Hybrid Phototubes in Neutrino Telescopes: Experience and Perspectives

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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)

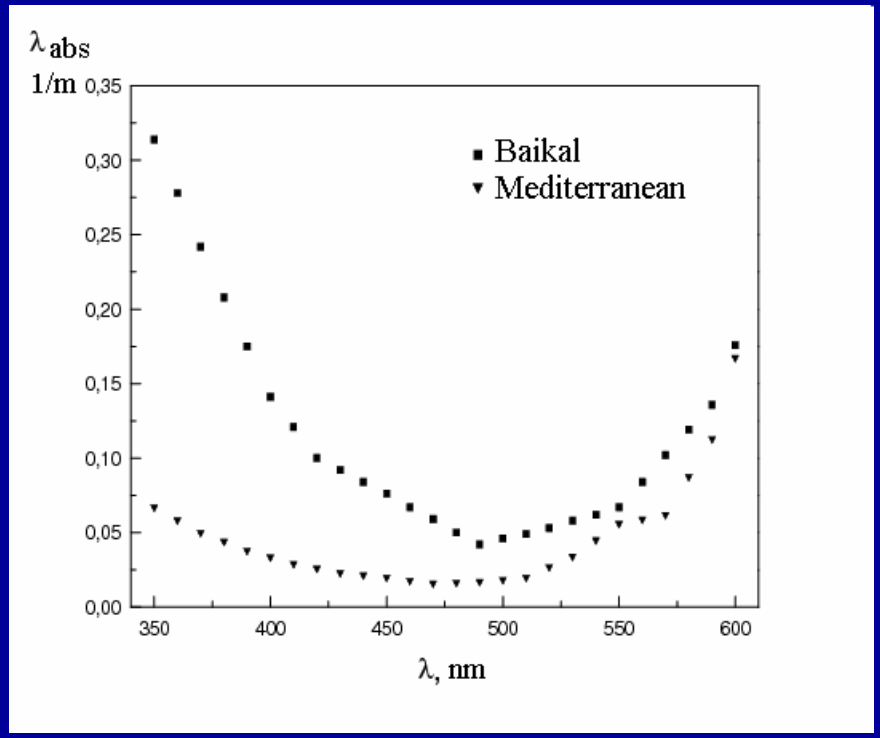
History of deep underwater neutrino telescopes spans more than 30 years.

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

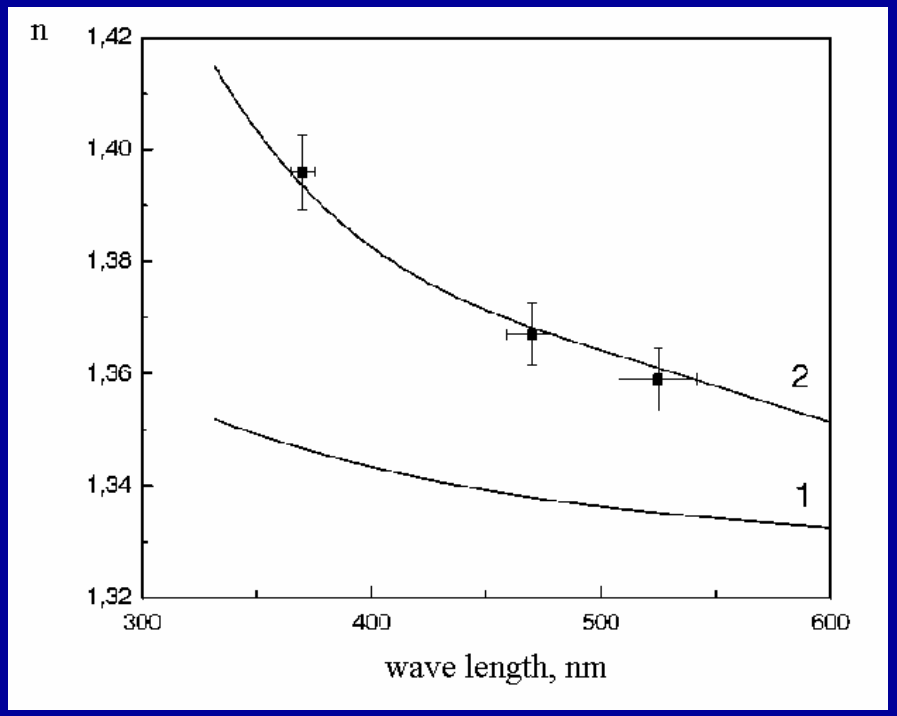
Now ANTARES is joining the club with their first neutrino events

Influence of water parameters

Water transparency

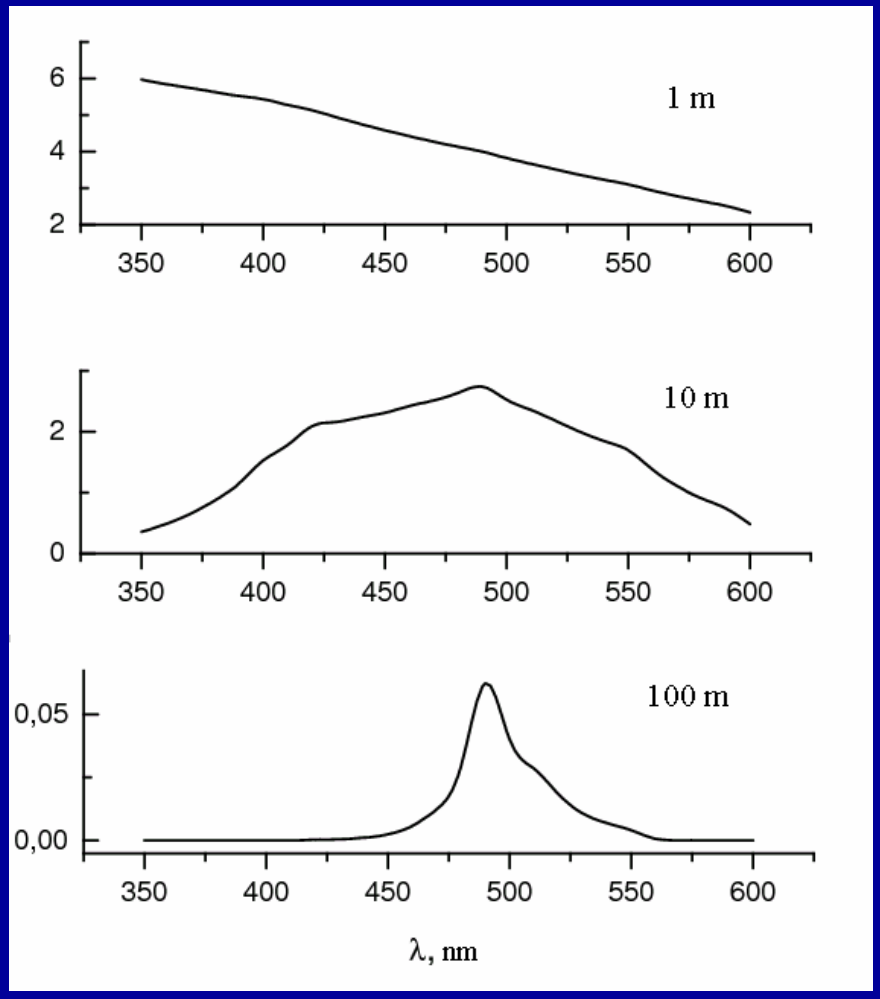


Light dispersion in deep Baikal water

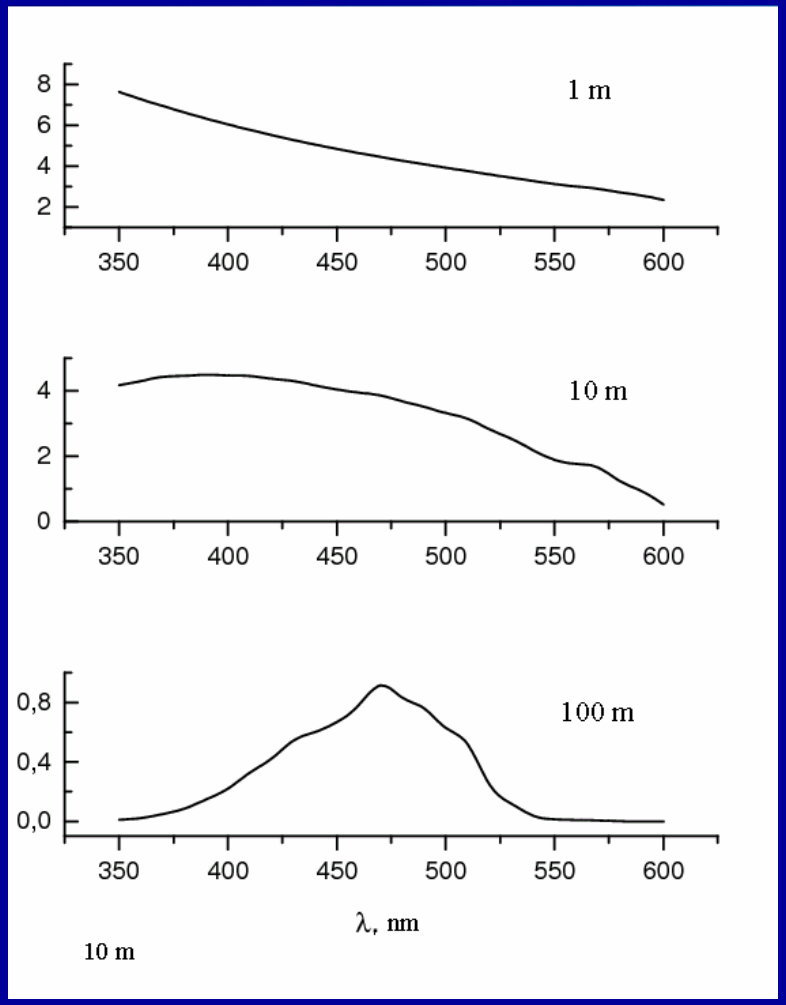


Transformation of Cherenkov light spectrum in water

Baikal



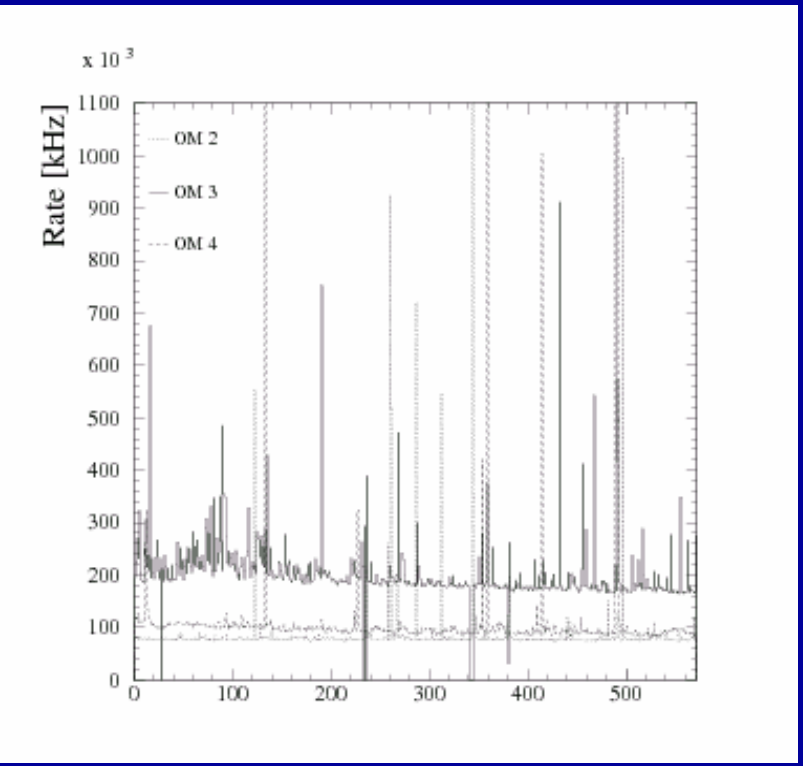
Mediterranean

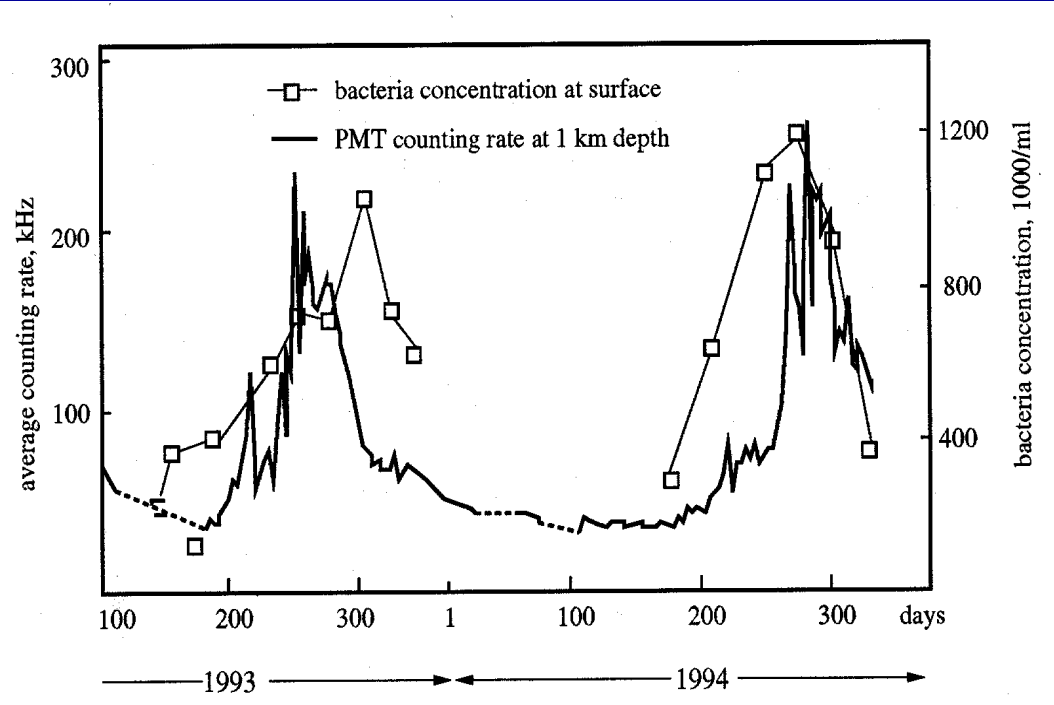


Light background in natural water - ocean, sea, lake

Lake Baikal, NT-36 and NT-72

Pacific ocean, DUMAND





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

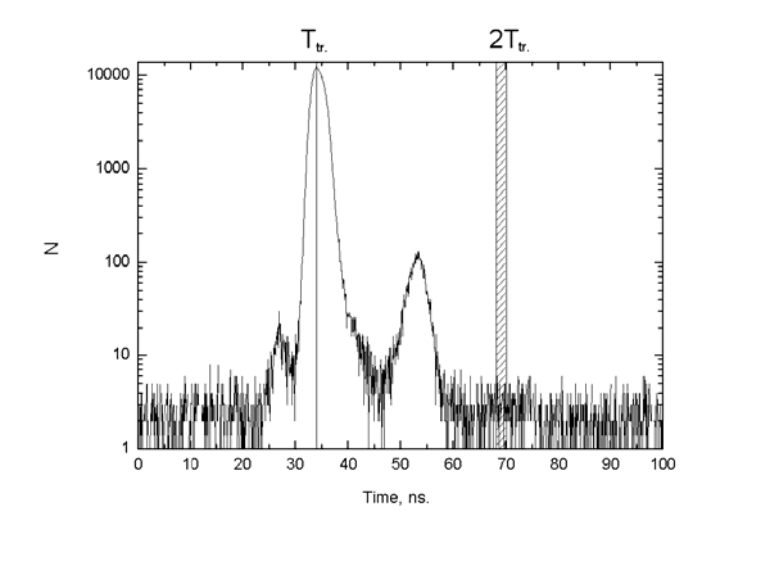
sensitivity in a wider range than conventional bialkali cathode (Ultra/Hyper Multialkali Cathode?)

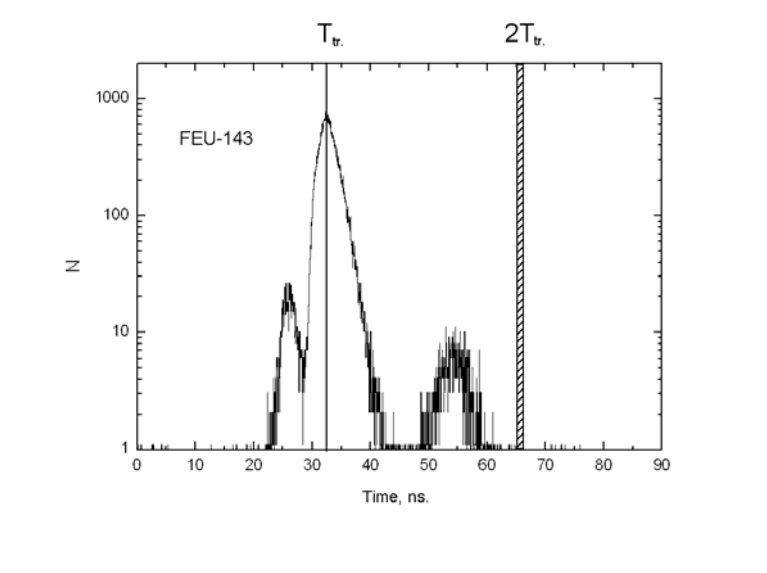
Counting rate due to water luminescence dominates over PMT's dark current

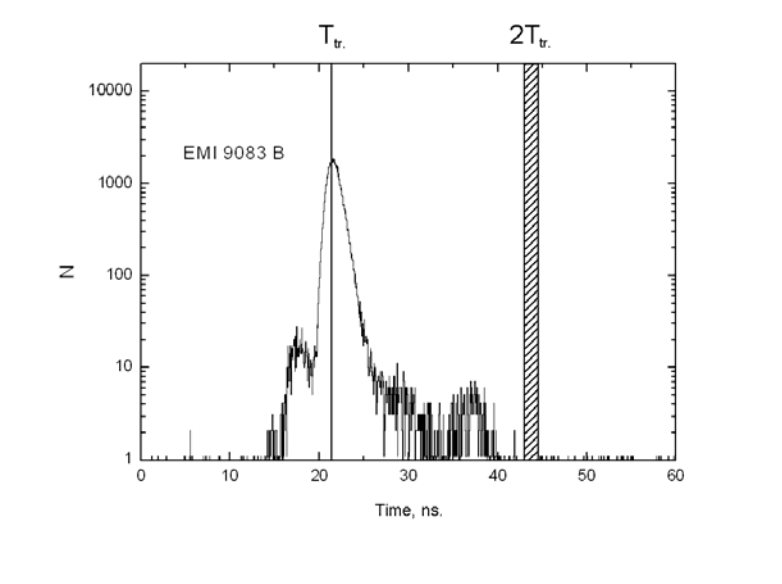
Disadvantages of classical PMTs

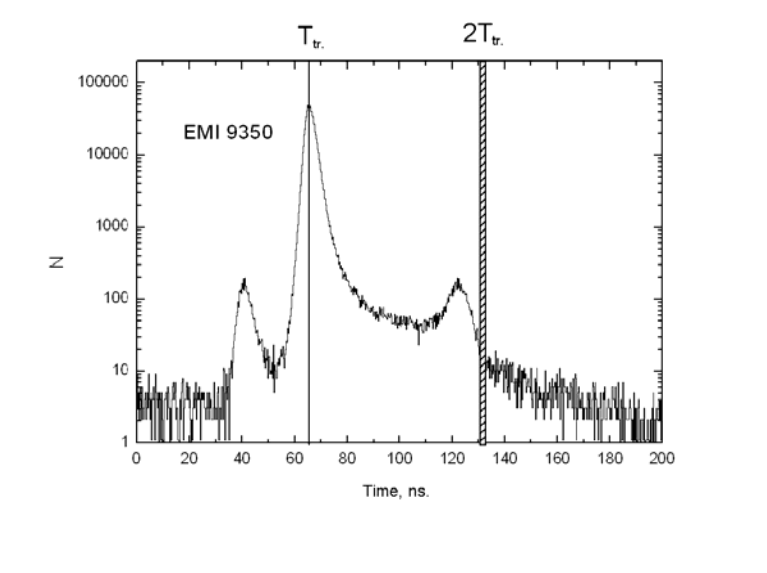
- Poor collection and effective quantum efficiencies
- Poor time resolution?
- prepulses
- late pulses
- afterpulses
- sensitivity to terrestrial magnetic field
- larger PMT size - larger dynode system (Dph/Dd1), practically impossible to provide 2π acceptance

XP2020


$T_{tr.}$
$2T_{tr.}$
N
Time, ns.


$T_{tr.}$
$2T_{tr.}$
FEU-143
N
Time, ns.


$T_{tr.}$
$2T_{tr.}$
EMI 9083 B
N
Time, ns.


$T_{tr.}$
$2T_{tr.}$
EMI 9350
N
Time, ns.

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.

L.Bezrukov, B.Lubsandorzhiev, A.Panfilov 1988-90 - concept of hydrostatic-pressure-proof Quasar 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

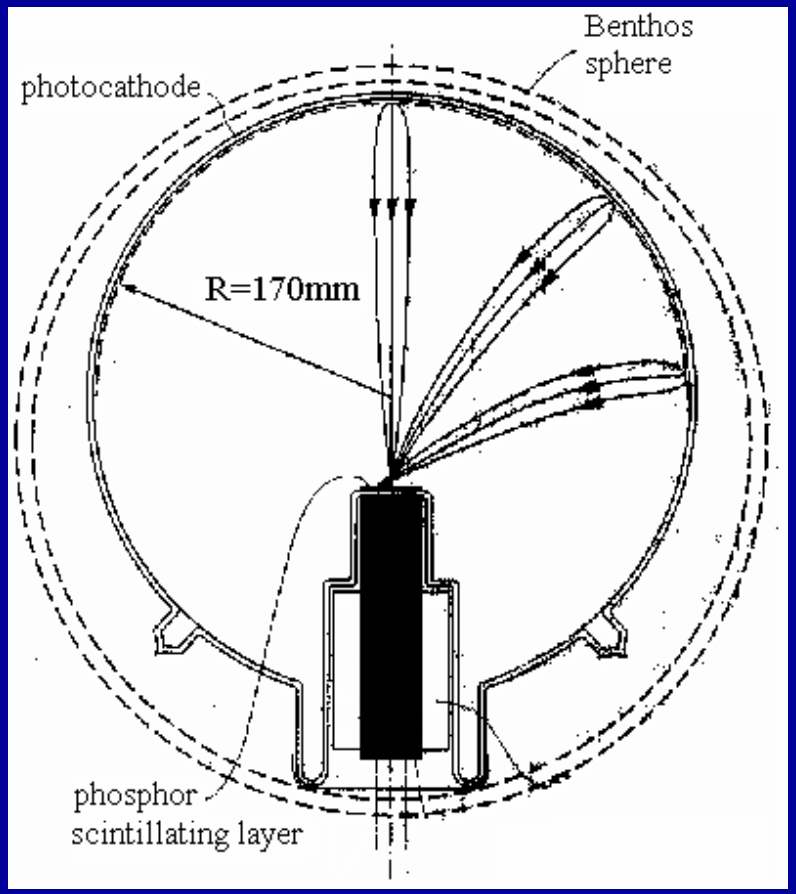
A number of scintillators are available only as phosphors (ZnO:Ga, LS, etc).

Sometimes it’s better to work with phosphors.

X-HPD is just part of the whole photodetector (Light preamplifier)

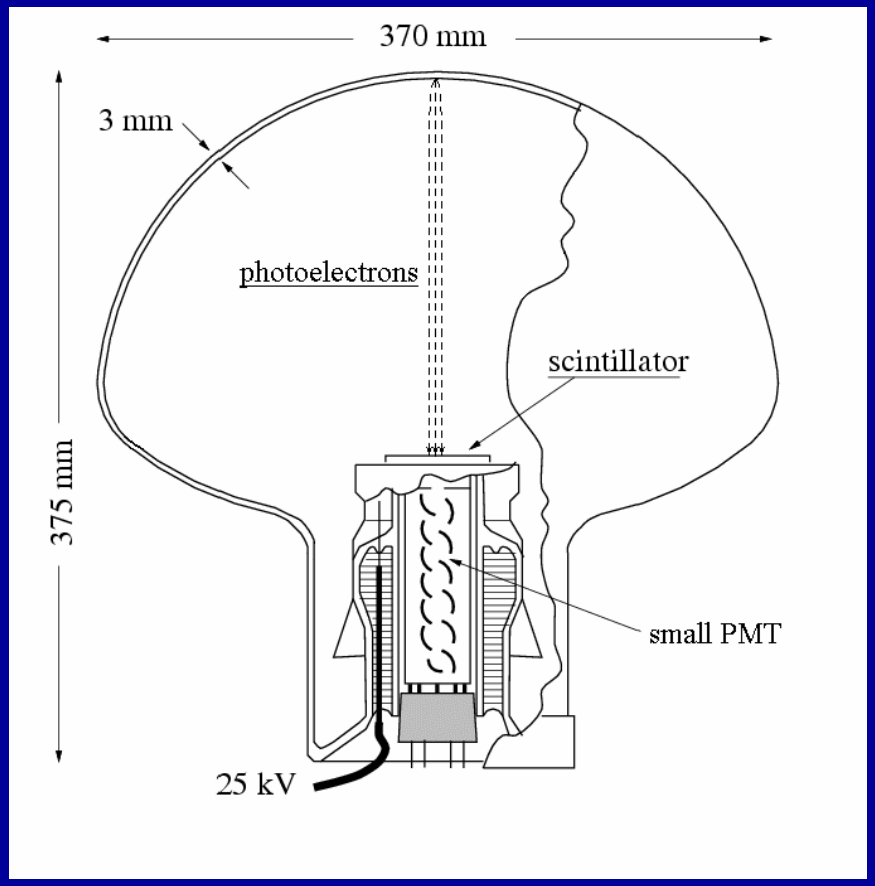
LS-HP instead of X-HPD???

XP2600



Transit time difference ~5ns.

QUASAR-370

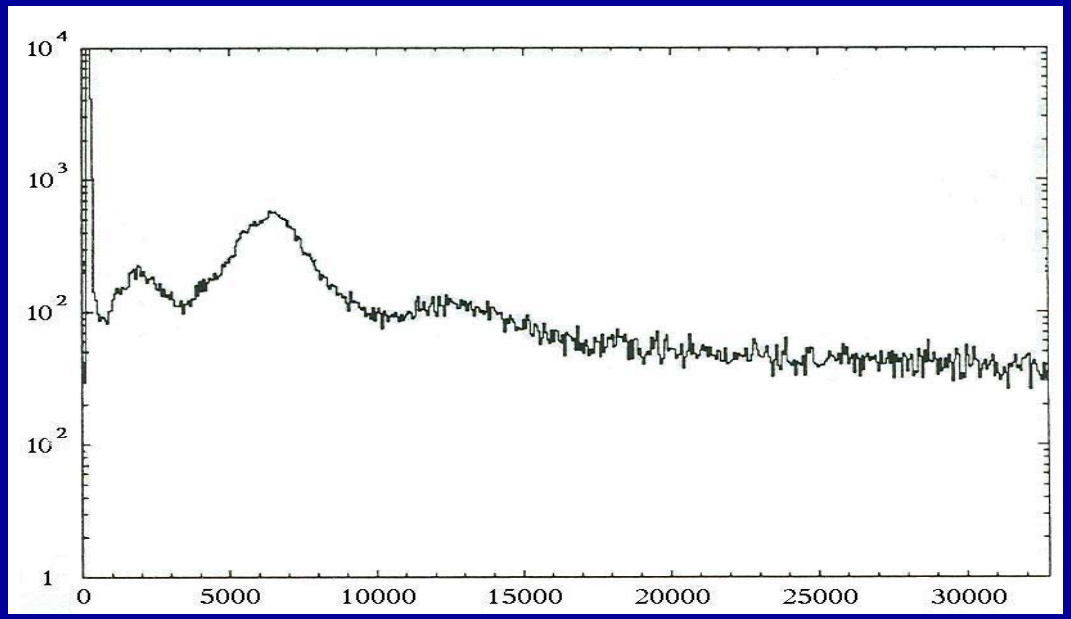


Transit tiem difference ~0.8ns!

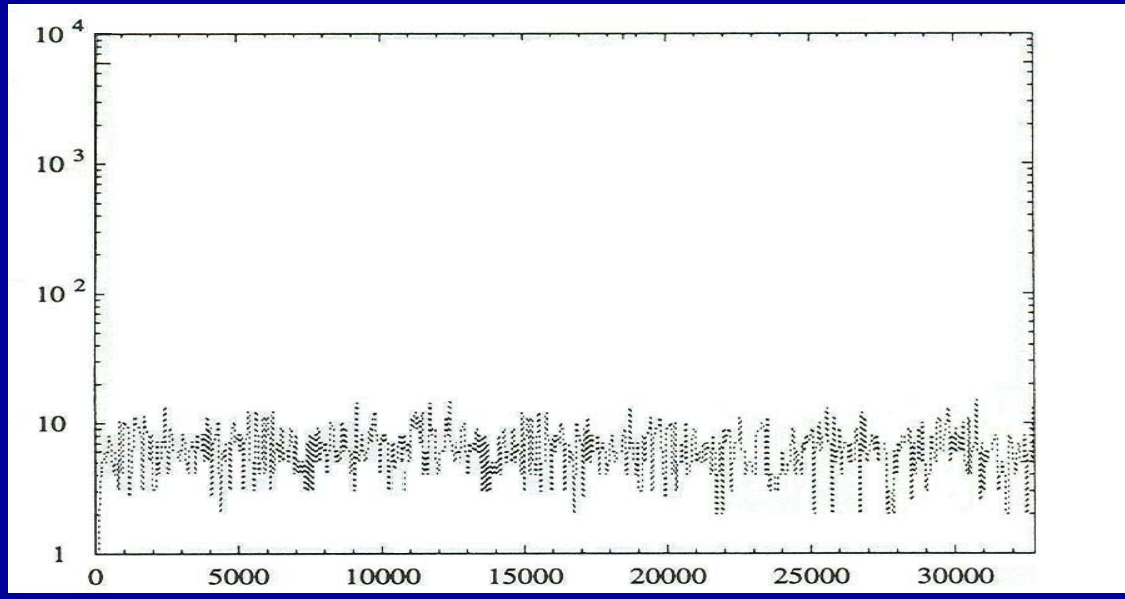
“…the largest eye ever recorded, by the way, is a colossal 37 cm in diameter. The leviathan that could afford to carry such eyes around is a giant squid with 10-metre tentacles.. ”

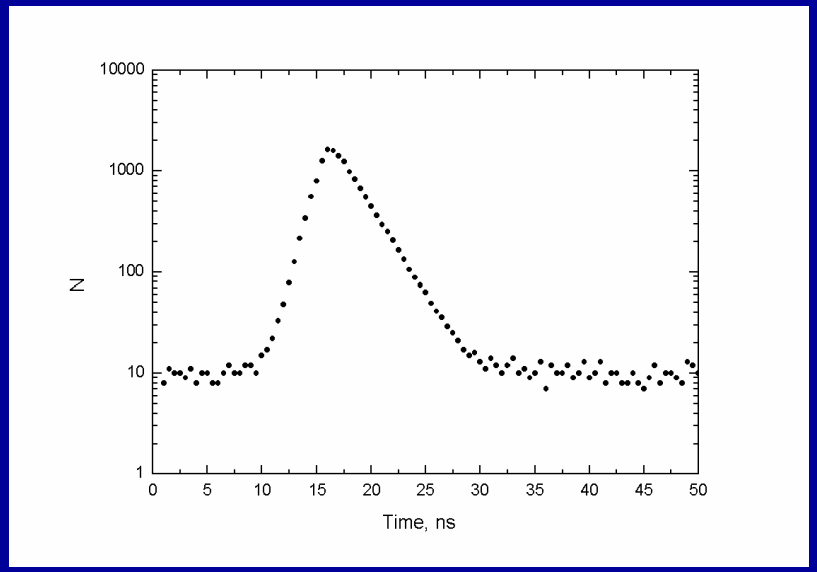
Richard Dawkins.
Climbing Mount Improbable. 1997

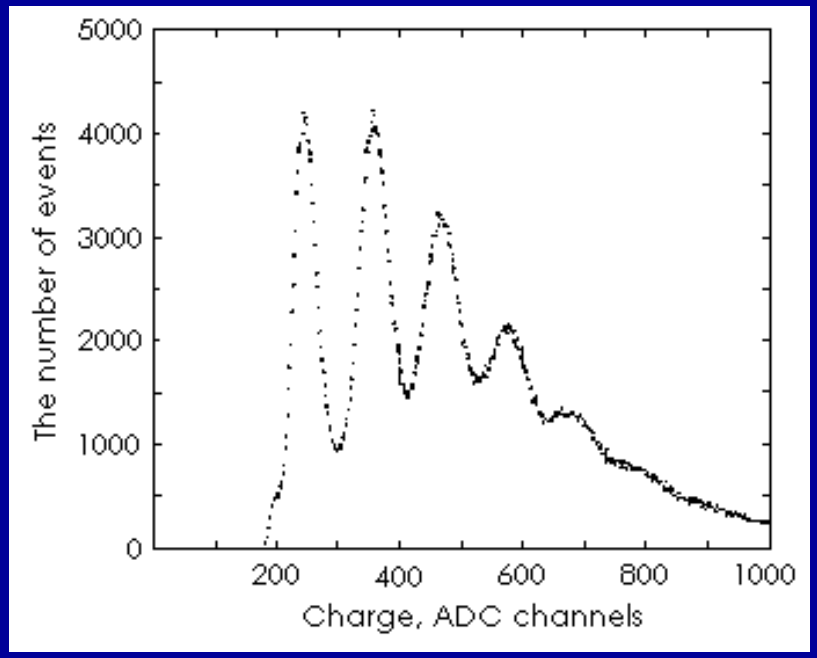
R5912
α~10%



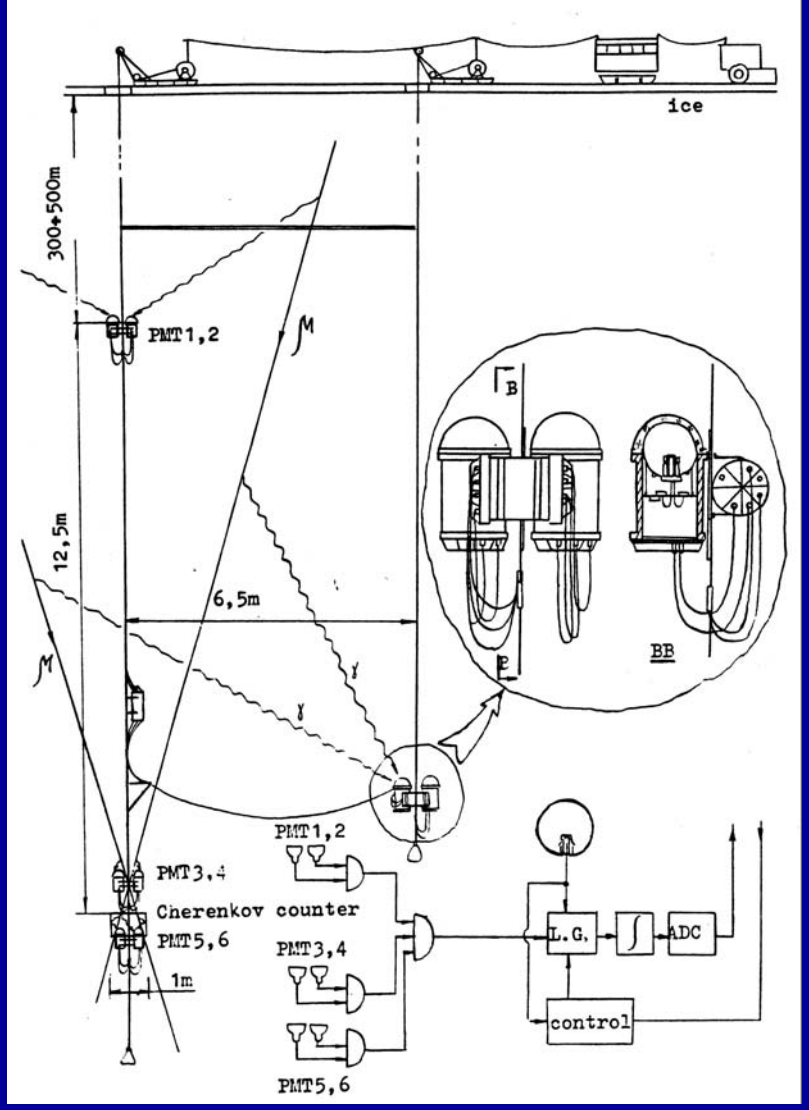
QUASAR-370
α<1%




10000
1000
100
10
1
N
0
5
10
15
20
25
30
35
40
45
50
Time, ns


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

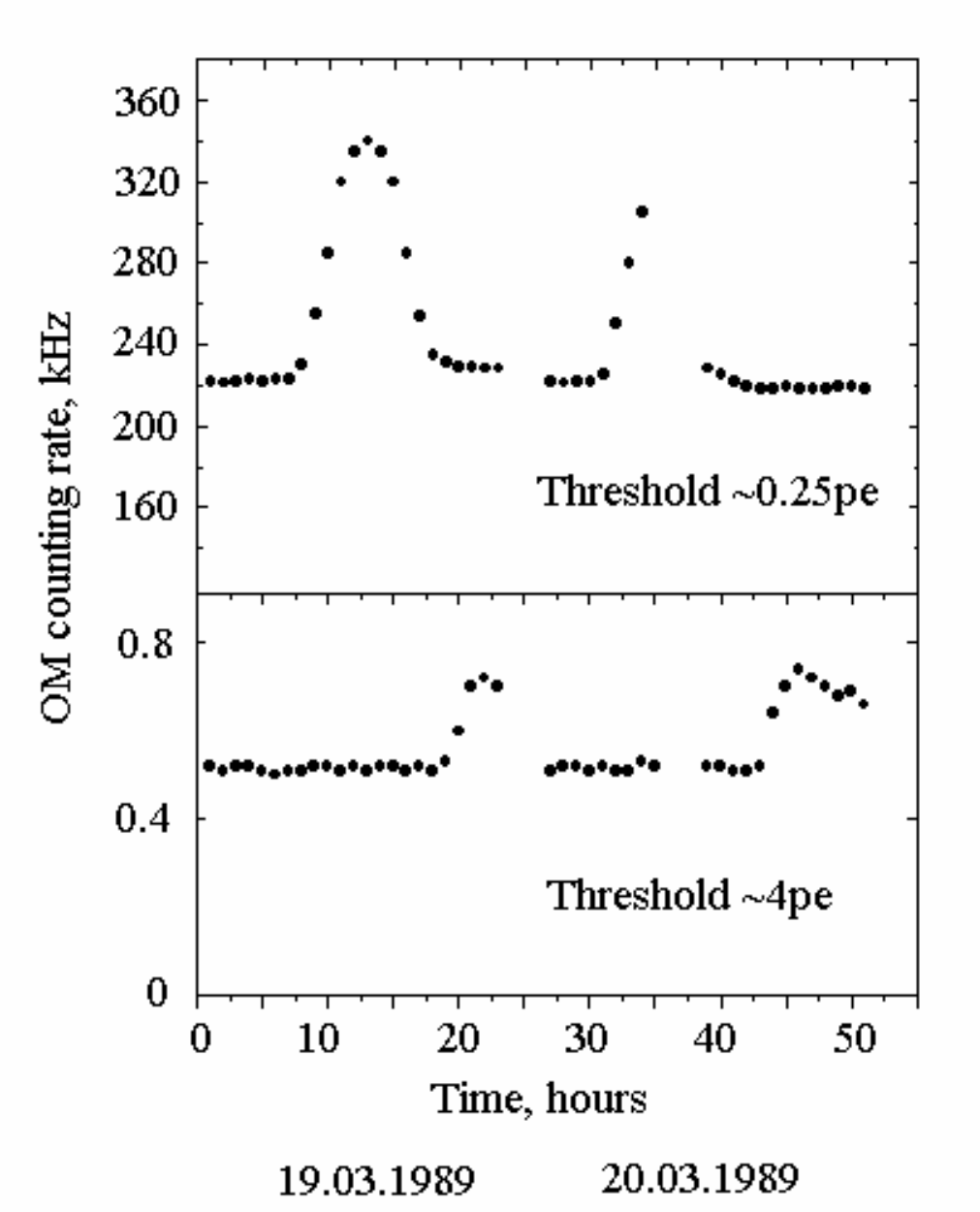
From FEU-49B to QUASAR-370

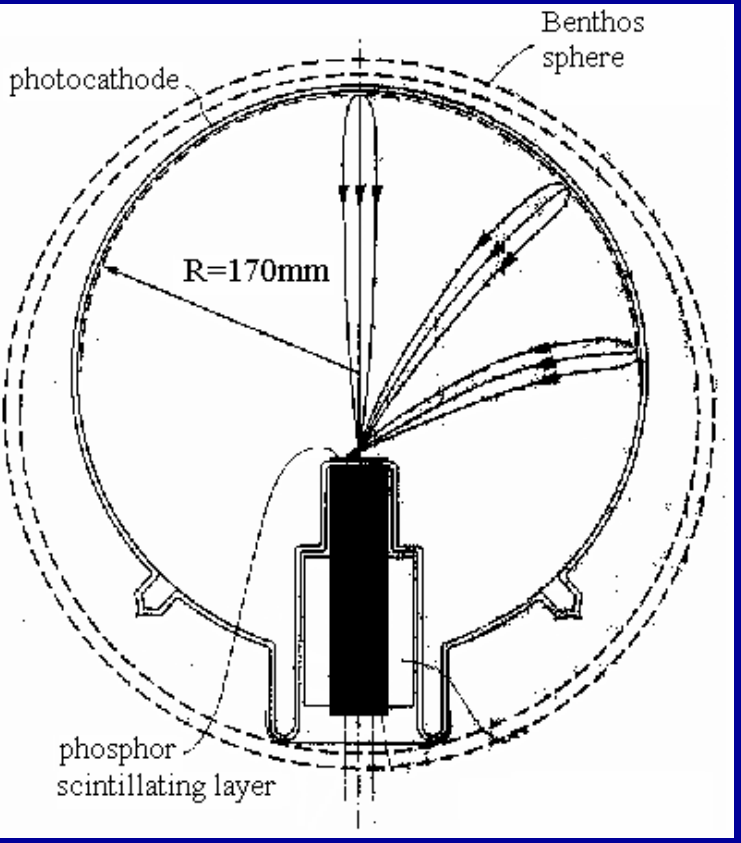


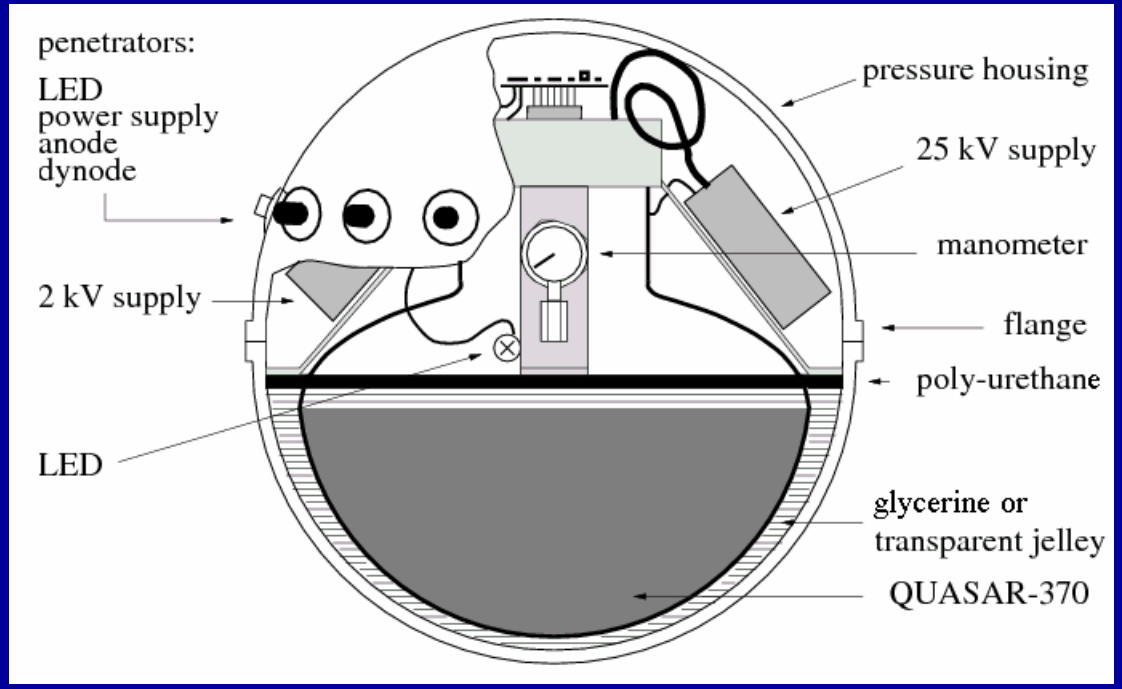
1987-1989 tests of first large area hybrid phototubes at Lake Baikal

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

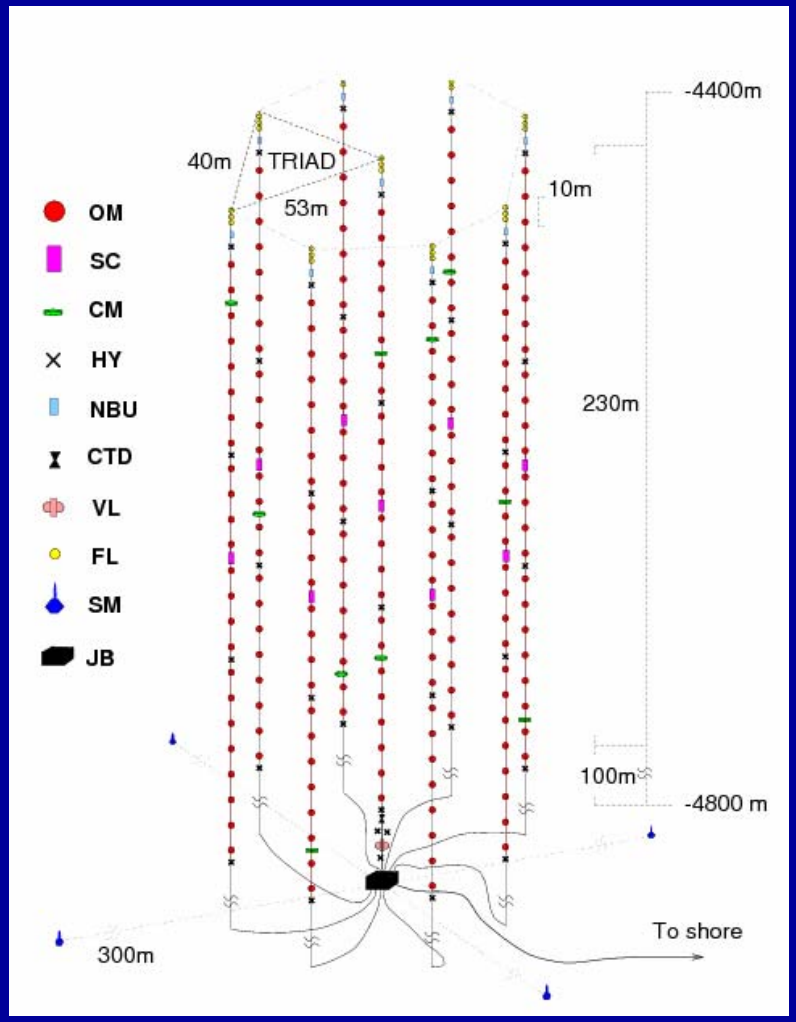
This phenomenon was discovered only owing to the fact that afterpulses in hybrid phototubes are substantially suppressed in comparison with conventional PMTs!

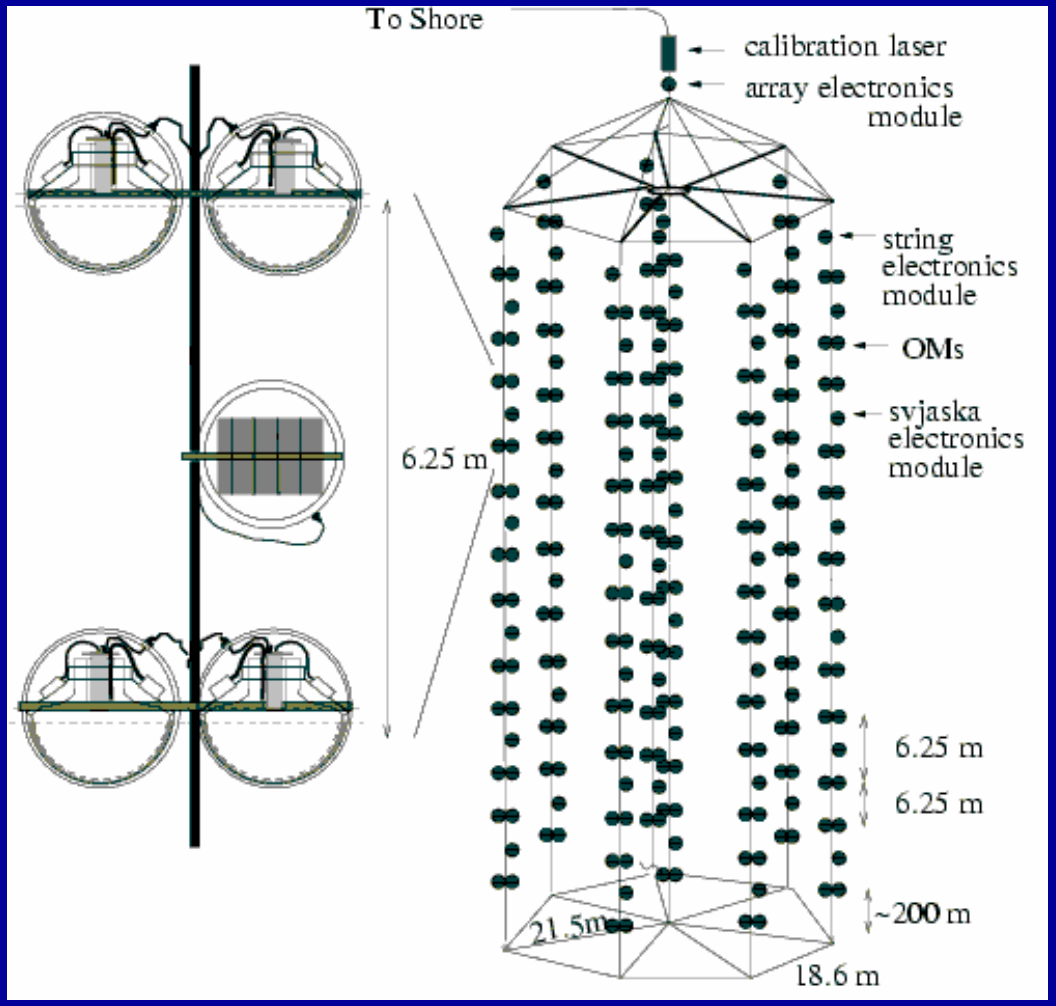






Suits well into 17’’ Benthos sphere
Glycerine is optically good but ….
Enough room for electronics





3 EOM in TRIAD,
13 OMs were produced altogether

>200 OMs

Ch.Wiebusch, RWTH Aachen 1995

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

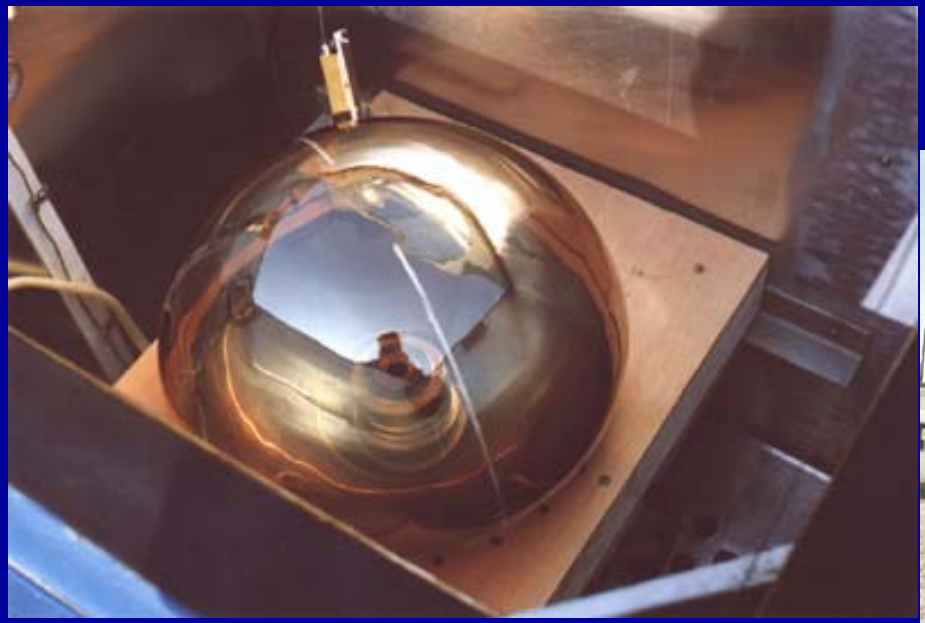
- no prepulses
- no late pulses in TTS
- low level of afterpulses
- ~100% effective collection effiency
- 1 ns TTS (FWHM)
- very good SER (competitive to HPD)
- immunity to terrestrial magnetic field

  $>2\pi$ sensitivity

QUASARs in Lake Baikal

QUASARs on the ice

QUASARs in Tunka Valley



TUNKA-25 Cherenkov EAS detector

QUASARs in Campo Imperatore

QUEST detector in frame of EAS-TOP
QUasars in Eas-Top

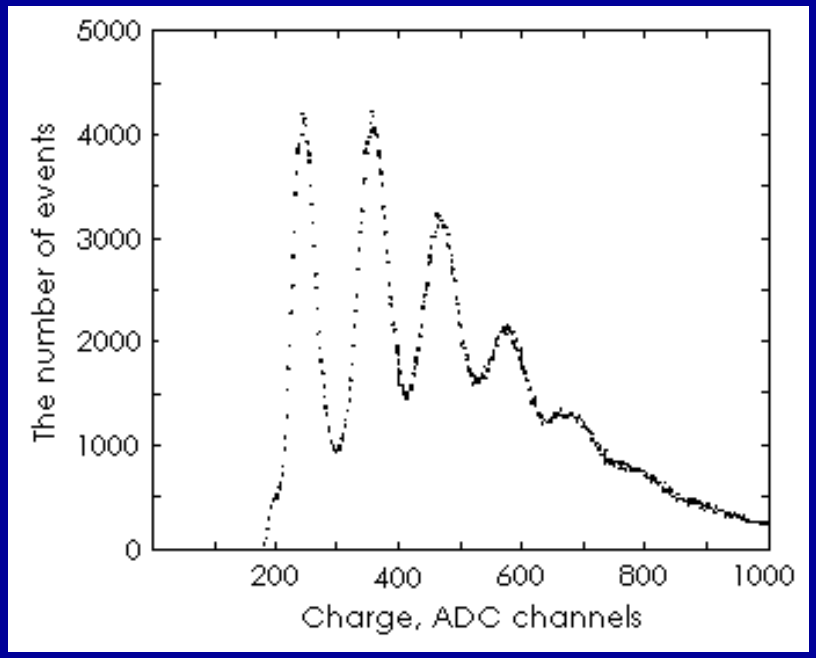
Successful operations of several astroparticle physics experiments (BAIKAL, TUNKA, SMECA, QUEST) prove the phototube's high performances, high reliability and robustness.

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

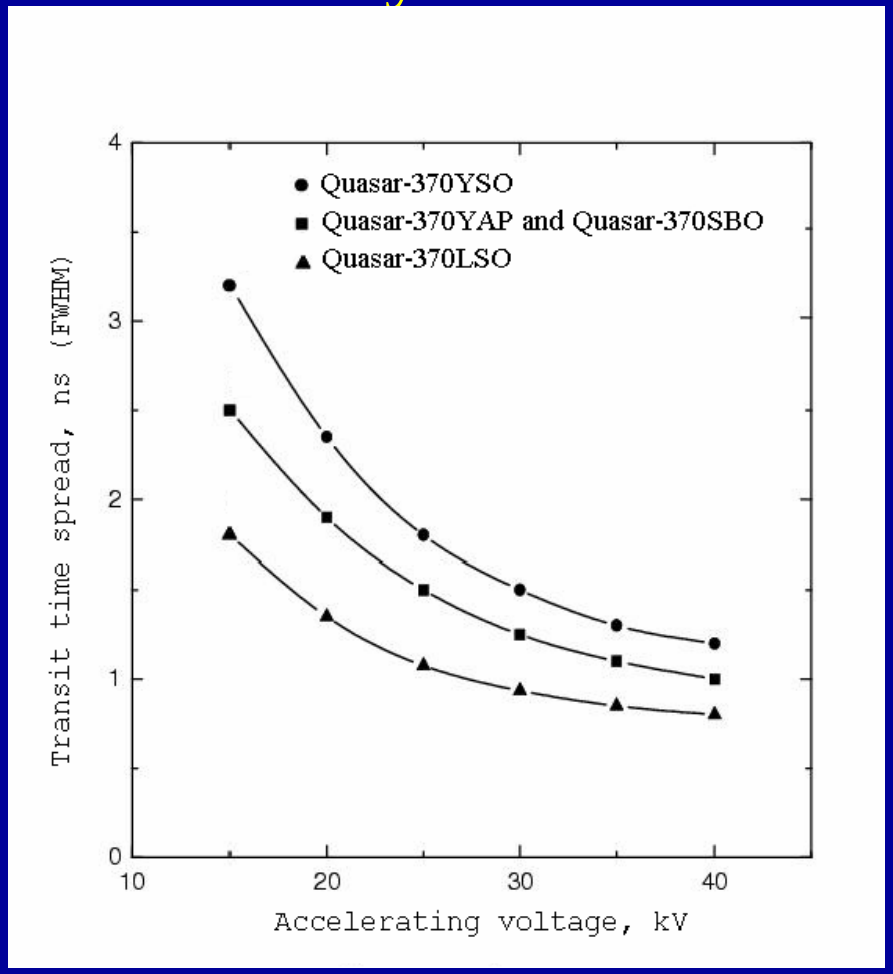
YSO, YAP, SBO, LSO, LPO etc.

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 - the first stage amplification factor

$$G = Y \times k \times \eta(eff)$$

Y - scintillator light yield

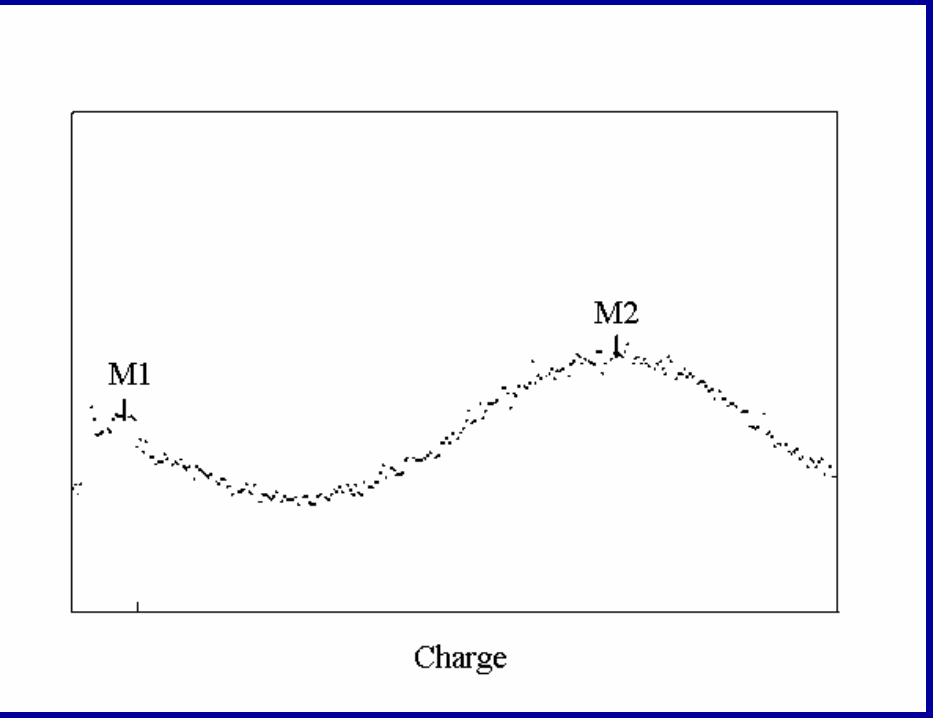
k - colection efficiency of photons on small PMT's cathode

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 with YSO scintillator

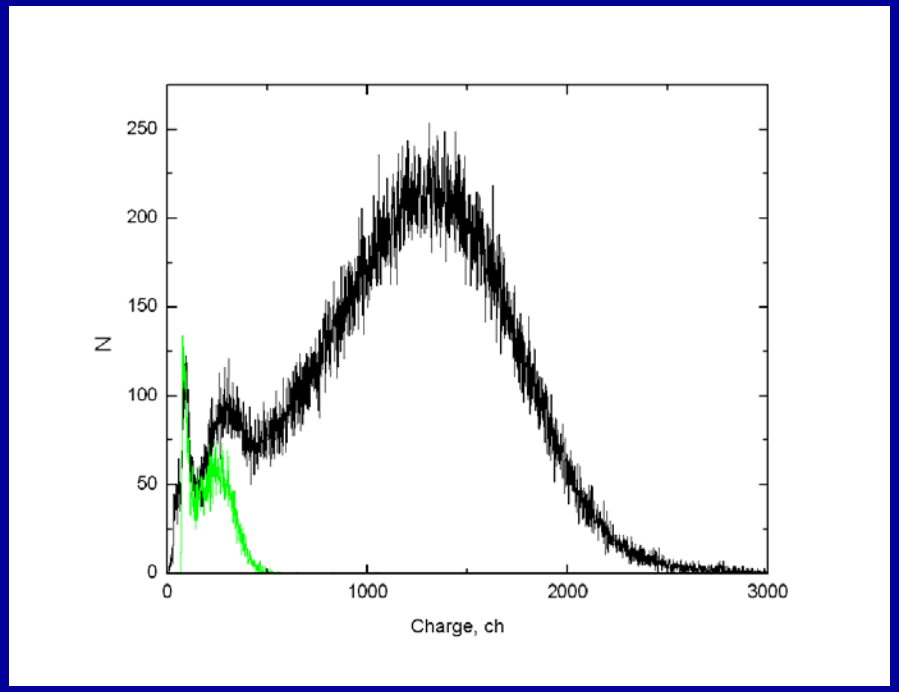


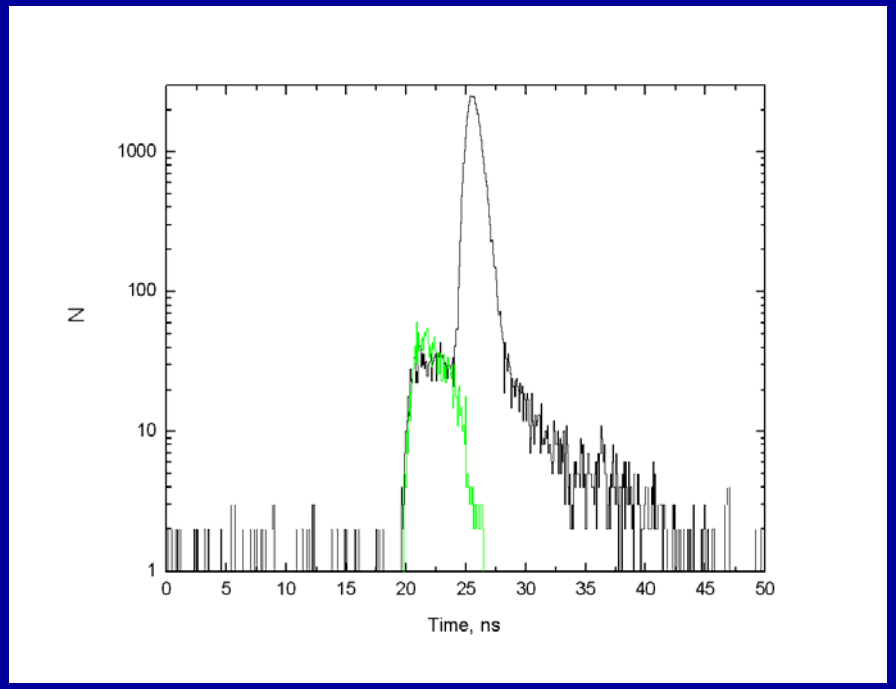
M1 - single pe peak of small PMT

M2 - single pe peak of Quasar-370

Threshold - ~0.005 pe!

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

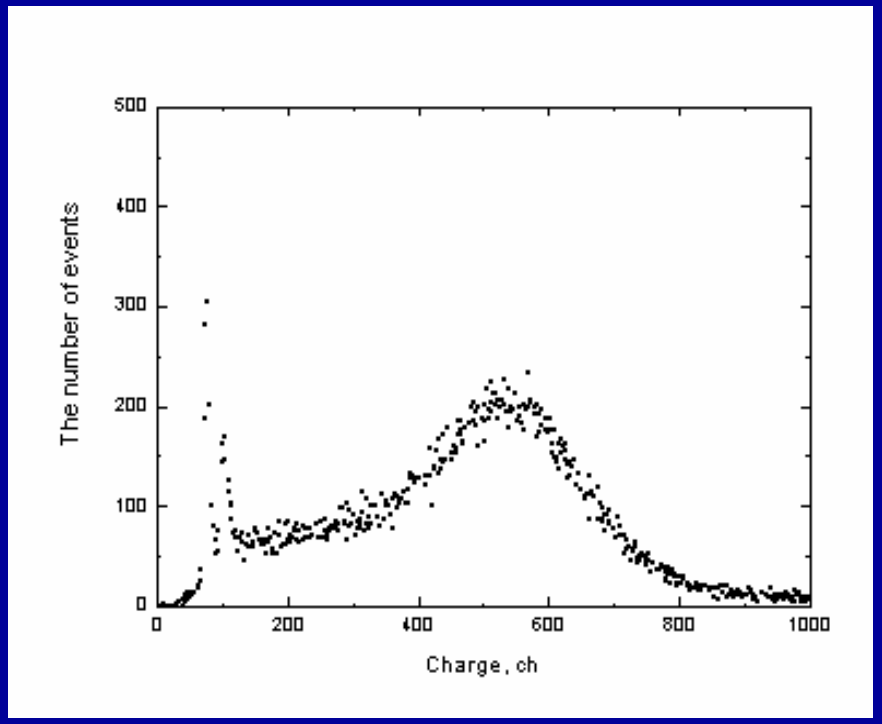


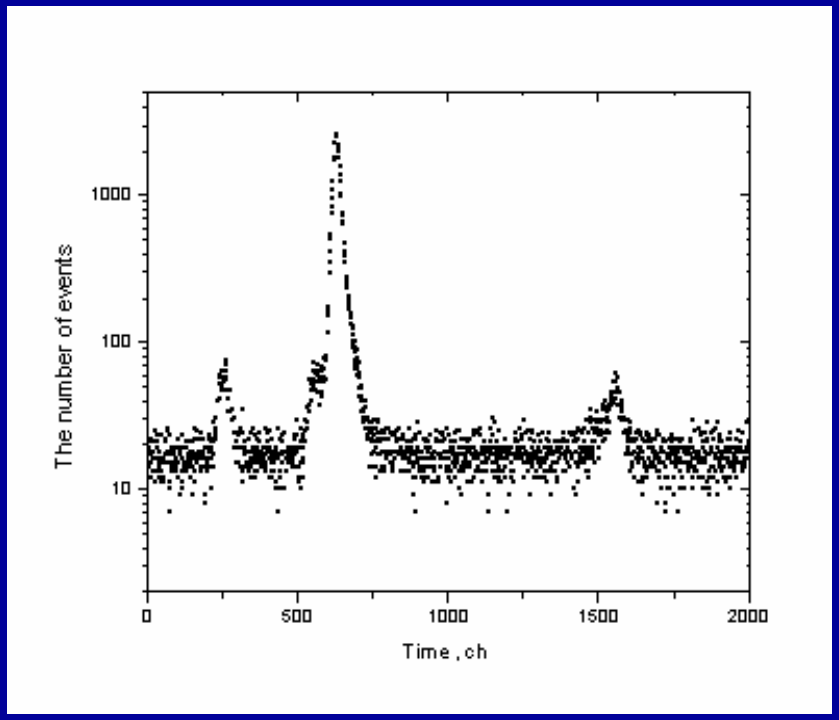


- Threshold - ~ 0.005 pe!
- Green - spectra measured with cathode camera switched off, i.e. cathode and 1 dynode are short circuited

Big hemispherical PMTs at low thresholds

Hamamatsu R8055 (13’’)



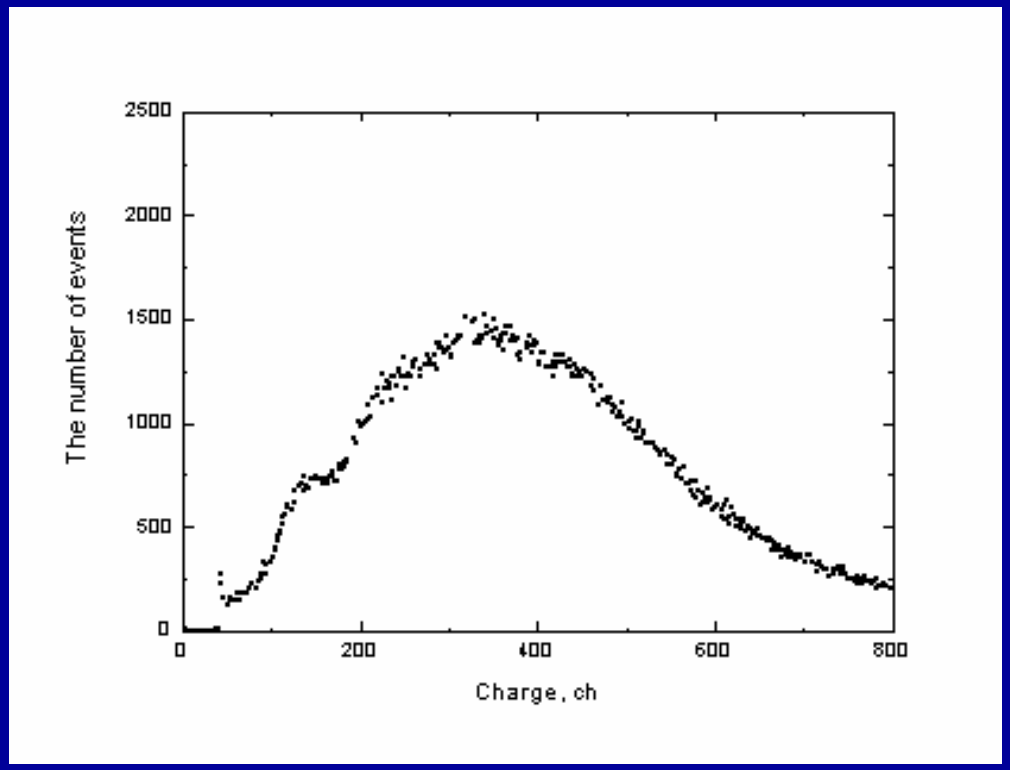


SER ~70% (fwhm)
0.005 pe threshold!

Jitter ~ 1.8 ns (fwhm)

Photonis XP1807 (12’’)

R8055



$\sigma \sim 35$

strong nonpoissonian behaviour!

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

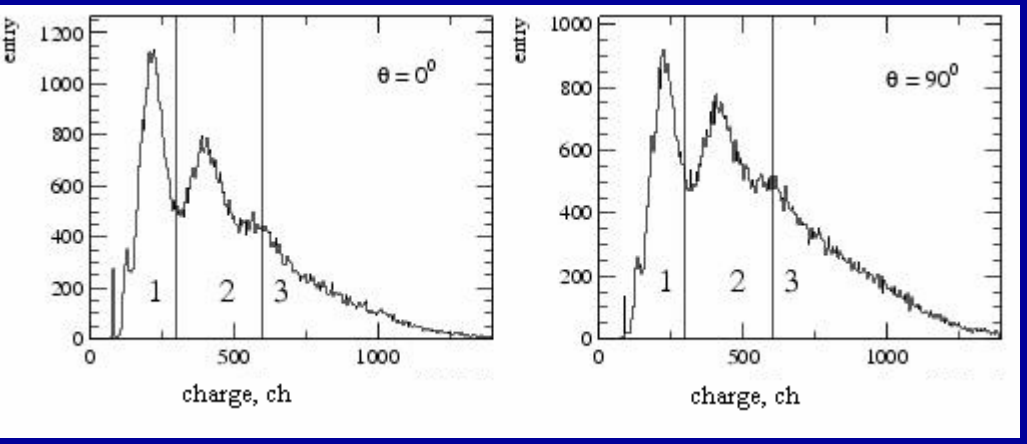
Afterpulses - ~20% heavy caesiation?

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

Impressive improvements of conventional PMTs perfomance!

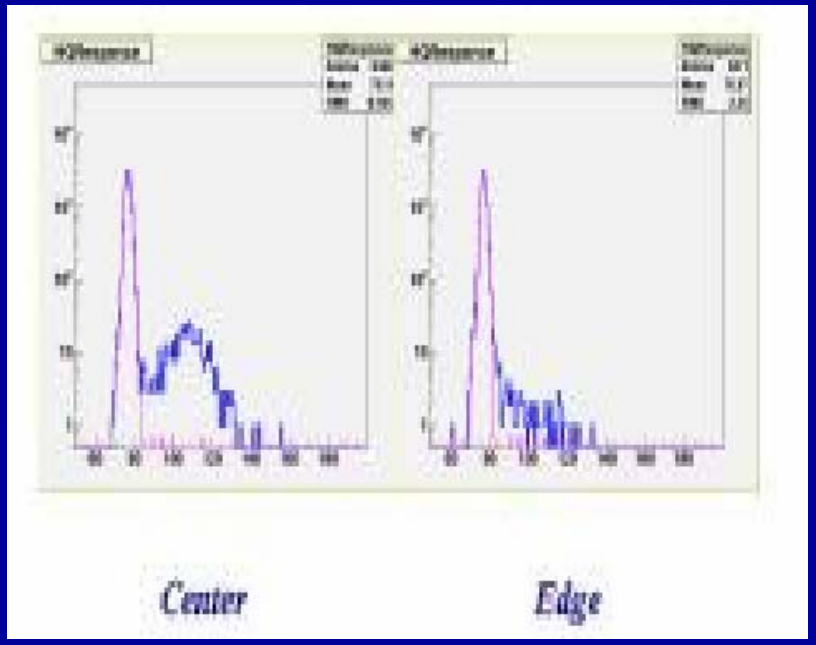
13'' R8055 Hamamatsu and 12'' XP1807 Photonis

XP2600, Quasar-370

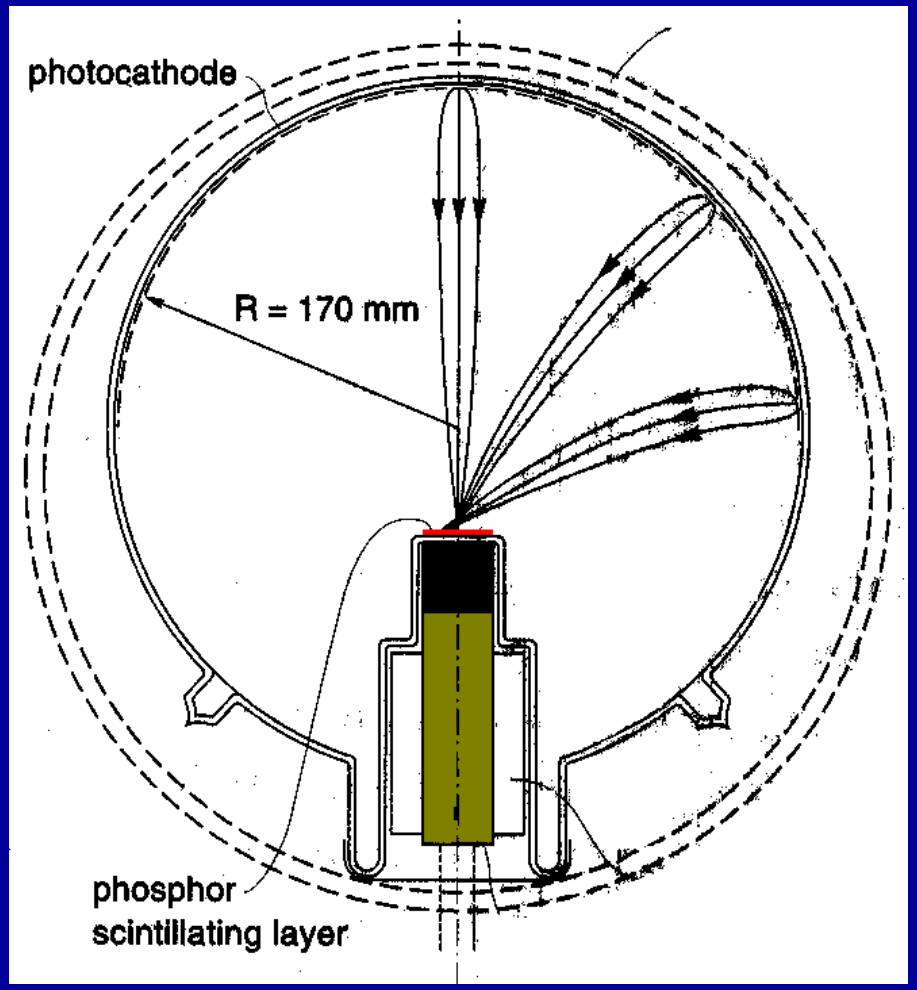


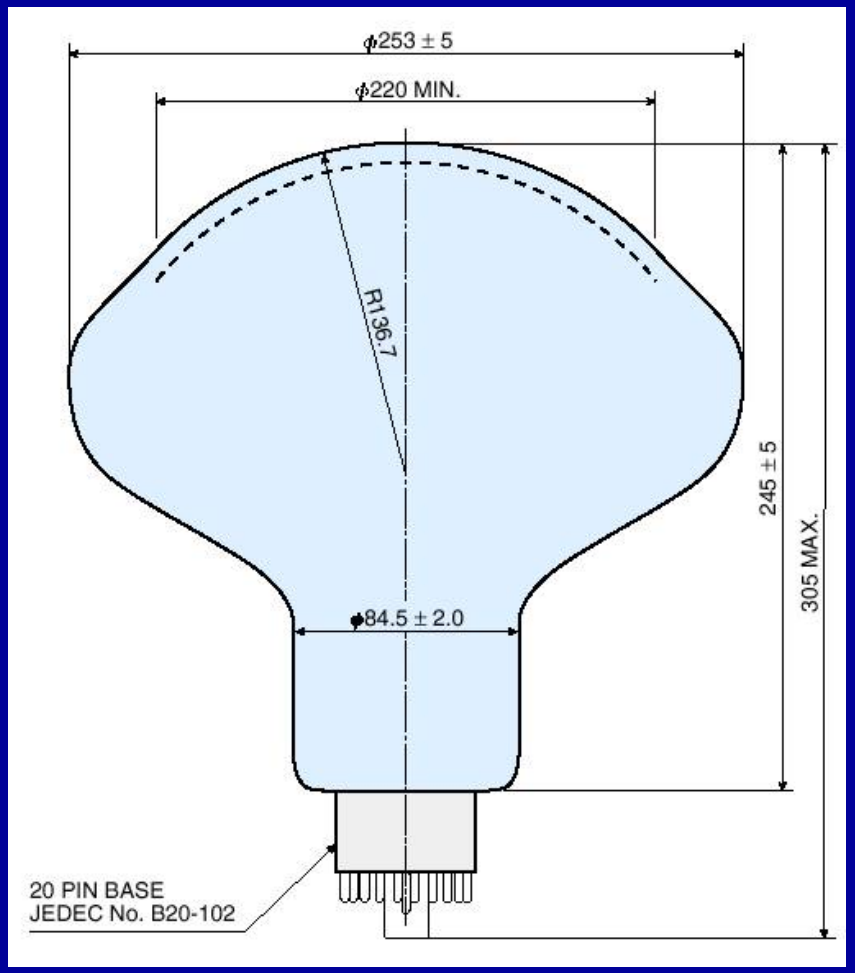
C.Wiebusch, RWTH-Aachen 1995

R7081



H.Miyamoto, Chiba University

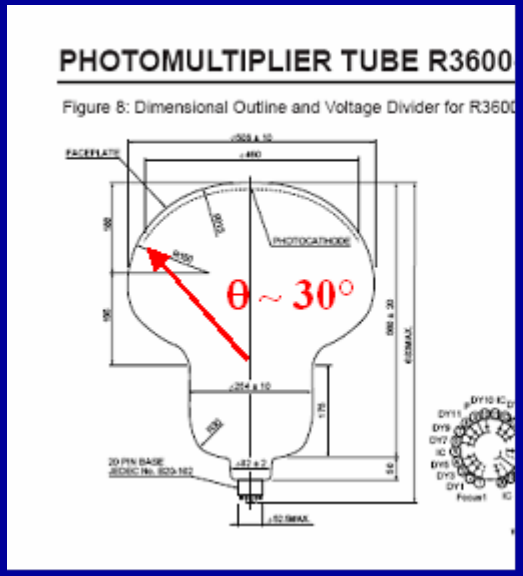


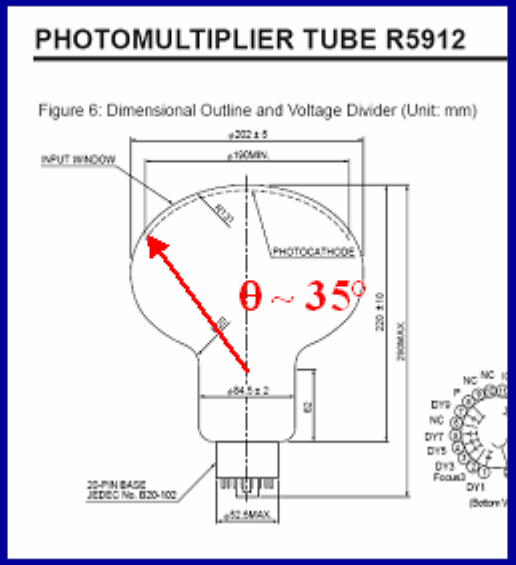


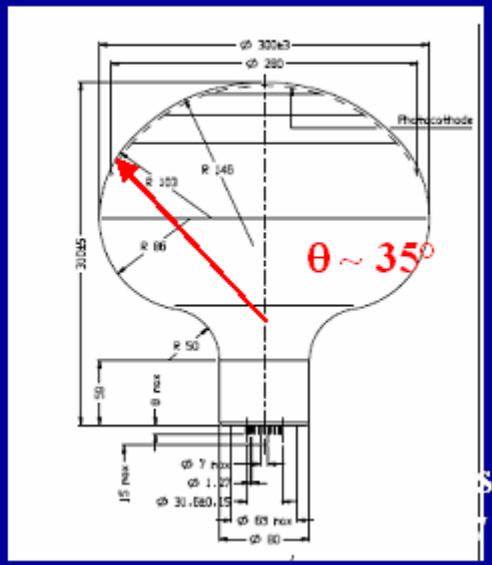
New parameter - effective photocathode occupancy E=Sph/Stotal !?

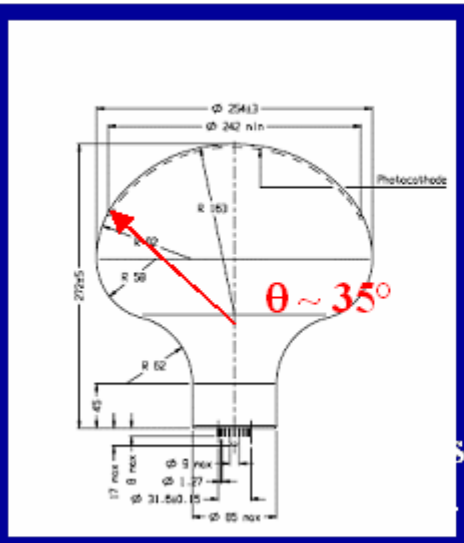
Quasar-370

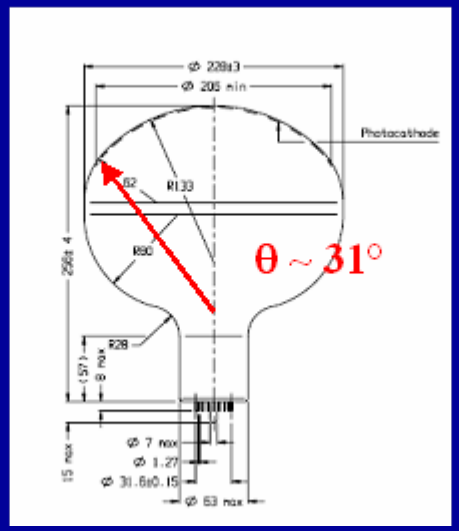
XP2600

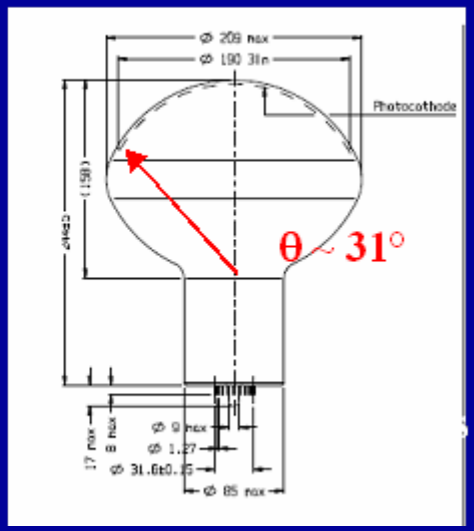










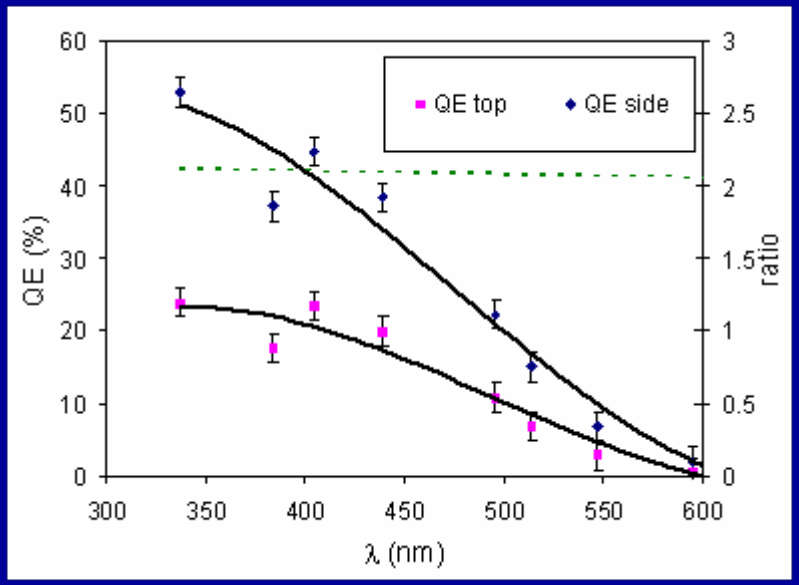


G.Hallewell CPPM Marseille

Conventional large are hemispherical PMTs are good for detectors like S-K where they look into the inner volume of vessels and there are no need for large angular acceptance.

12’’, 13’’ conventional PMTs are very important for new giant projects like H-Kamiokande, LENA etc.

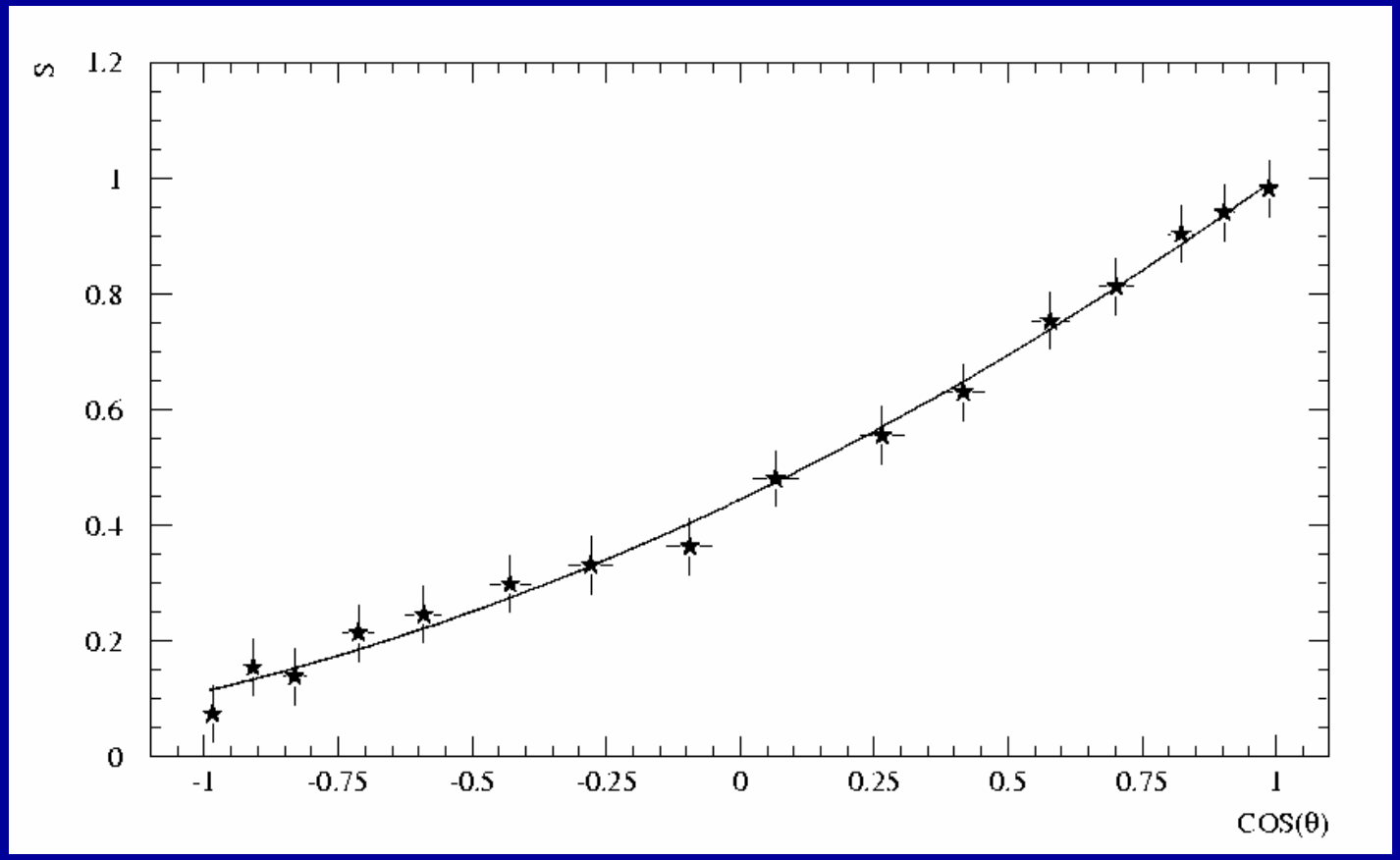
But they can’t compete with hybrid phototubes in angular acceptance



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

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

OM's (XP2600 and QUASAR-370) response to plane wave vs incident angle of plane wave



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

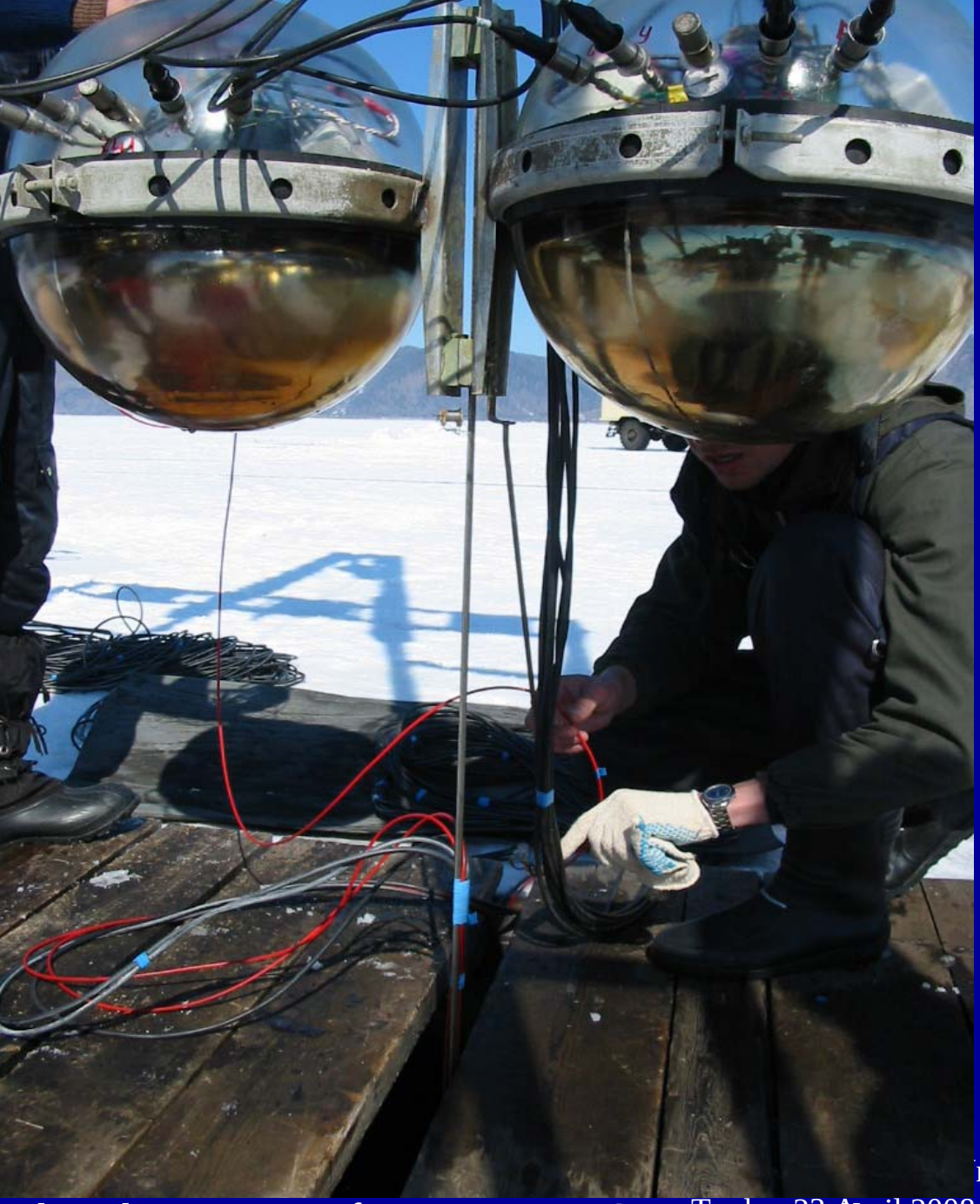
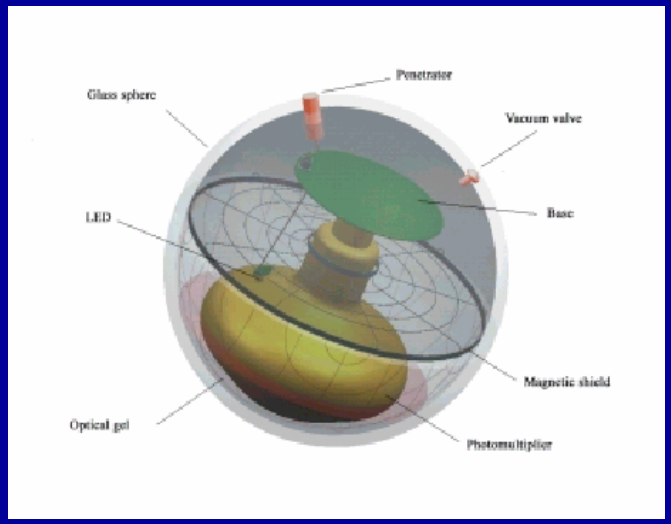


Photo by courtesy of Dr. V.Bertin, CPPM Marseille



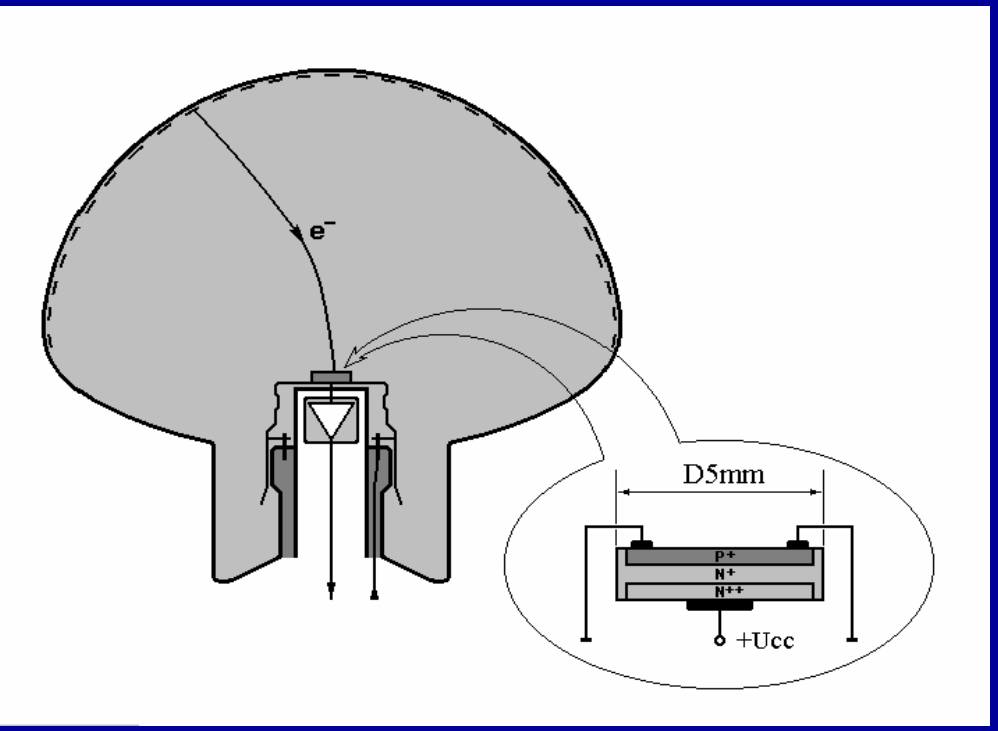
1987
Lake Baikal

1994
Lake Baikal

1998
Deutsche Museum, Bonn

Quasar-370D

1995-1997 Lubsandorzhiev, Putilov, Stepanenko
ICRC1997, COMO2001



- High mechanical precision
- Diode protection
- Subject to terrestrial magnetic field influence. (small size of diode, 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

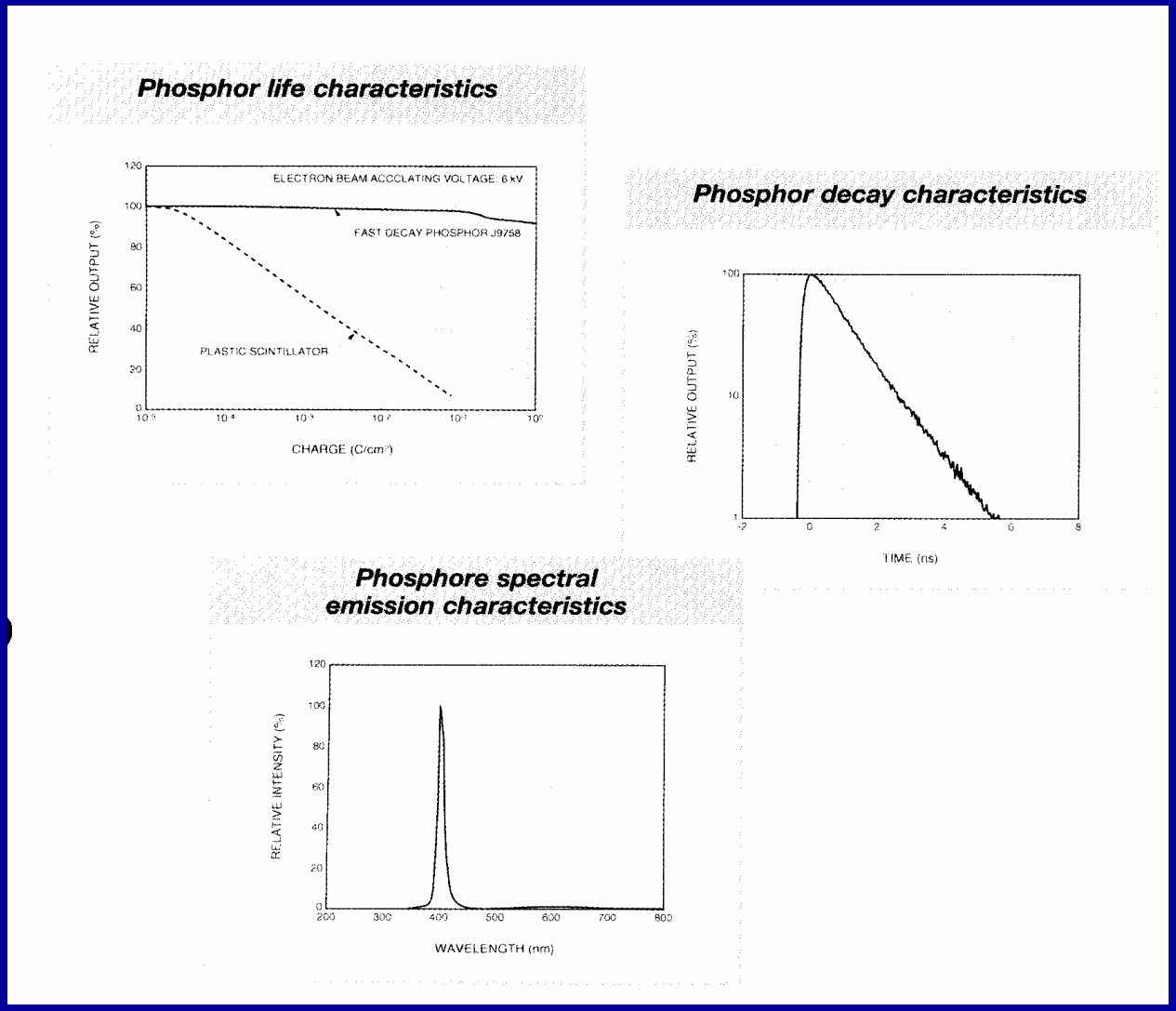
ZnO:Ga

F1 = F2 = 250!

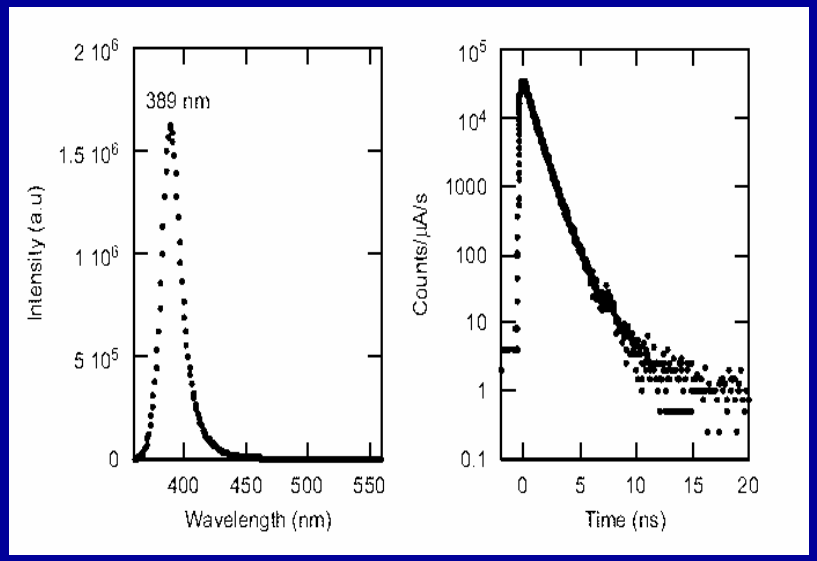
Challenge:

- 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)

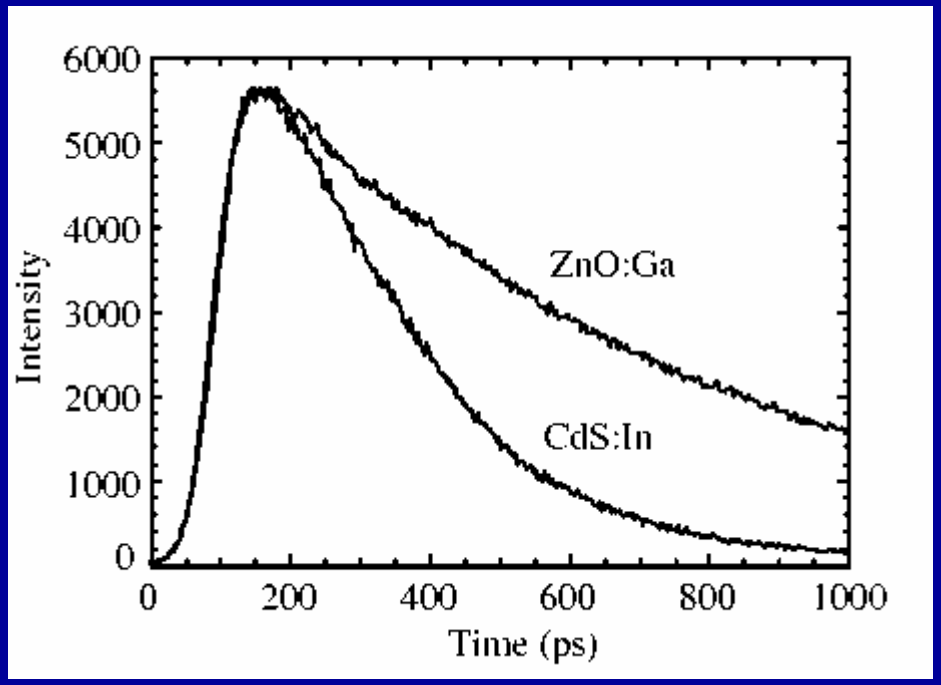


Hamamatsu news 2006, pp18-19



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 >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 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.