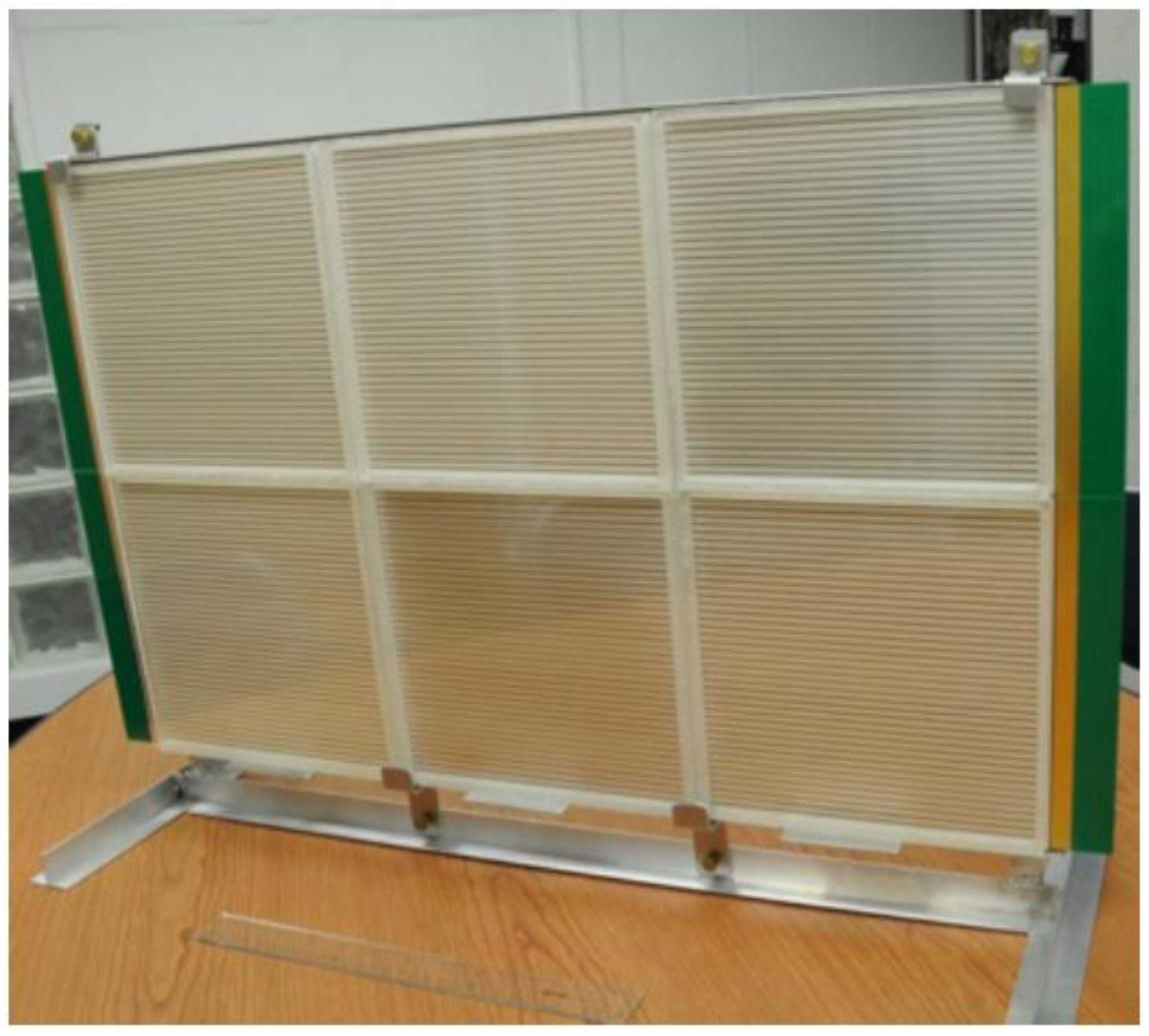
LIGHT11 – 01Nov2011

ADIT Electron Tubes

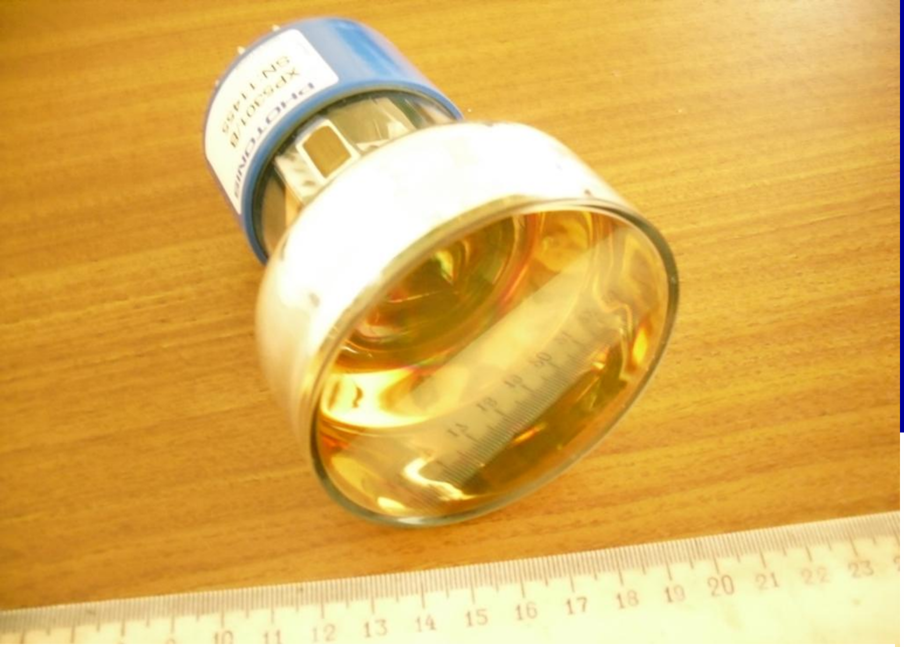
ABALONE



LAPPD – large area MCP-PMT

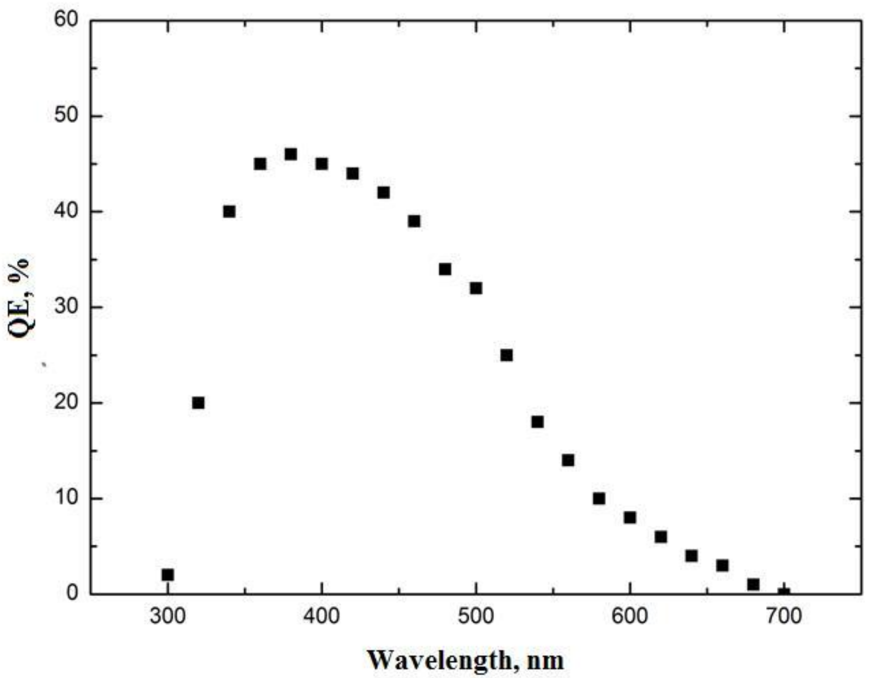


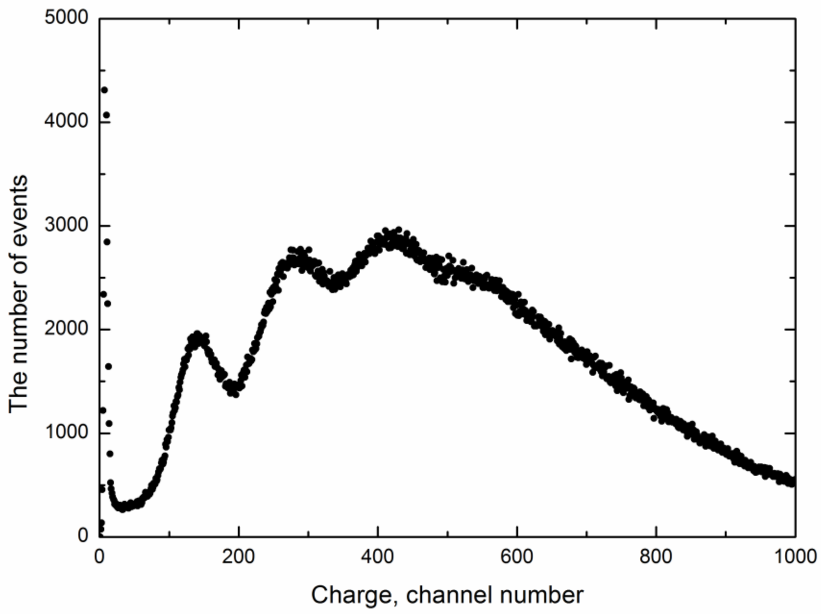
High QE PMTs Photonis 3” (UBA) XP5301B



Collection effeciency - ~100%!

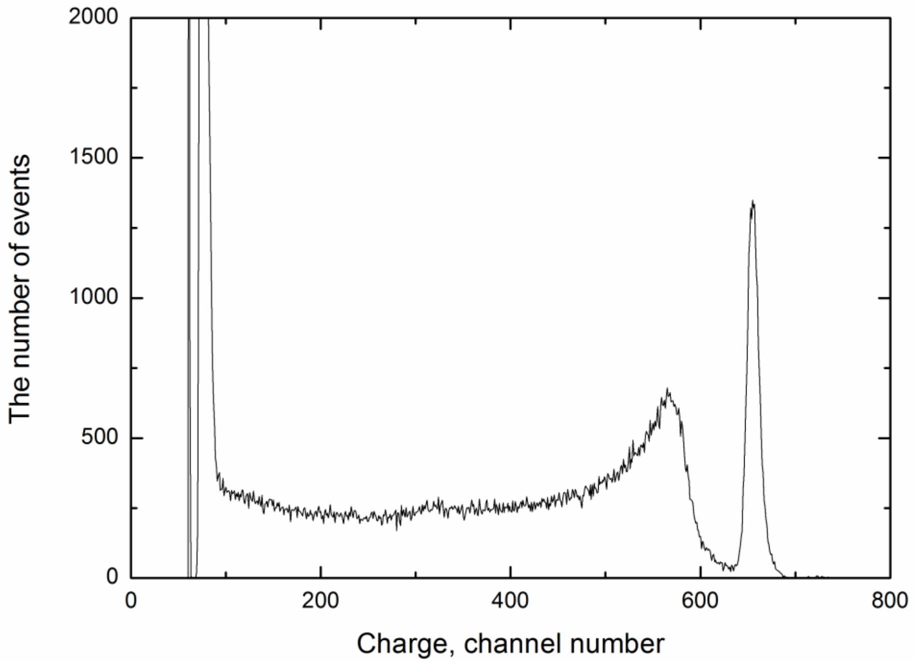
Q_{eff} – high!

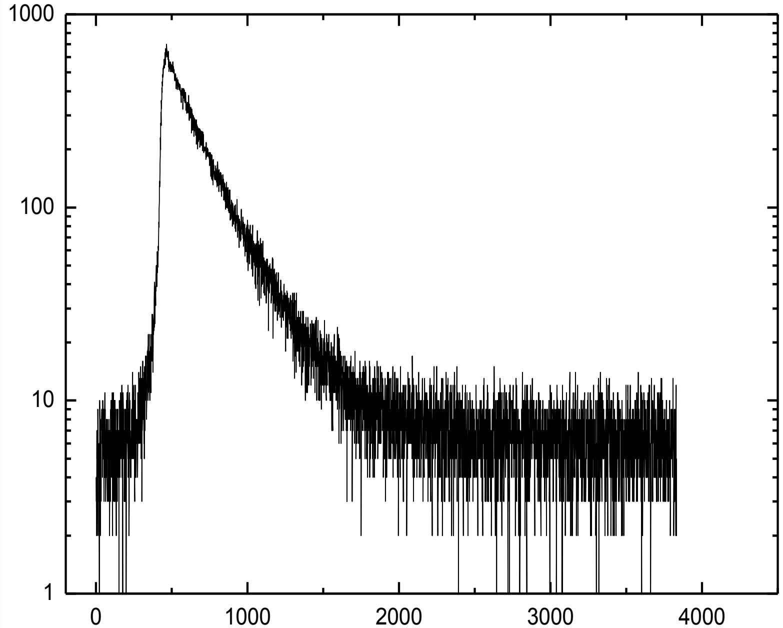




QE ~ 56%!!!

$LaBr_3$:Ce, $CeBr_3$ for GRIPS





R ≤ 2.4%!!! XP5301B τ ~ 17-19 ns

Light yield - ~70000 ph/MeV! Very hygroscopic

Lubsandorzhiev et al. 2008.