THE QUEST FOR THE IDEAL PHOTODETECTOR FOR THE NEXT GENERATION OF NEUTRINO TELESCOPES

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

DUMAND, BAIKAL

GRANDE, NEVOD, 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)

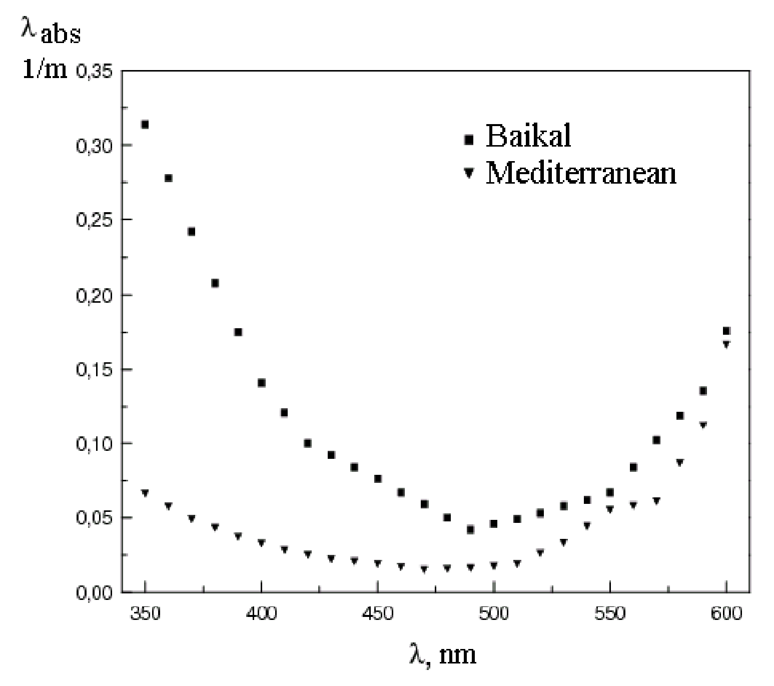
History of deep underwater neutrino telescopes spans more than 30 years.

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

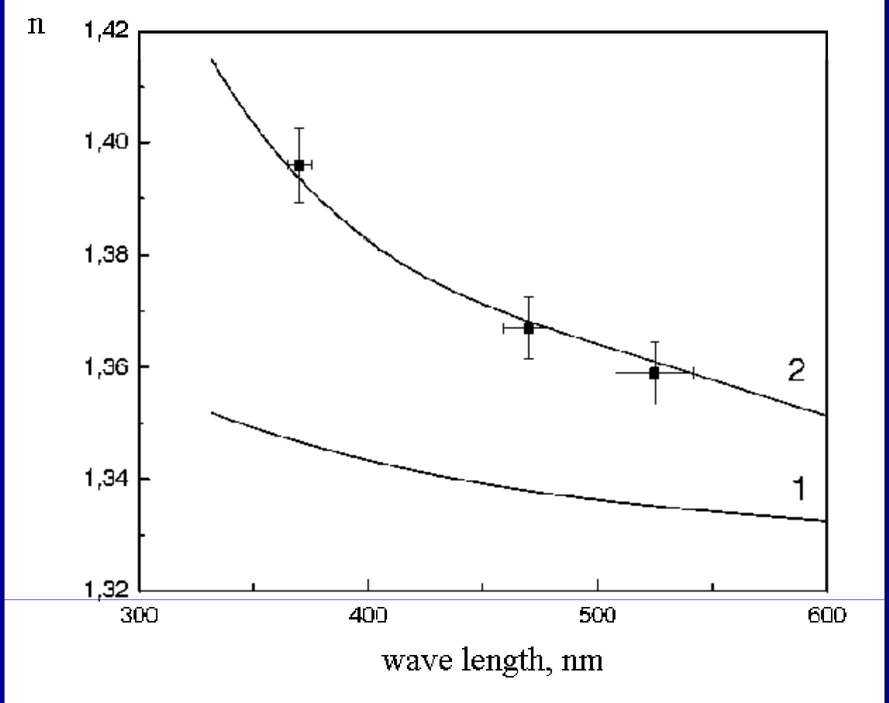
Now ANTARES is joining the club with their first neutrino events

Influence of water parameters

Water transparency



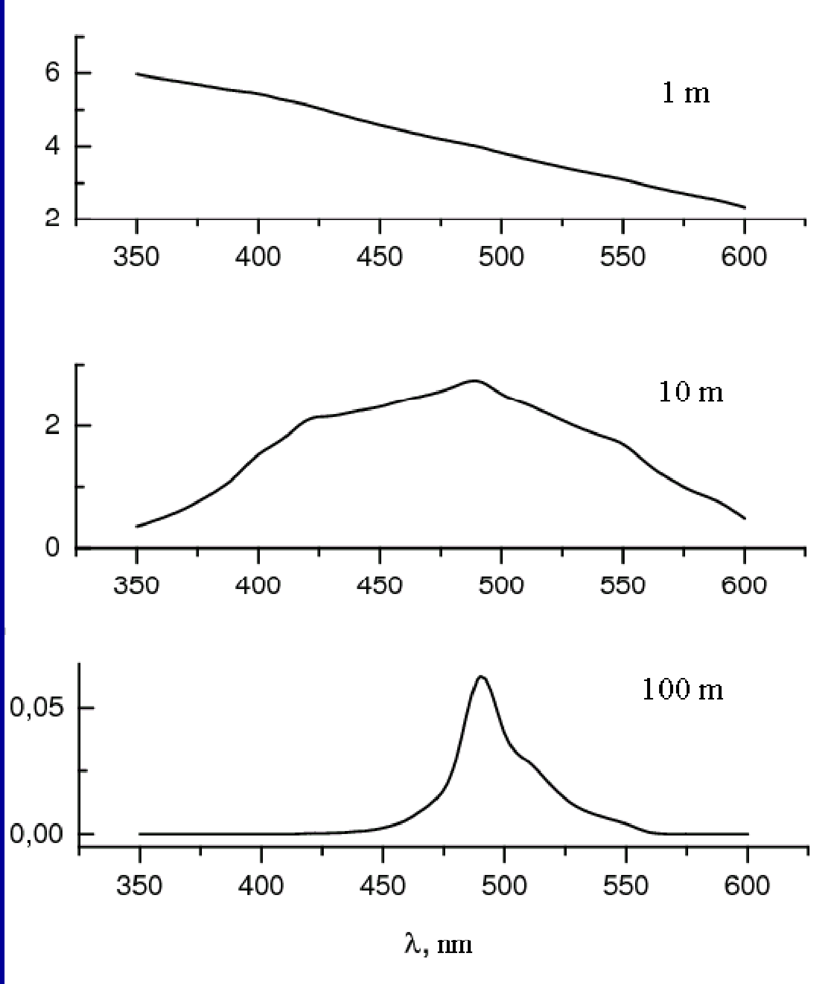
Light dispersion in deep Baikal water



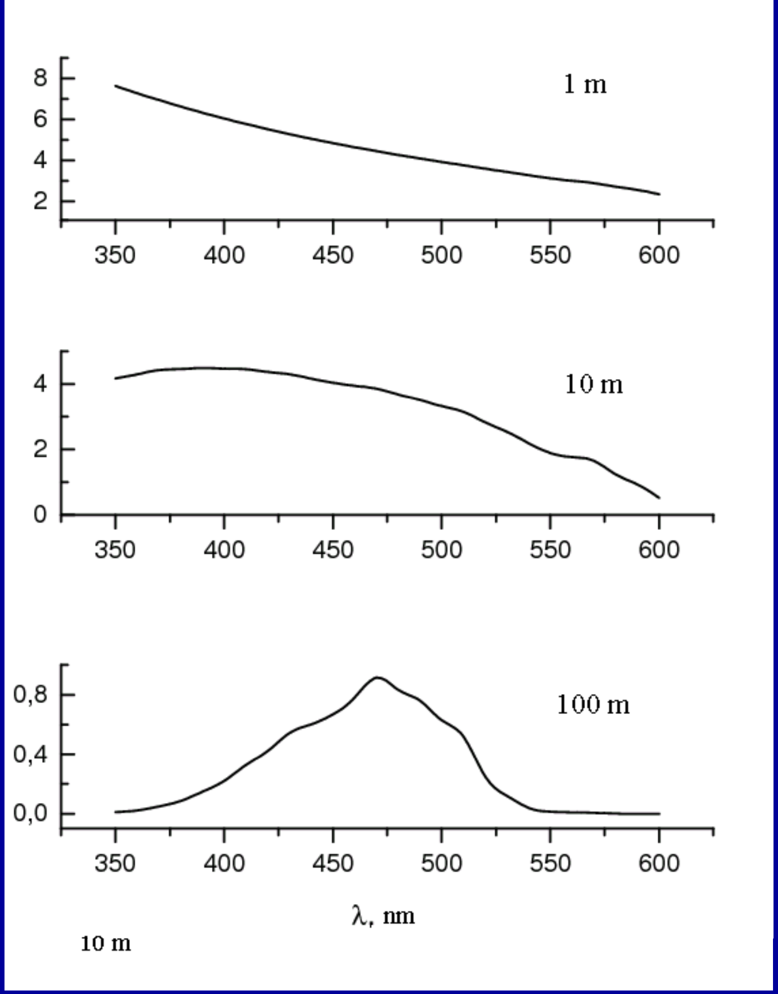
B.K.Lubsandorzhiev, RICH2007
Trieste 15-20 October 2007

Transformation of Cherenkov light spectrum in water

Baikal



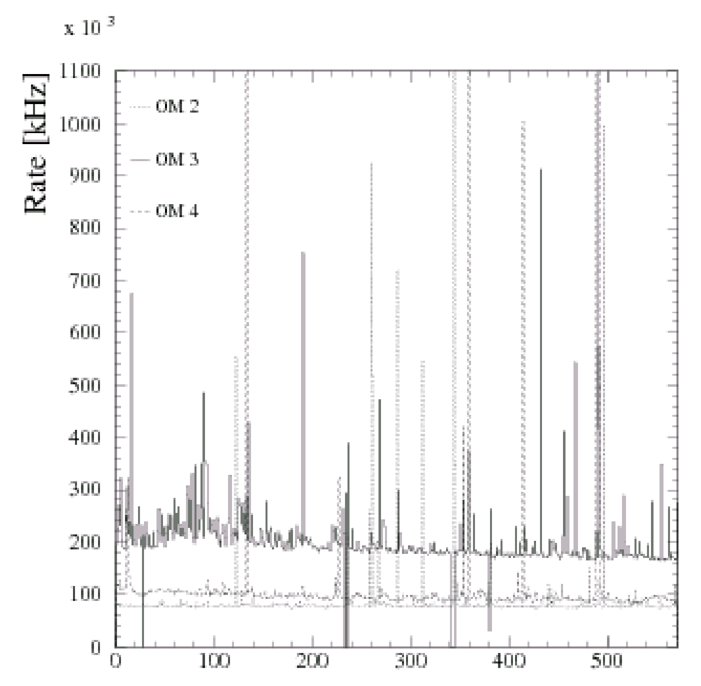
Mediterranean

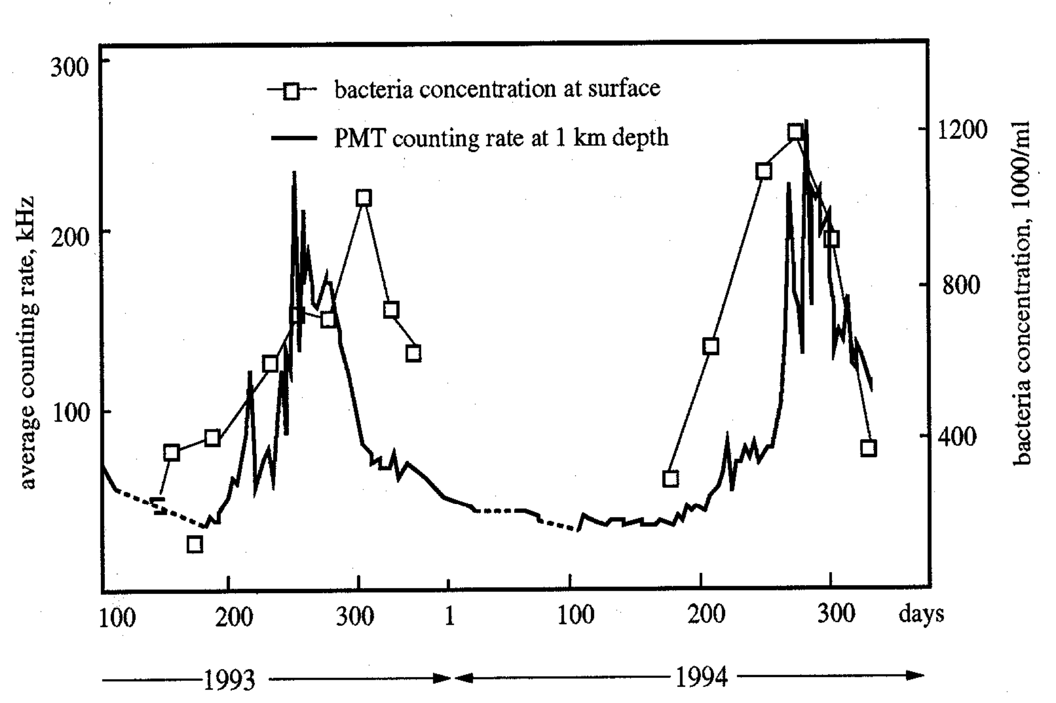


Light background in natural water - ocean, sea, lake

Pacific ocean, DUMAND

Lake Baikal, NT-200





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

Disadvantages of classical PMTs

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

Hybrid phototubes with luminescent screen

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

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

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

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

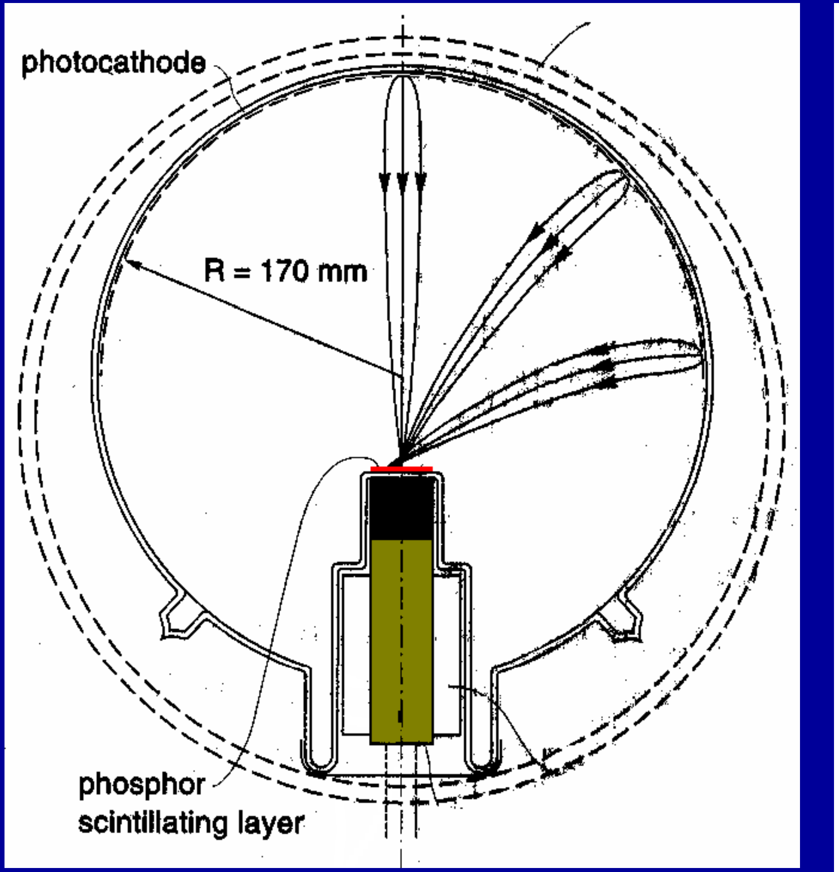
L.Bezrukov, B.Lubsandorzhiev et al. 1987 - Tests of XP2600 and Quasar -300 tubes in Lake Baikal

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

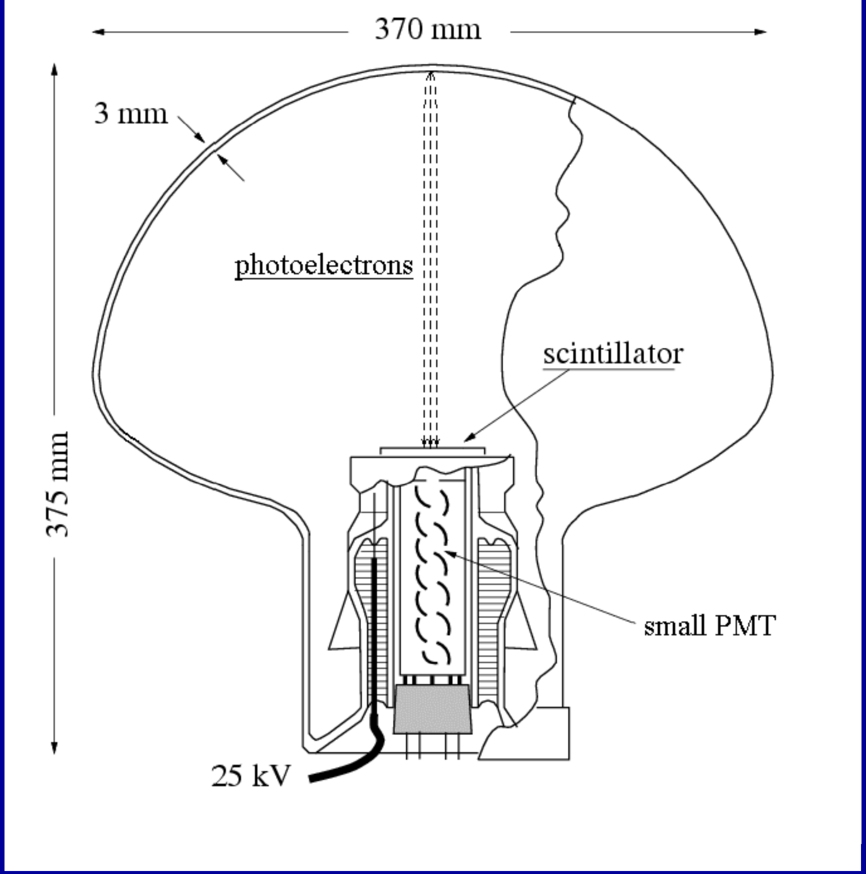
Hybrid phototube with luminescent screen

Light amplifier + small conventional type PMT

XP2600



QUASAR-370



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

  >2π sensitivity

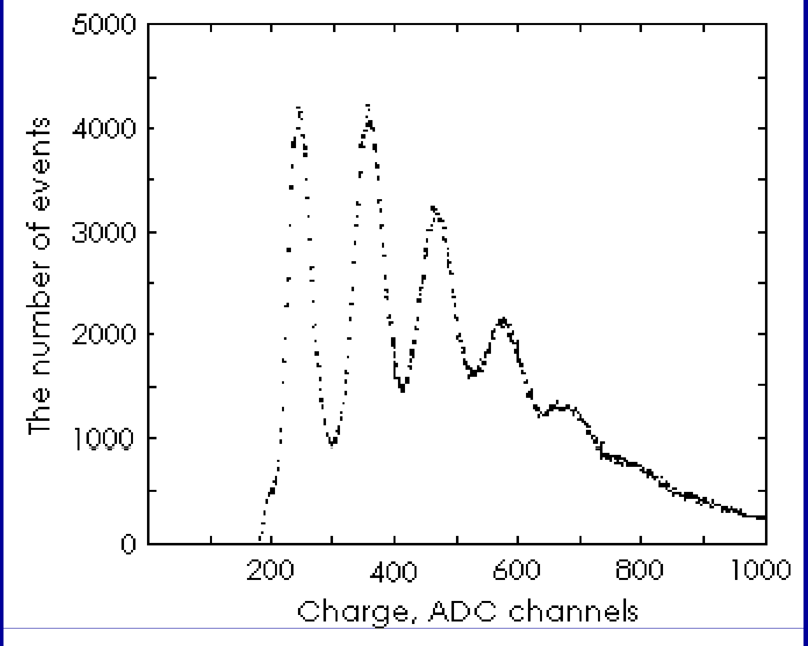
Successful operations of several astroparticle physics experiments (BAIKAL, TUNKA, SMECA, QUEST) prove the phototube’s high performances, high reliability and robustness.

A number of modifications of the Quasar-370 tube have been developed with different scintillators in its luminescent screen

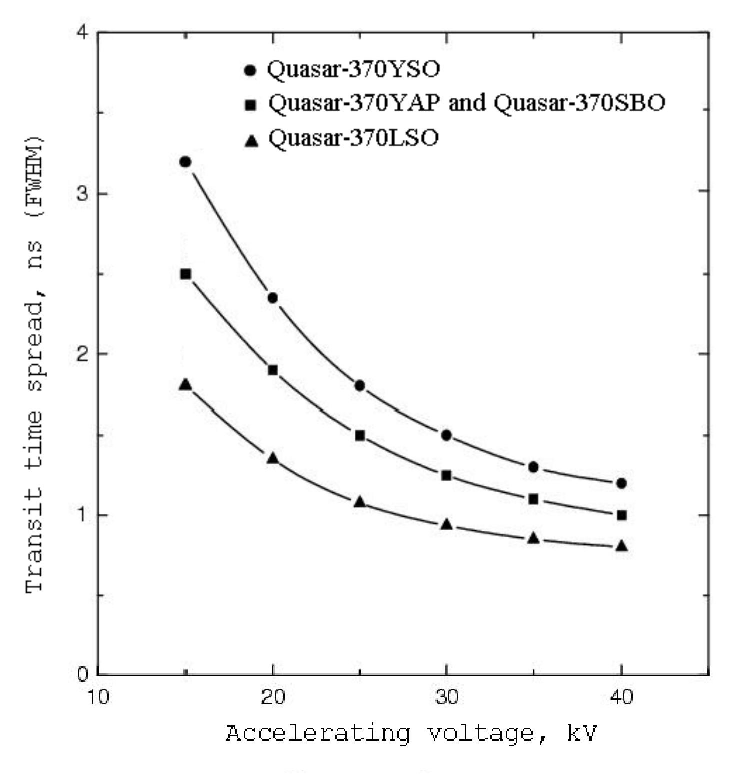
YSO, YAP, SBO, LSO, LPO etc.

Quasar-370LSO with LSO crystal

1996-97, ICRC1997



Single electron resolution ~35% (fwhm)



Jitter ~ 1 ns (fwhm)

The PMT used in the Quasar-370LSO had ~17% η(eff)

$$G = Y \times k \times \eta(\mathrm{eff})$$

Y - scintillator light yield

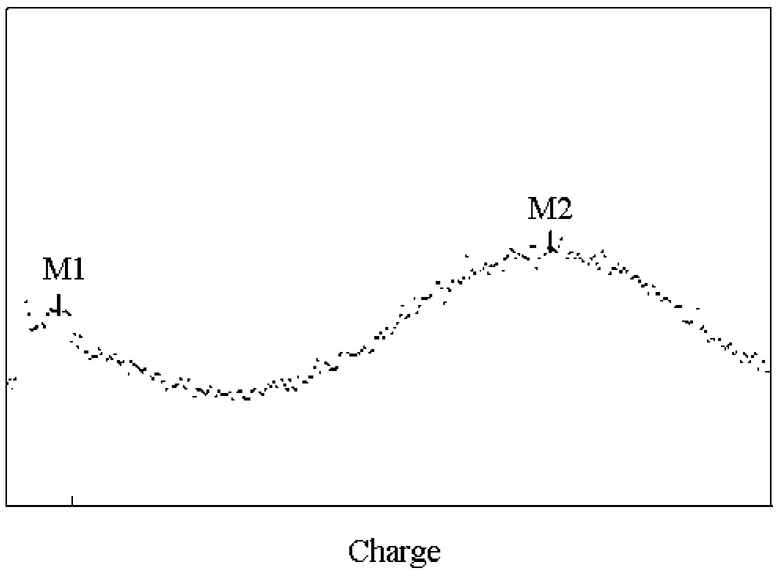
k - colection efficiency of photons on small PMT's cathode

η(eff) - effective quantum efficiency of small PMT

Small PMT with higher η(eff) will provide better parameters of Quasar-370!

Studies of Quasar-370 and XP2600 at very low thresholds

Single pe charge spectrum of Quasar-370

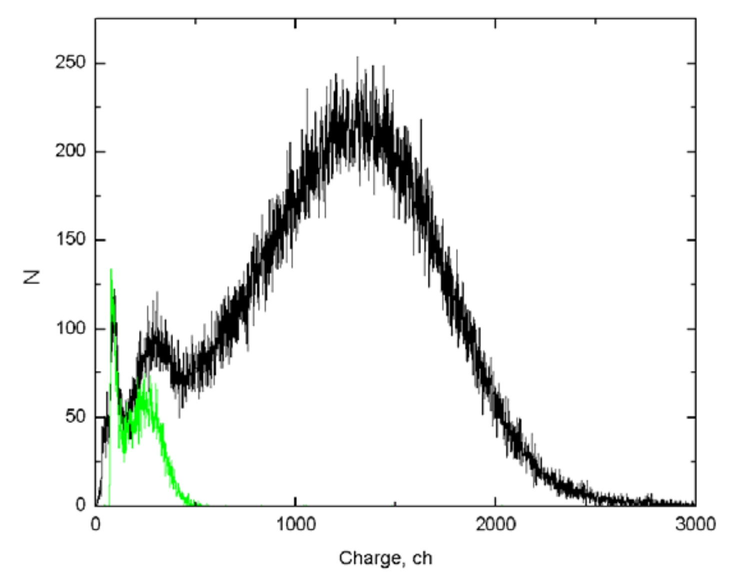


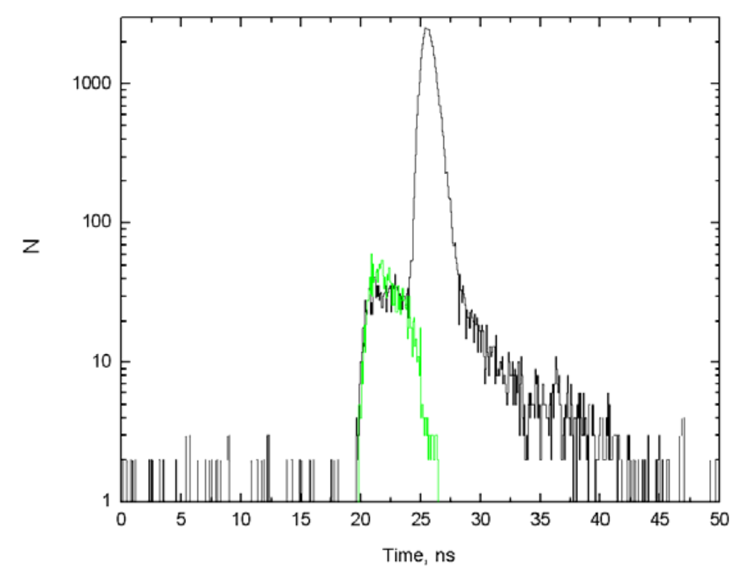
M1 - single pe peak of small PMT

M2 - single pe peak of Quasar-370

Threshold - ~0.005 pe

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

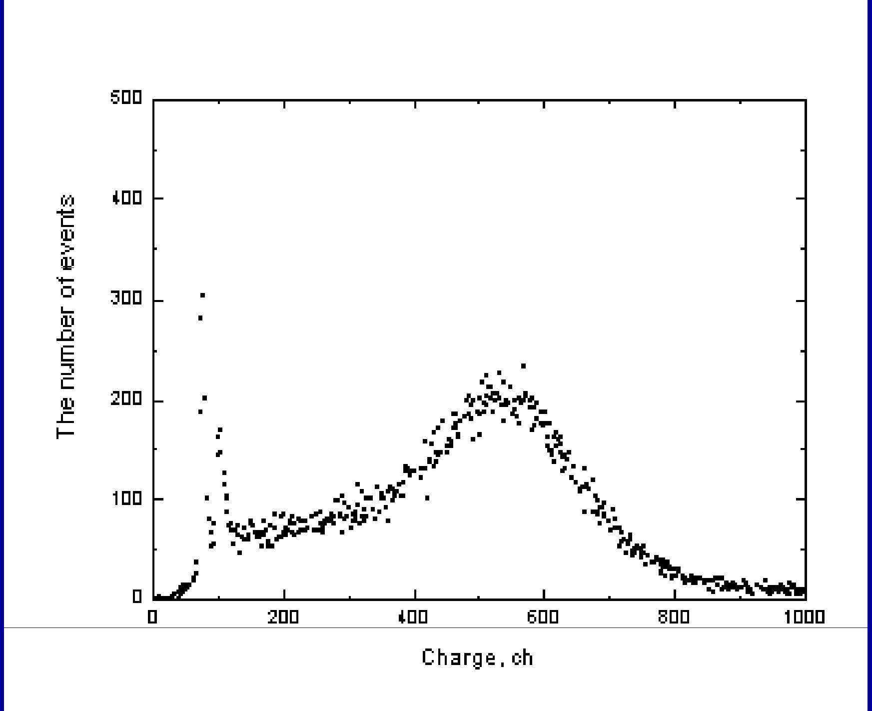


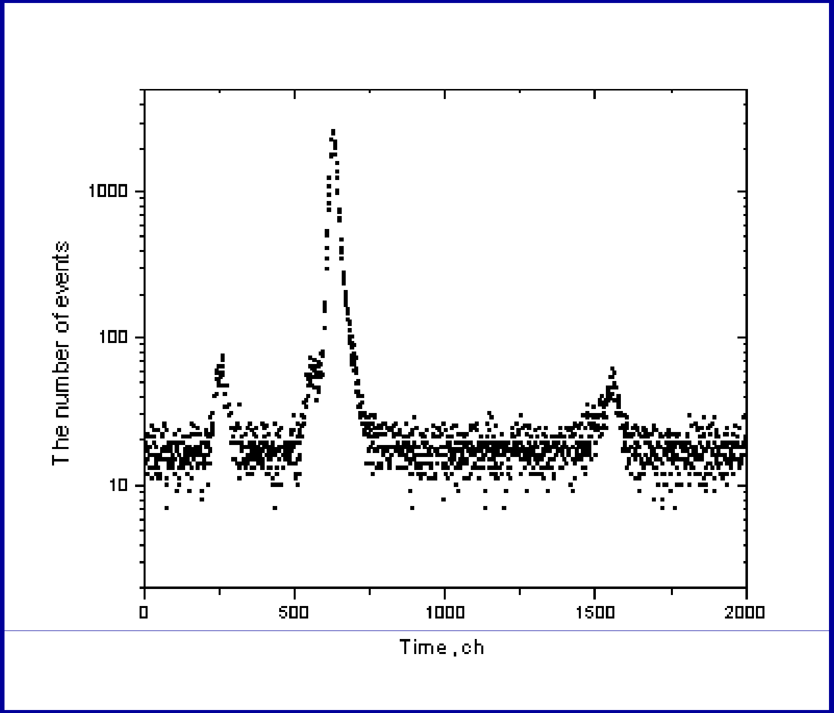


- Threshold - ~ 0.005 p.e.!
- Green - spectra measured with cathode camera switched off, i.e. cathode and 1 dynode are short circuited

Big hemispherical PMTs at low thresholds

Hamamatsu R8055 (13”)

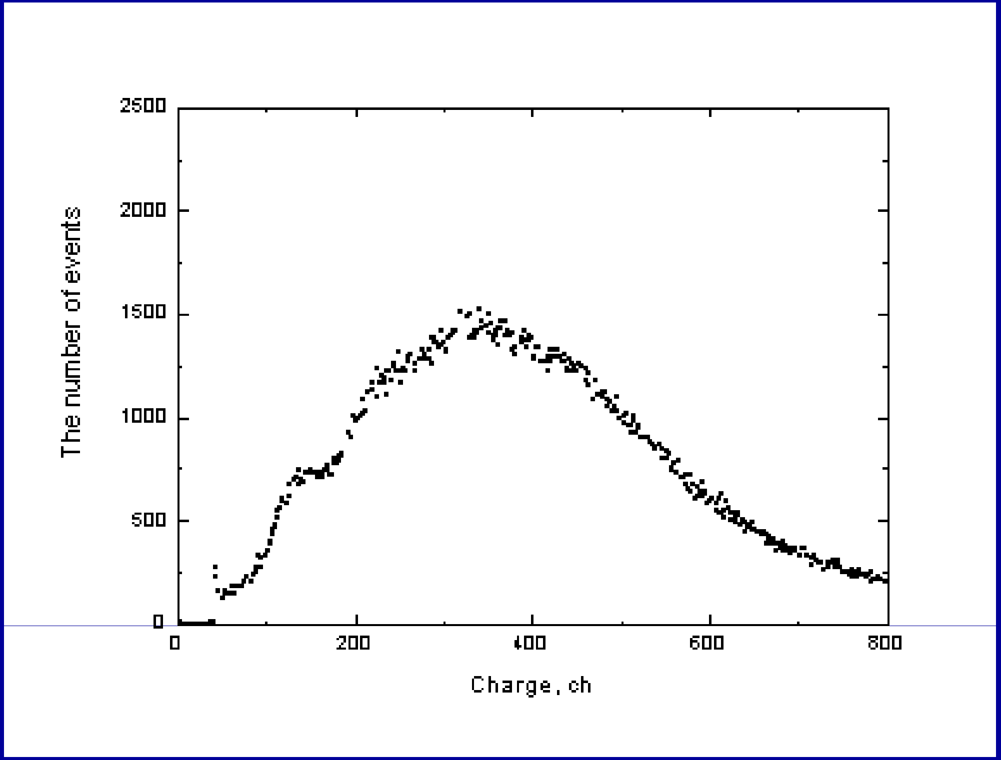




SER ~70% (fwhm)
0.005 pe threshold!

Jitter ~ 1.8 ns (fwhm)

Photonis XP1807 (12”)



σ ~ 35

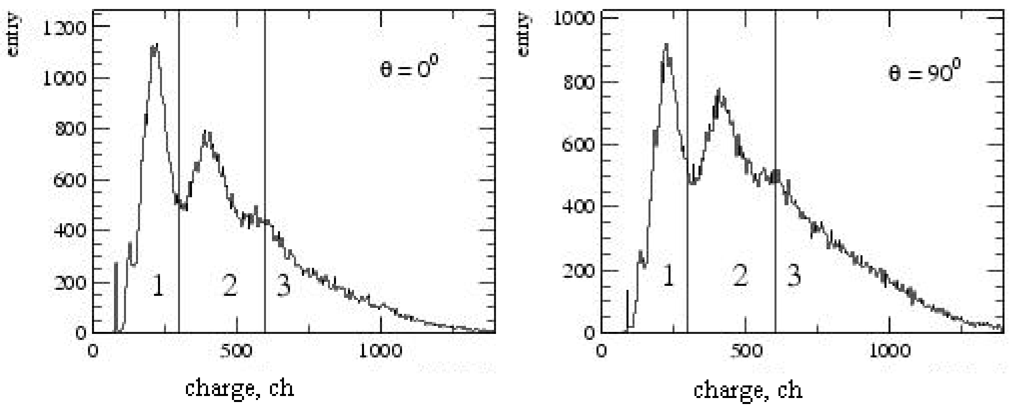
strong nonpoissonian behaviour

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

Afterpulses - ~20%
heavy caesiation

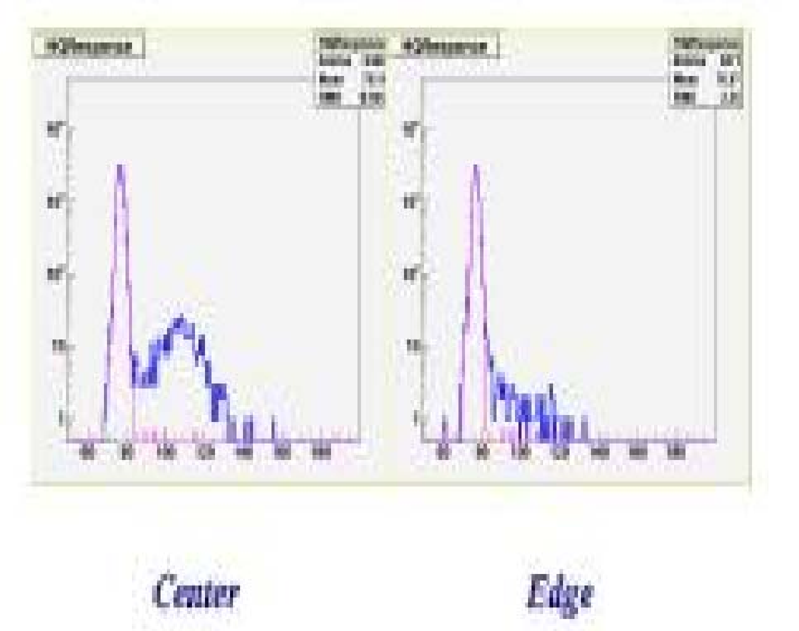
New parameter to evaluate PMT's quality - its ability to work at low thresholds

XP2600, Quasar-370

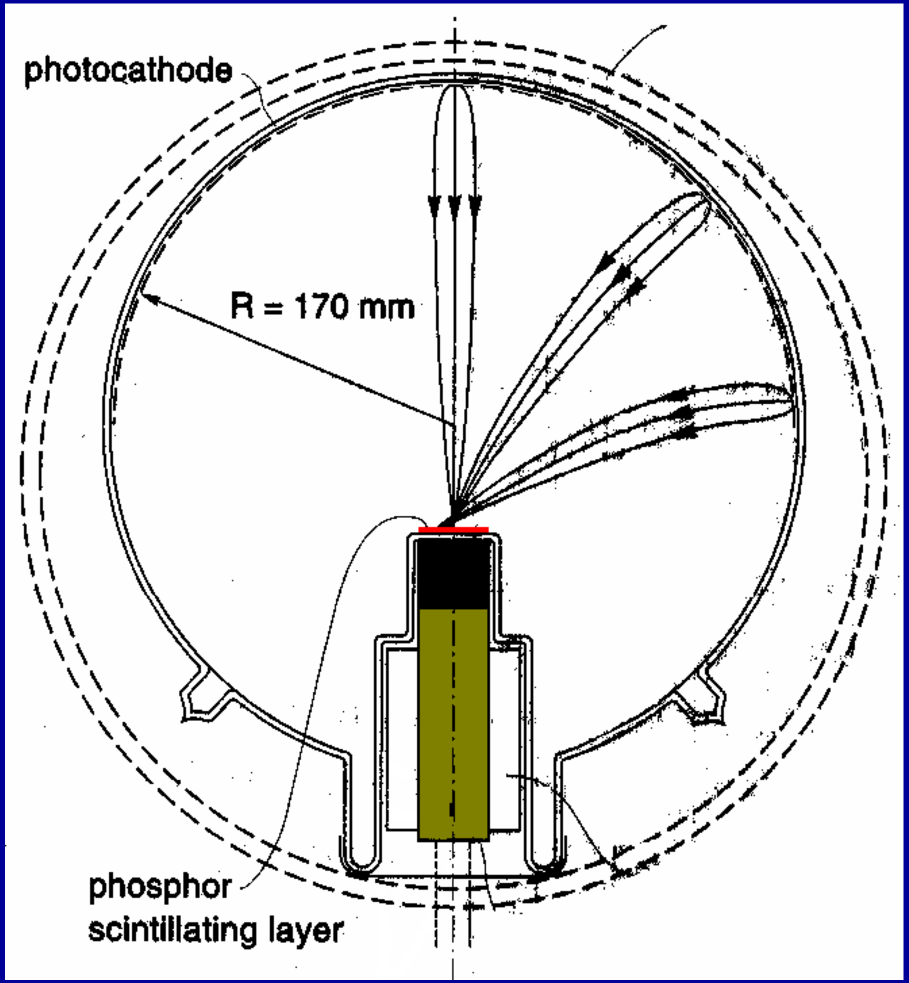


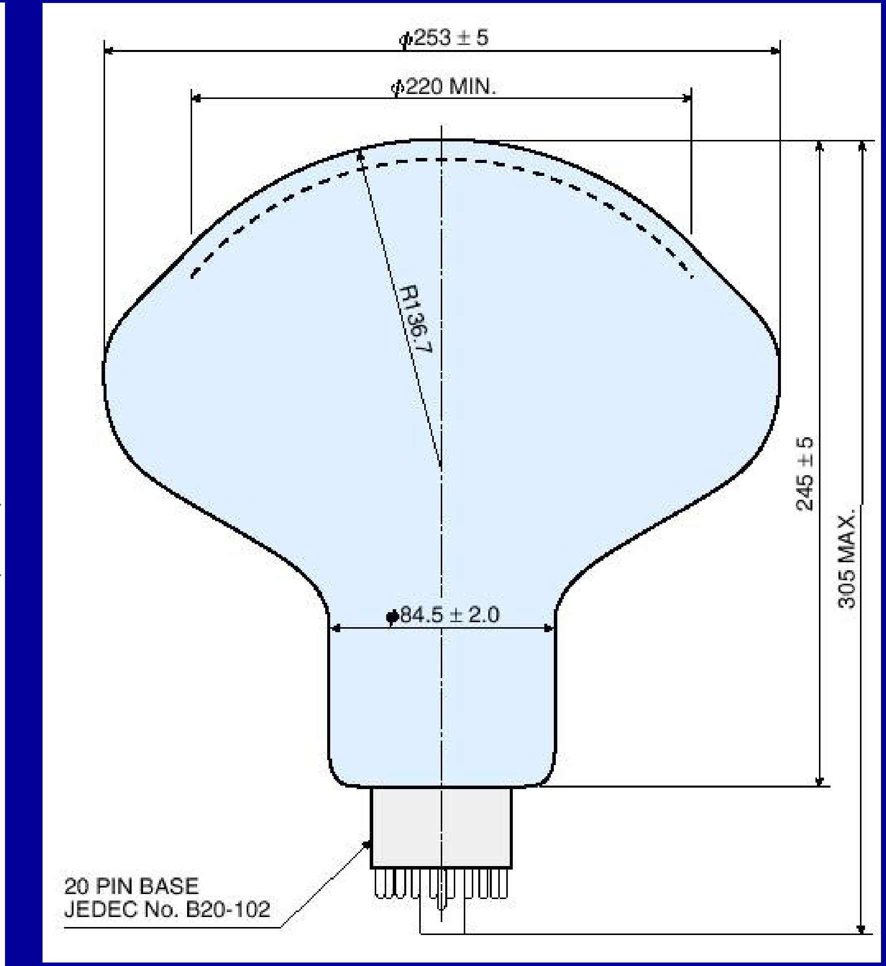
C.Wiebusch, RWTH-Aachen 1995

R7081



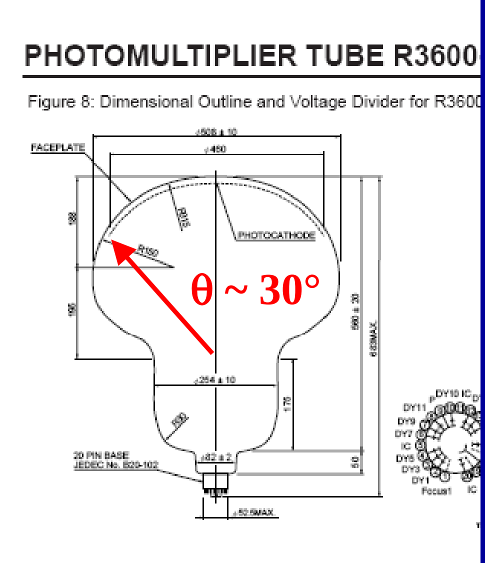
H.Miyamoto, Chiba University


photocathode
R = 170 mm
phosphor
scintillating layer


φ253 ± 5
φ220 MIN.
R136.7
φ84.5 ± 2.0
245 ± 5
305 MAX.
20 PIN BASE
JEDEC No. B20-102

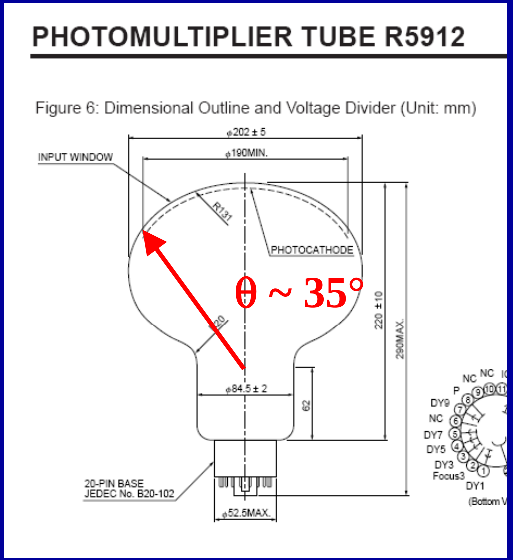
Quasar-370

XP2600



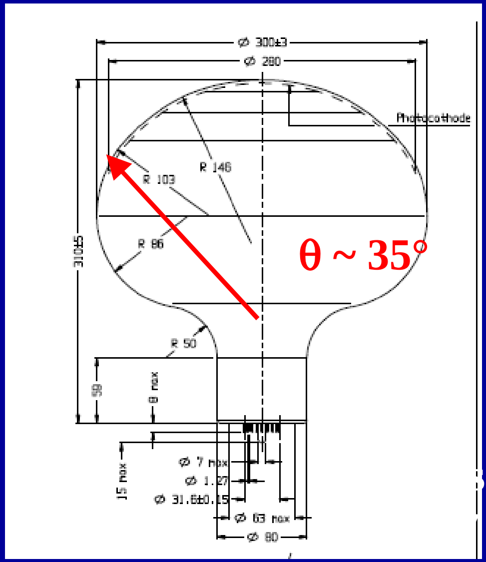
PHOTOMULTIPLIER TUBE R3600

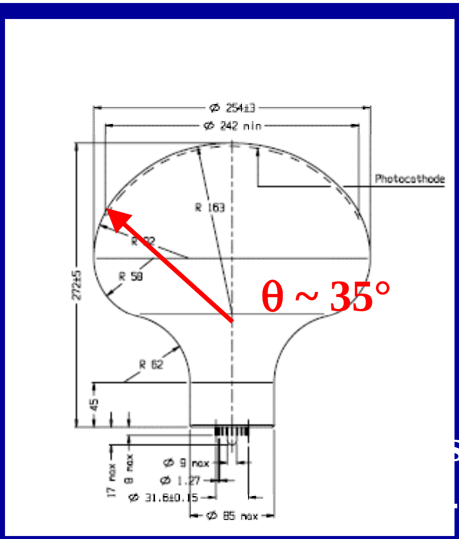
Figure 8: Dimensional Outline and Voltage Divider for R3600

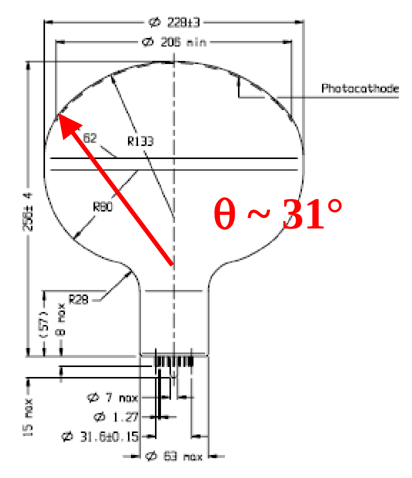


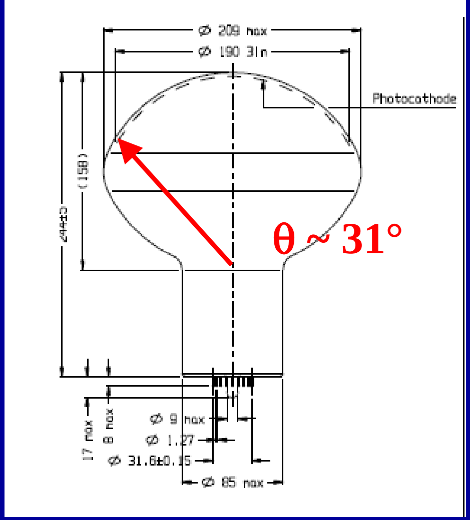
PHOTOMULTIPLIER TUBE R5912

Figure 6: Dimensional Outline and Voltage Divider (Unit: mm)

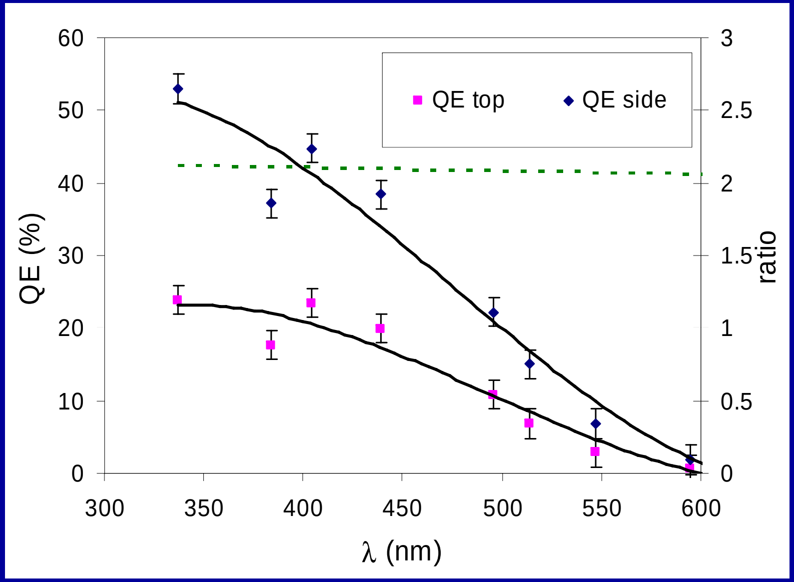








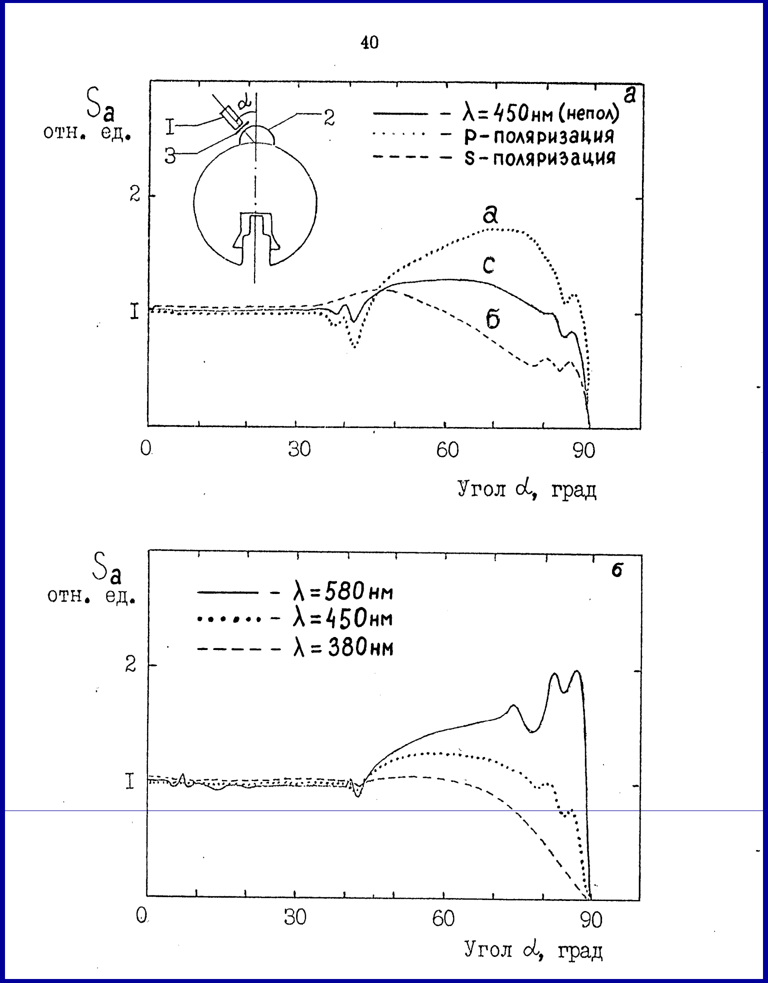
G.Hallewell

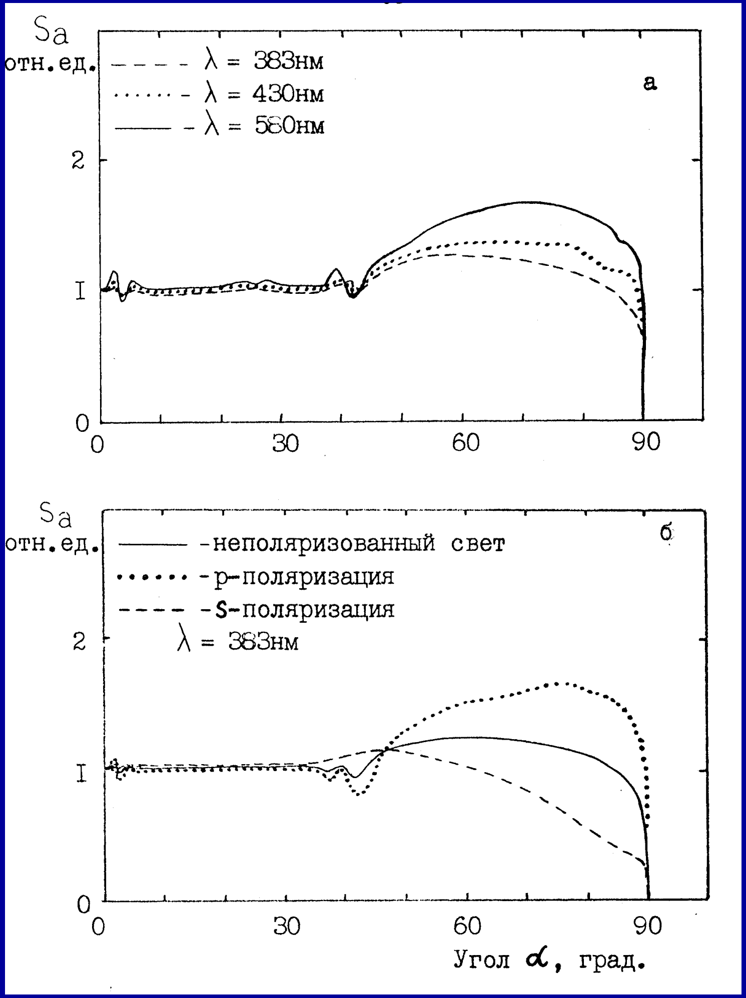


A.Braem et al. NIMA 570 (2007) 467
Photonis measurements

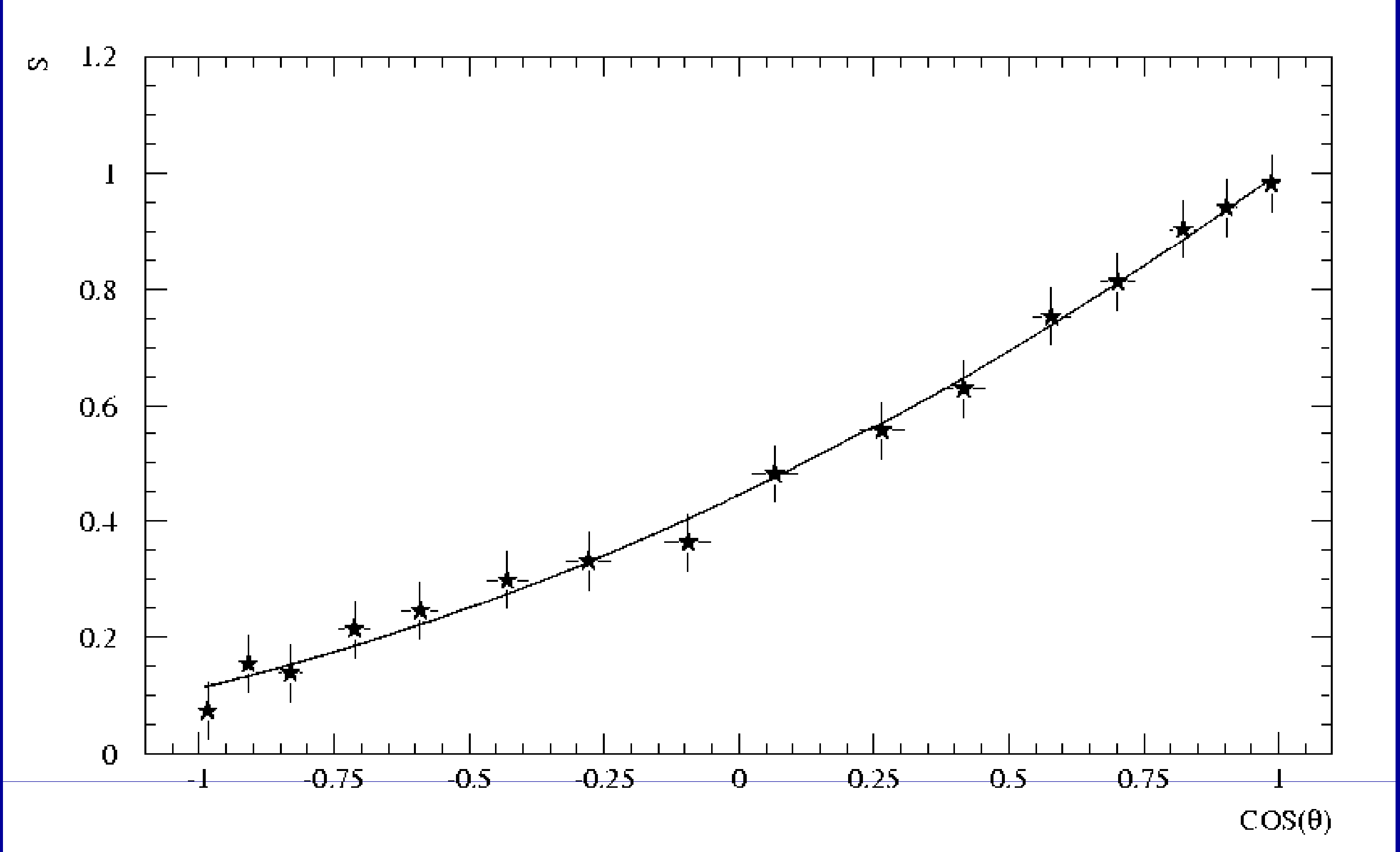
1987-1990 XP2600 30-50% effect
Quasar-370 - 10-20%

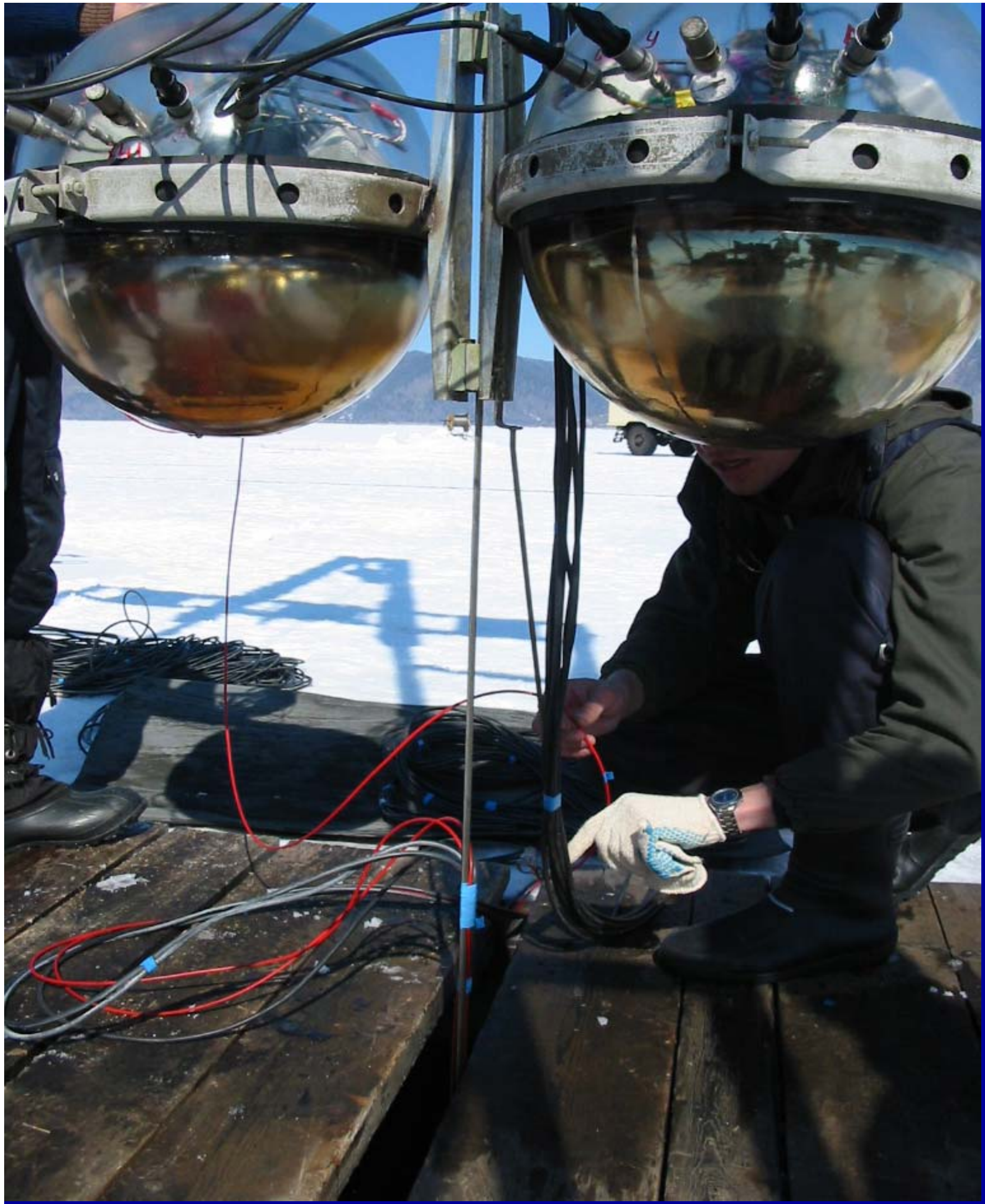
XP2600 and Quasar-370 sensitivity vs photons incident angle



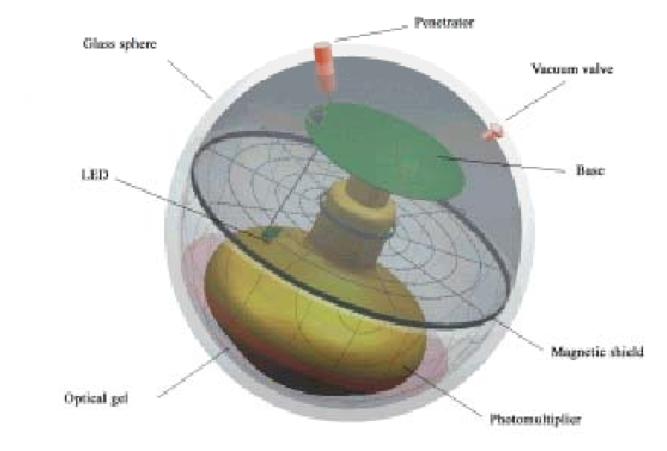


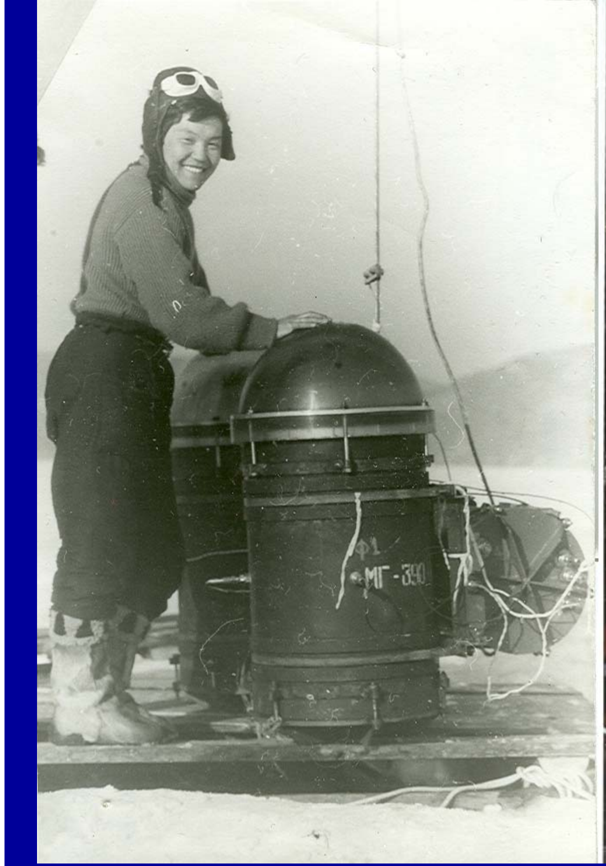
OM’s response to plane wave vs incident angle of plane wave





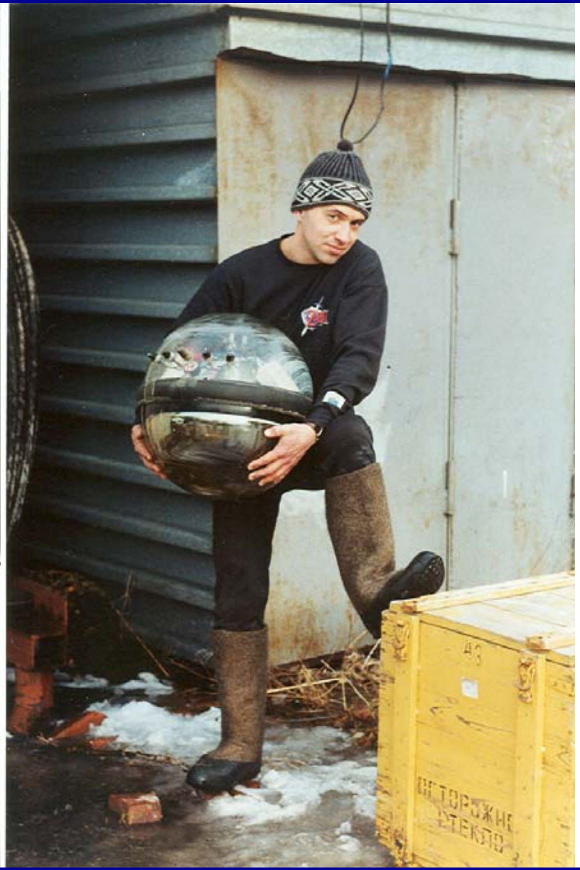
Quasar-370 - ~2000 cm**2
R7081 - ~500 cm**2





1987

Lake Baikal



1994

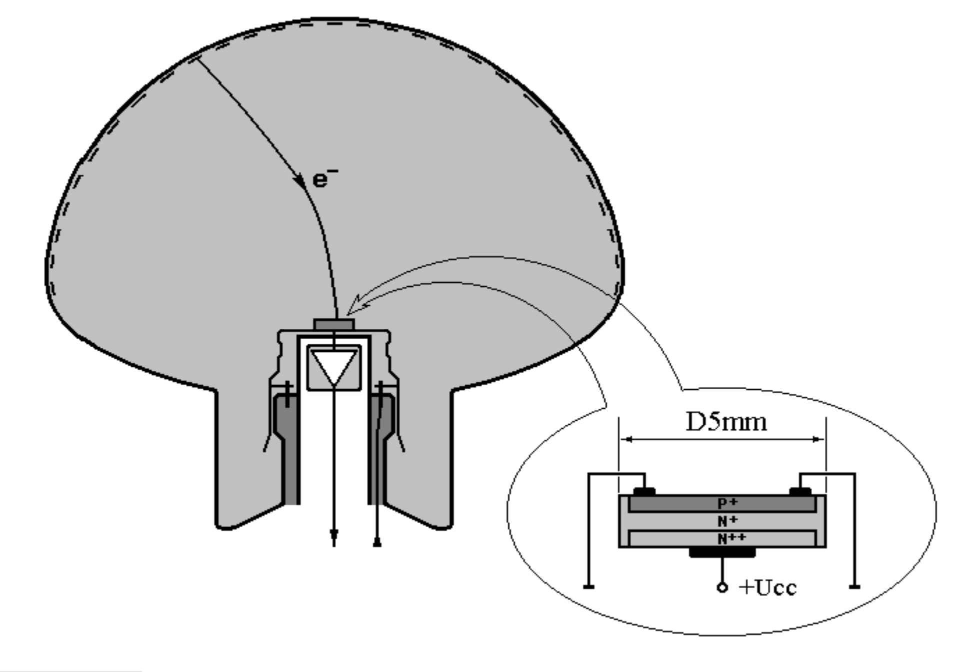
Lake Baikal

1998

Deutsche Museum, Bonn

Quasar-370D

1995-1997 ICRC1997, COMO2001



- High mechanical precision
- Diode protection
- Subjected to terrestrial magnetic field influence.

  (Larger diode - larger capacitance - timing deteriorates)

The quest for the ideal scintillator for Quasar-370 like tubes

Requirements:

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

Scintillators must be:

Inorganic scintillators

Nonhygroscopic

Time resolution of hybrid phototubes and scintillator parameters

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

G - the first stage amplification factor

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

$G \sim Y(E_e)$

Y - scintillator light yield

τ - scintillator decay time

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

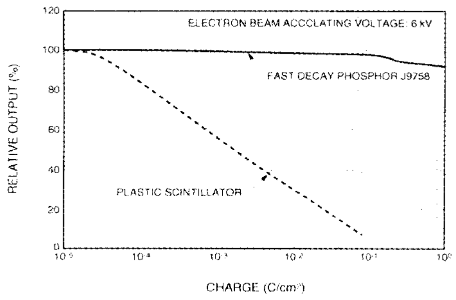
F1 = F2 = 250!

Challenge:

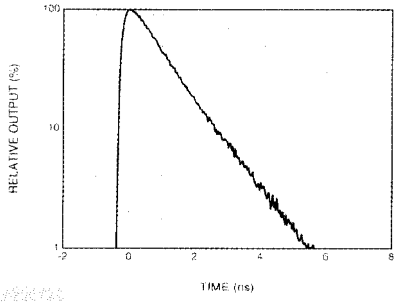
- the material should be extremelly pure
- problems with monocrystal growth but phosphor will be O'K for luminescent screen

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

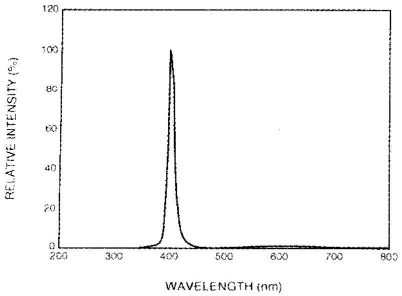
Phosphor life characteristics



Phosphor decay characteristics

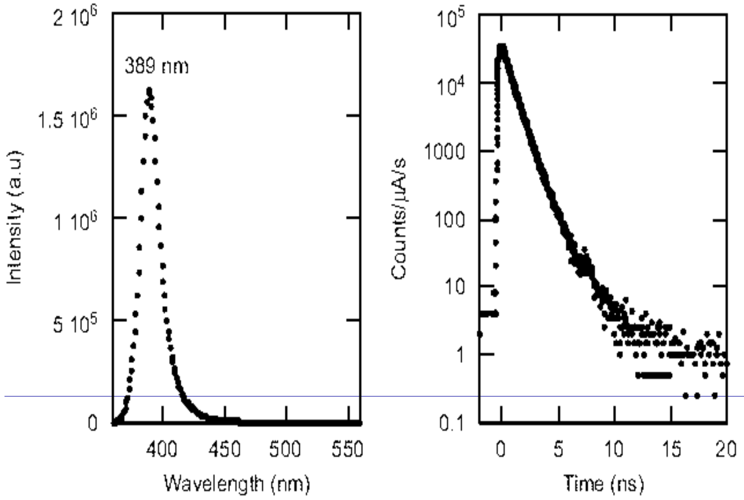


Phosphore spectral emission characteristics



Hamamatsu news 2006, pp18-19

ZnO(Ga)



E.D.Bourret-Courchesne et al. NIMA

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

Spherical (up to 50 cm dia) with >2π 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 Phototube with luminescent screen

Quasar-370 is very close to the ideal photodetector

Anyway it is very good prototype of the ideal photodetector for the next generation of neutrino telescopes