QUASAR-370 Hybrid Phototube as a prototype of a photodetector for the next generation of deep underwater neutrino telescopes

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

Experimental high energy neutrino astrophysics is entering its mature stage

2 deep underwater neutrino telescopes are running
The Lake Baikal and the ANTARES Deep Underwater Neutrino telescopes
Half of the ICECUBE Under-ice Neutrino Telescope is already operating.

So far there are no high energy cosmic neutrinos!

Larger arrays are needed!?

The next generation high energy neutrino telescopes is in the offing

One of the main points of the discussions is a photodetector development

There are two competing trends in the photodetector development for such application

Large sensitive area conventional (classical) type PMT (hemispherical)

Large area hybrid phototube (hemispherical or spherical)

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 angular acceptance

There is a large sensitive area photodetector which is free of all above mentioned disadvantages

Hybrid phototube with a luminescent screen

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. 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.

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

Electro-optical preamplifier (light amplifier) with large photocathode + small conventional type PMT

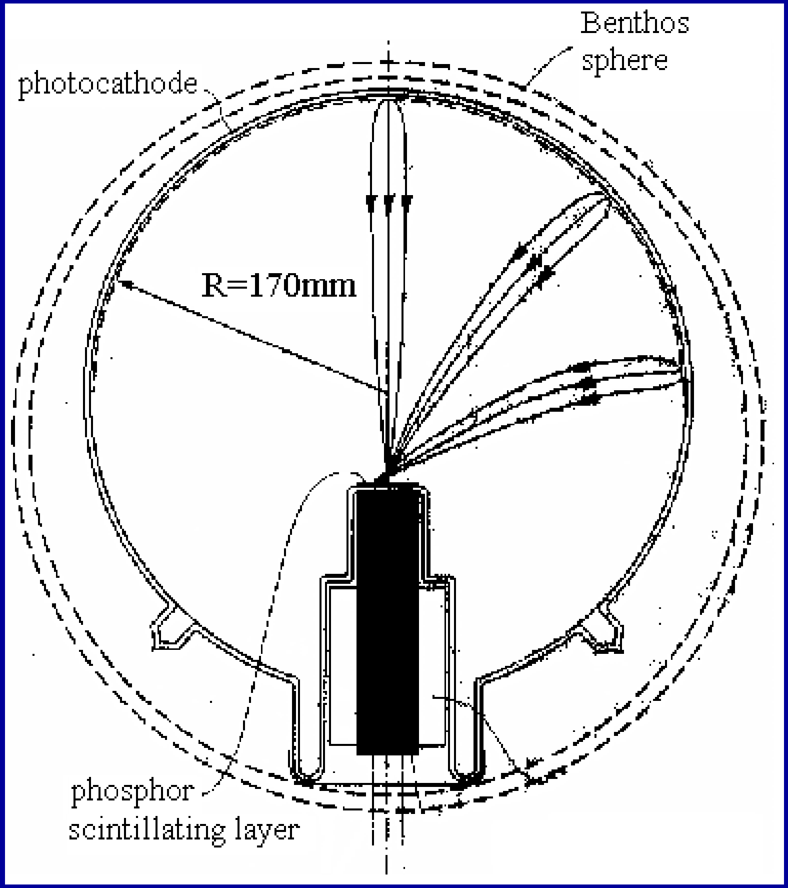
A number of scintillators are available only as phosphors (ZnO:Ga, LS, etc).

Sometimes it's better to work with phosphors.

X-HPD is just a part of the whole photodetector (Electro-optical preamplifier or light amplifier)

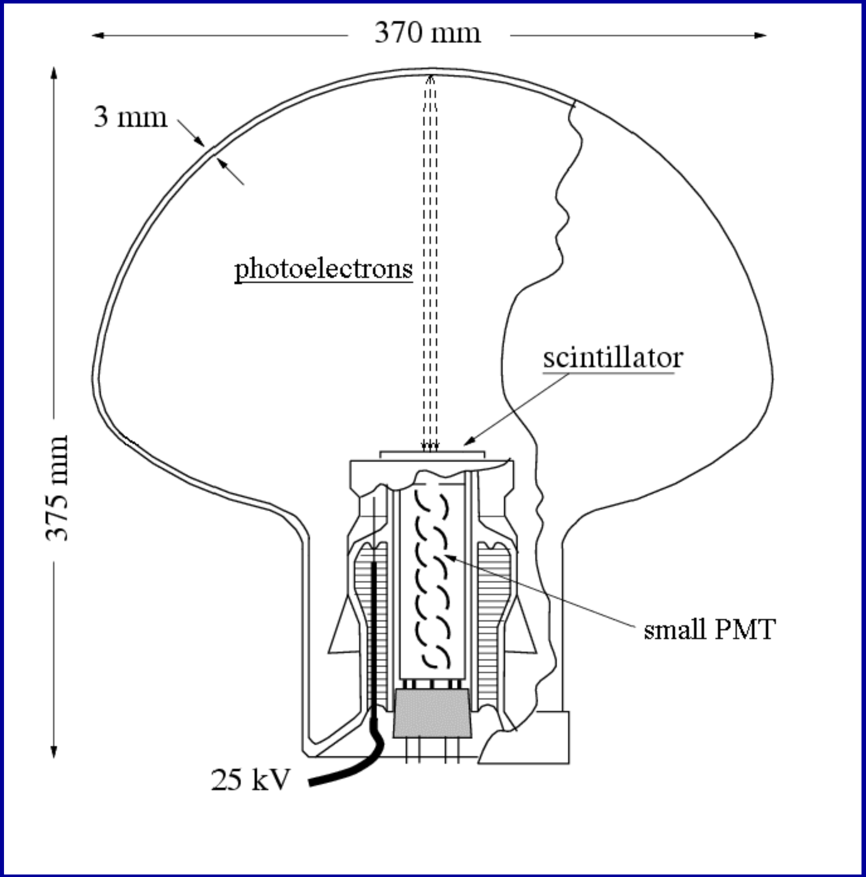
LS-HP instead of X-HPD???

XP2600



Transit time difference ~5ns.

QUASAR-370

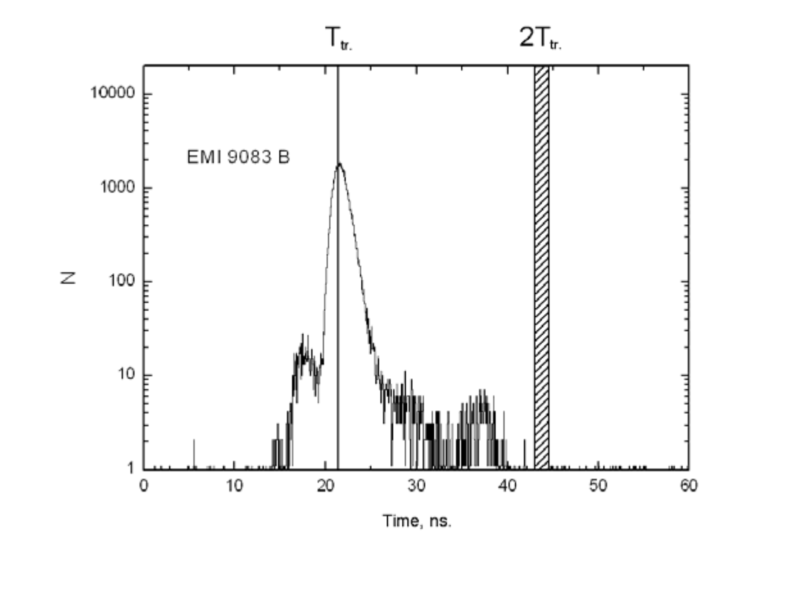


Transit time difference ~0.8ns!

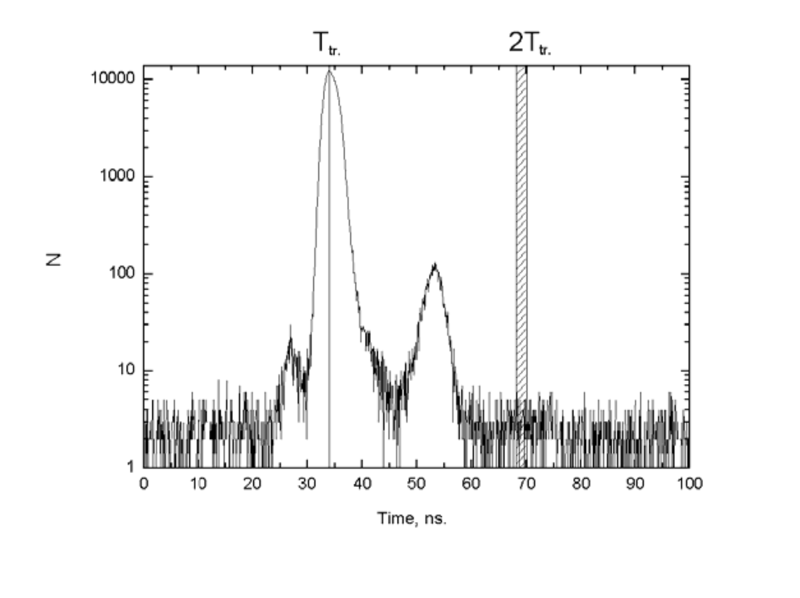
"…the largest eye ever recorded, by the way, is a colossal 37 cm in diameter. The leviathan that could afford to carry such eyes around is a giant squid with 10-metre tentacles.. "

Richard Dawkins.
Climbing Mount Improbable. 1997

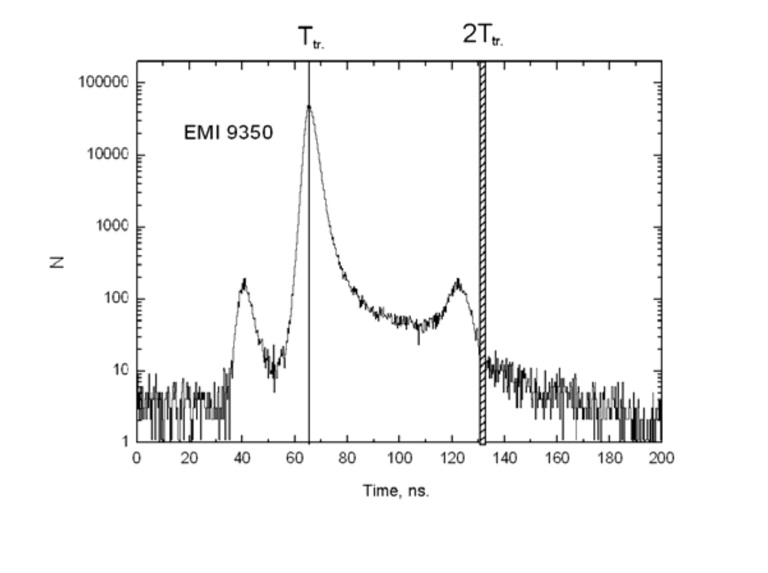
EMI 9083B



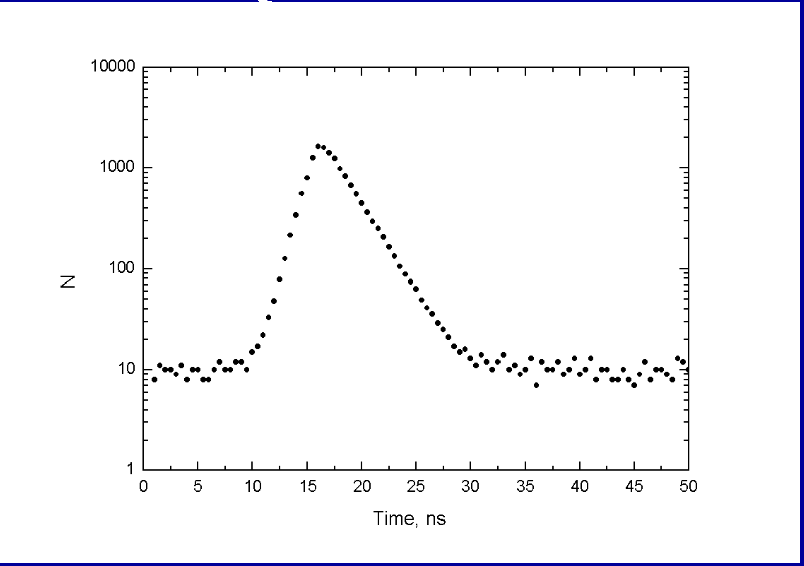
XP2020



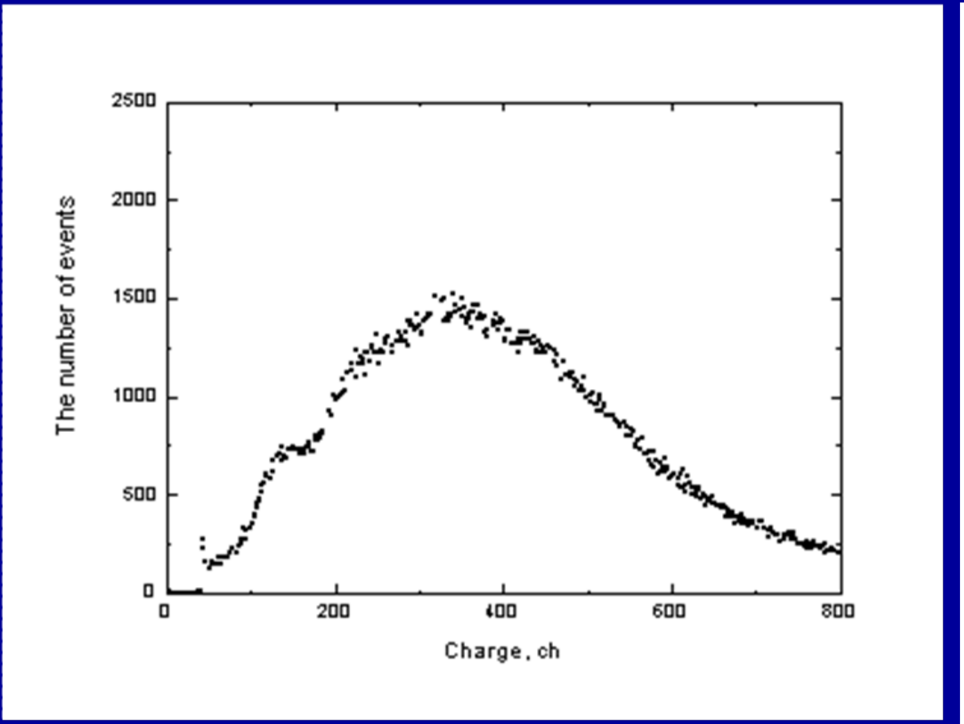
ET9350



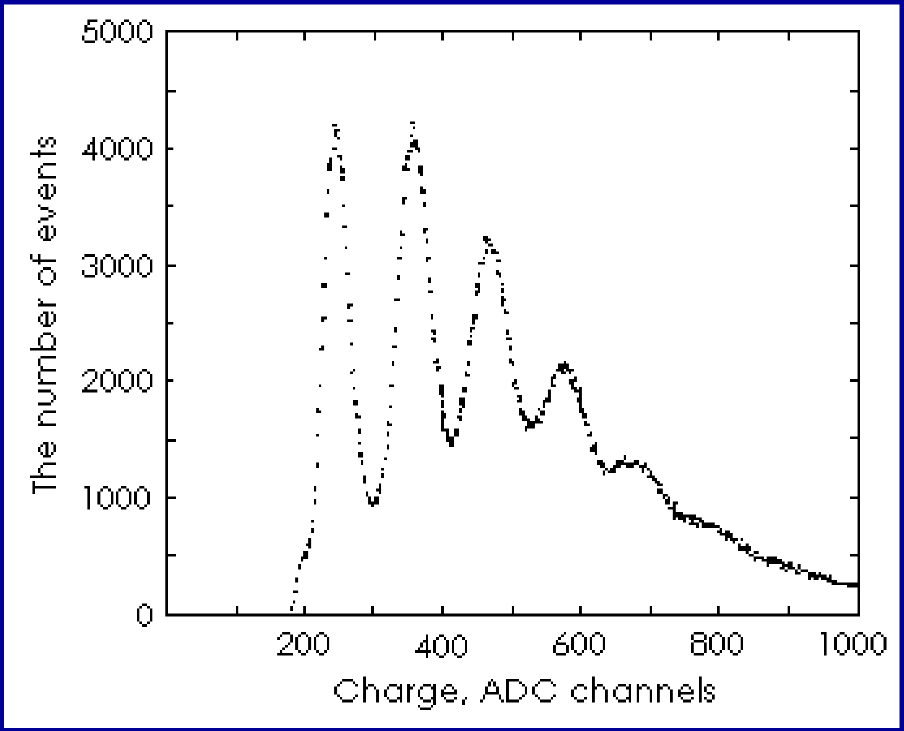
QUASAR-370



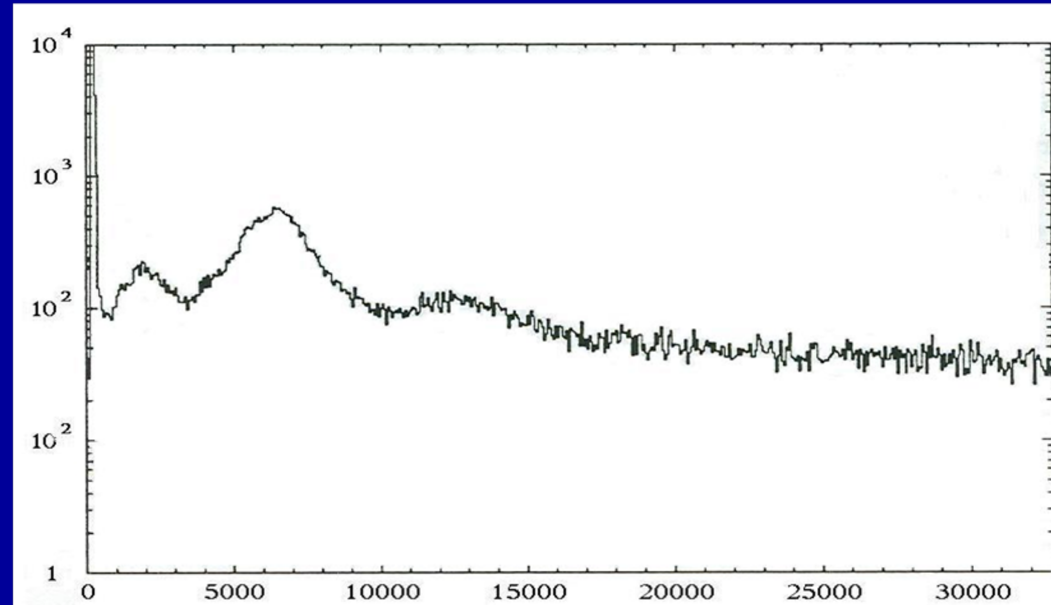
Hamamatsu R8055 (13'')



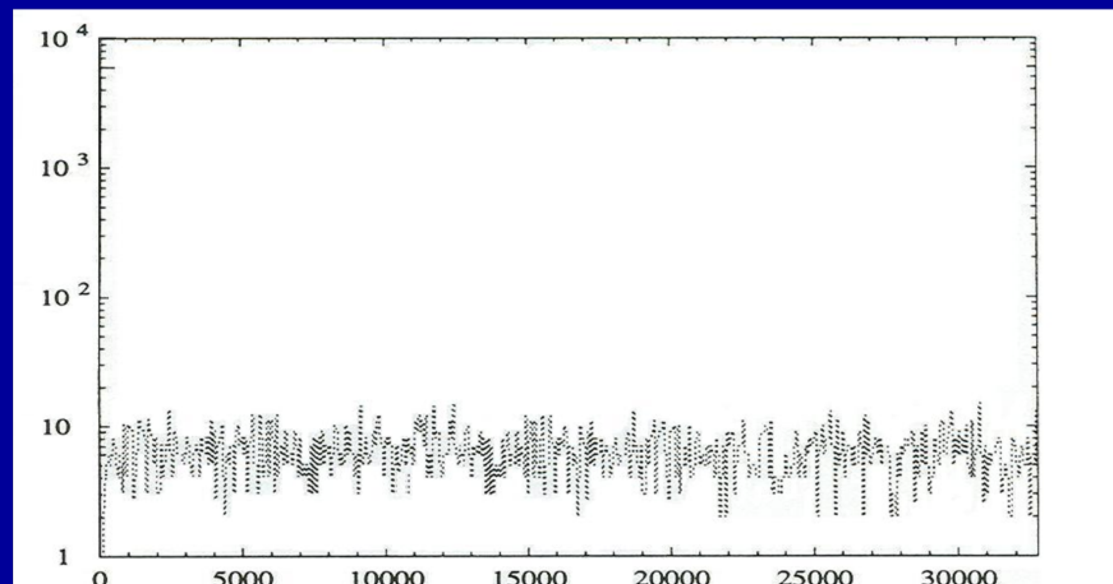
QUASAR-370



R5912 (8”)
α~10%

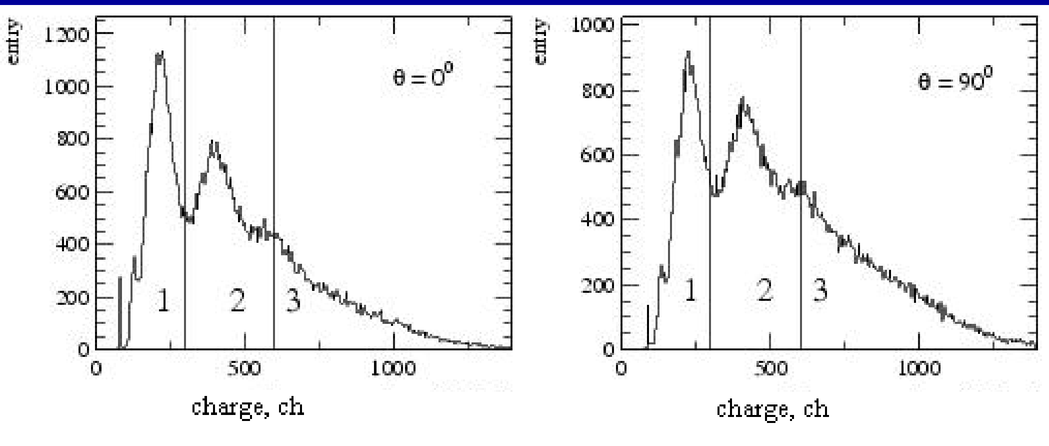


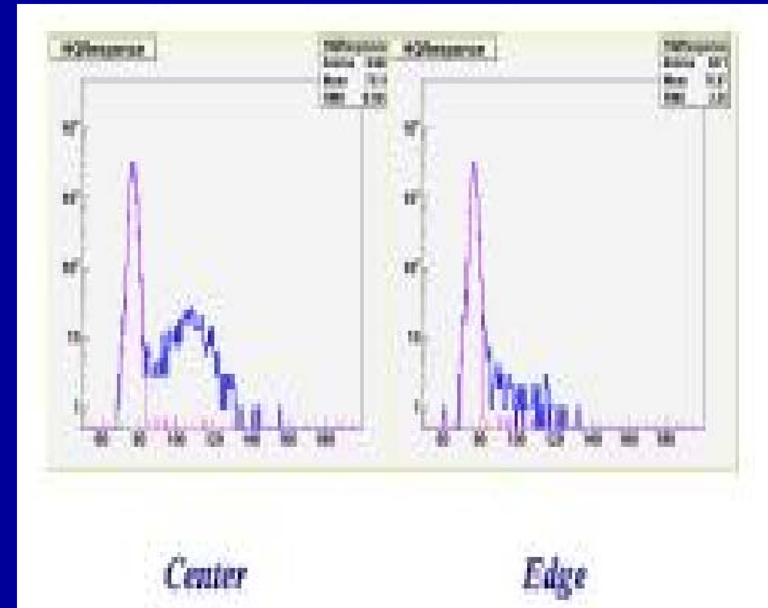
QUASAR-370 (16”)
α<1%



XP2600, Quasar-370

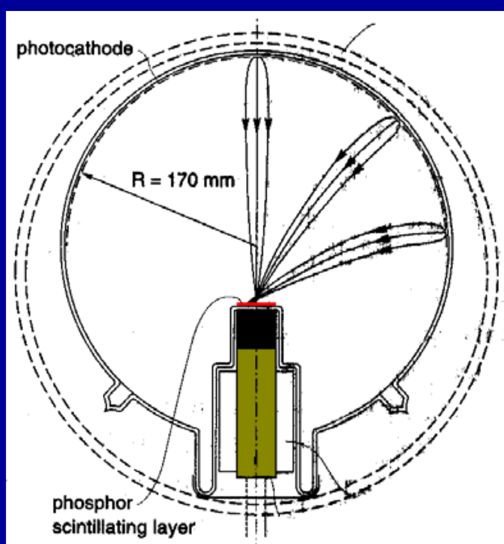
R7081

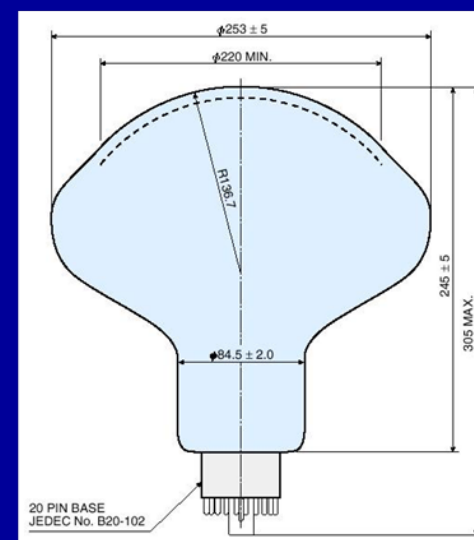


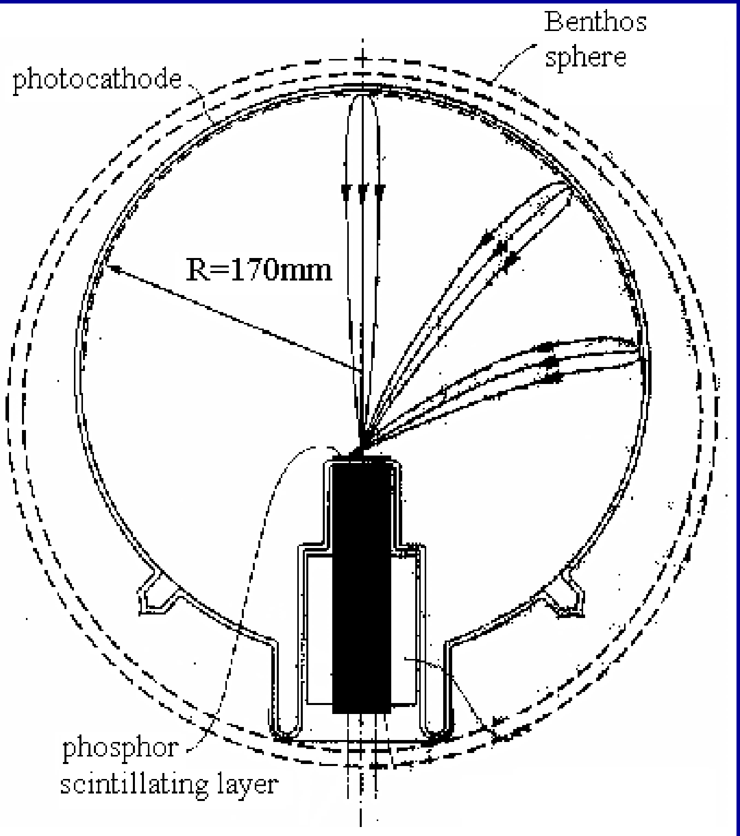


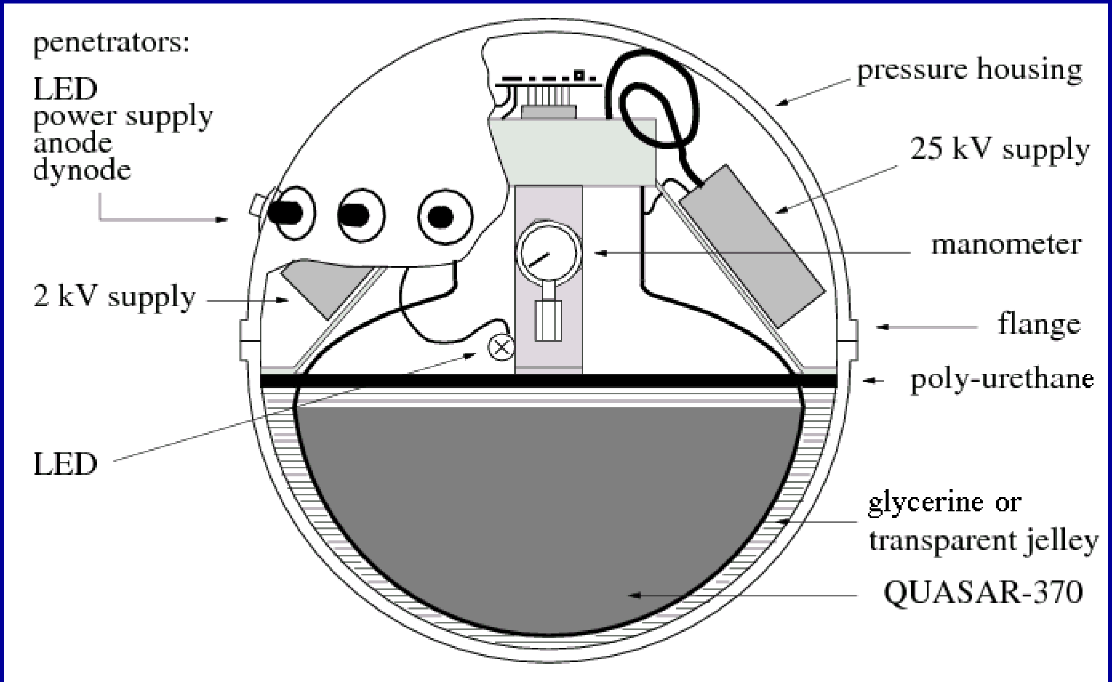
L.Bezrukov, B.Lubsandorzhiev 1987-1991
P.Bosetti, C.Wiebusch 1995

H.Miyamoto, Chiba University









Suits very well into the 17'' Benthos sphere

Enough room for electronics

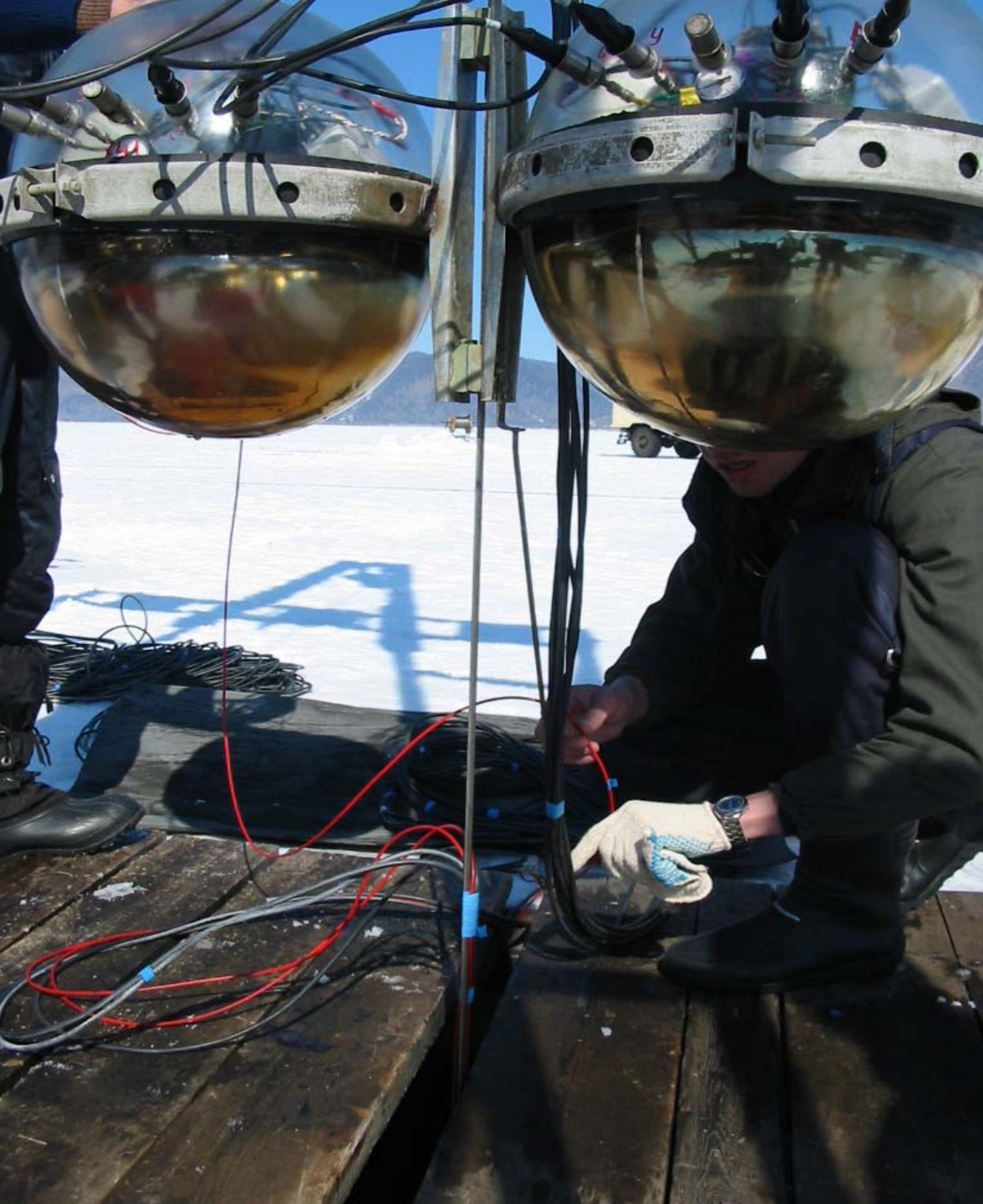
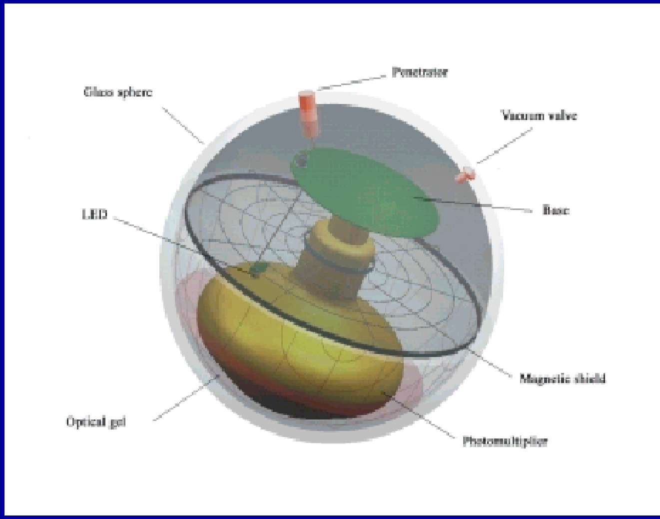
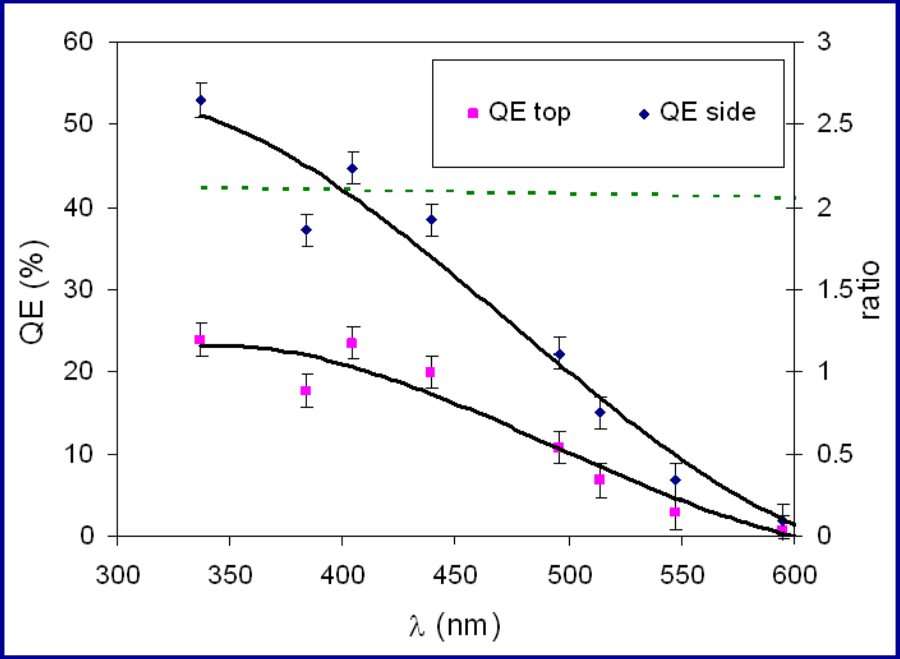


Photo by courtesy of Dr. V.Bertin, CPPM Marseille

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





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

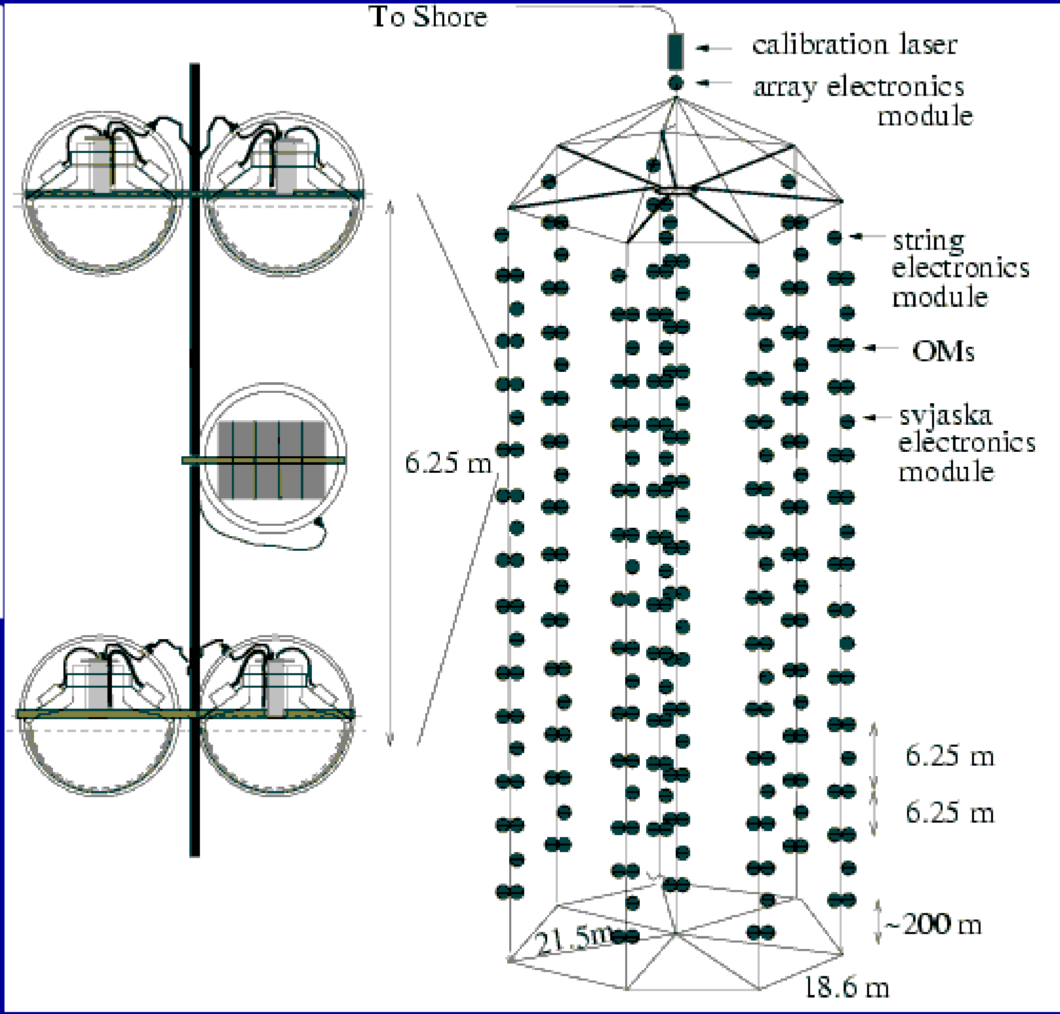
1987-1991
XP2600 - 30-50% effect
Quasar-370 - 10-25%

Conventional large are hemispherical PMTs are good for detectors like S-K where they look into the inner volume of the detector 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, time resolution and single electron response

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

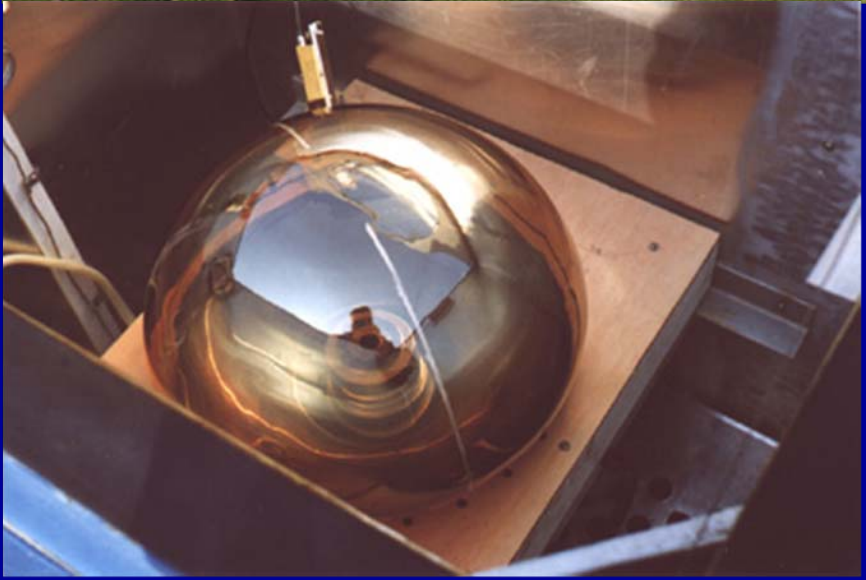
QUASARs in EAS-TOP EAS experiment in Campo Imperatore - QUEST detector (QUasars in Eas-Top)

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

Studies of EAS Cherenkov light lateral distribution and primary cosmic rays absolute intensity around the "knee" ($\sim 3\times10^{15}$ 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.

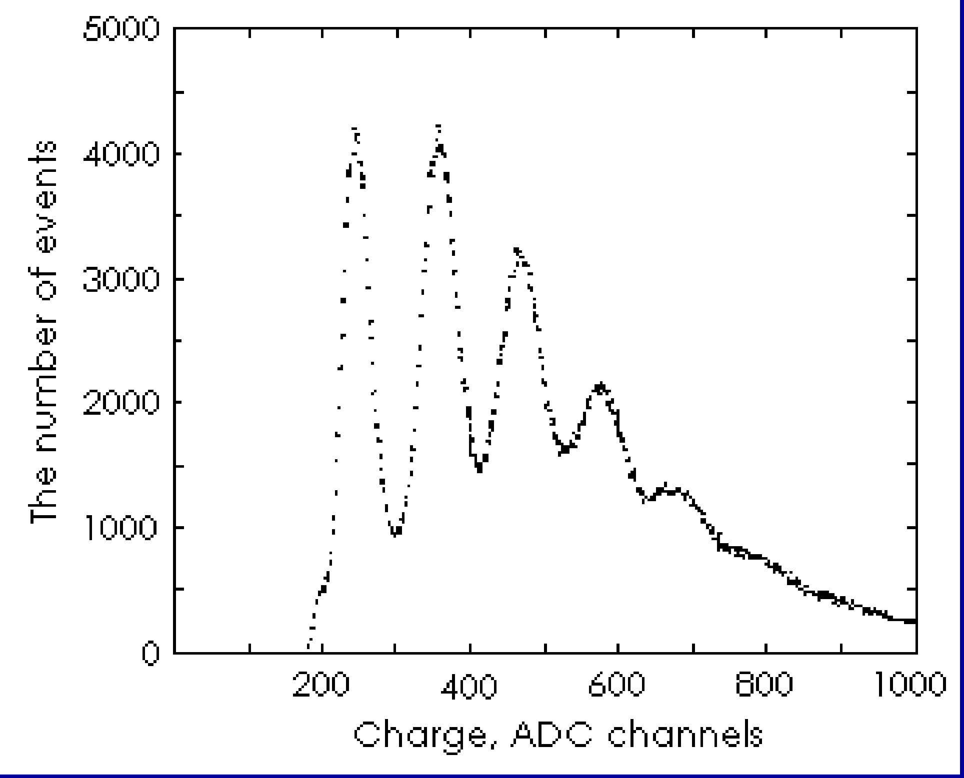
A number of modifications of the Quasar-370 phototube have been developed with different scintillators in its luminescent screen: YSO, YAP, SBO, LSO, LPO etc.

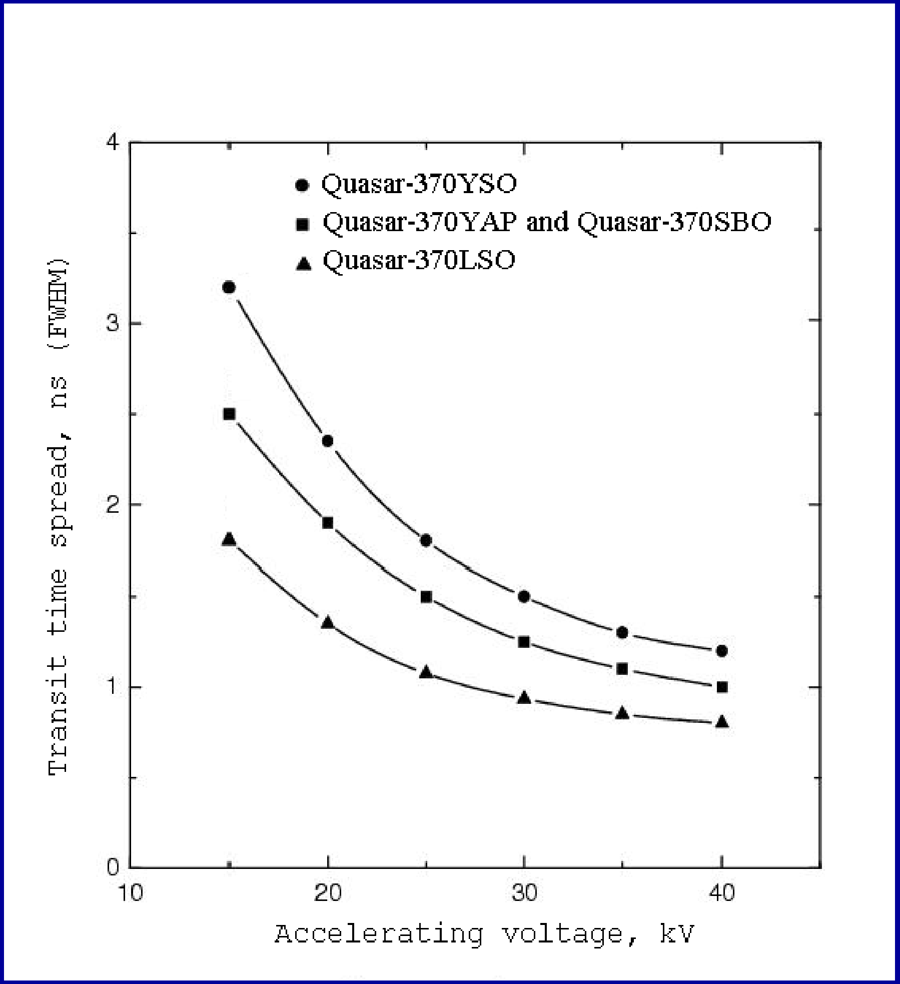
QUASAR-370 modifications

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-370LSO with LSO crystal





Single electron resolution ~35% (fwhm)

η(eff) < 20%

Jitter ~ 1 ns (fwhm)

G - the first stage amplification factor

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

Y - scintillator light yield

k - collection efficiency of photons of the small PMT’s photocathode

η(eff) - effective quantum efficiency of the small PMT

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

Other modifications developed so far

- QUASAR-370L with low background glass for low background experiments
- QUASAR-370G - with YSO+BaF_2 for EAS Cherenkov detectors: TUNKA, SMECA, QUEST
- QUASAR-370D - with PiN diode (HPD)
- QUASAR-370-2 - two channel phototube
- 2-channel OM (tested at the Lake Baikal)

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

- no prepulses
- no late pulses in TTS
- low level of afterpulses (<1%)
- ~100% effective collection effiency
- 1 ns TTS (FWHM)
- ~35% SER(FWHM) (competitive to HPD)
- immunity to terrestrial magnetic field

  $\geq 2\pi$ angular acceptance

QUASAR-370 is a large (~2000 cm^2) sensitive area and wide angular acceptance ($\geq 2\pi$) phototube with timing and SER of the best small conventional PMTs!!!

There is plenty of room to improve its parameters:

to use new small PMTs with more sensistive photocathodes;

to use more efficient, faster scintillators

Requirements for scintillator:

- 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

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

$n_{p.e.}$ - # 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 be with 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

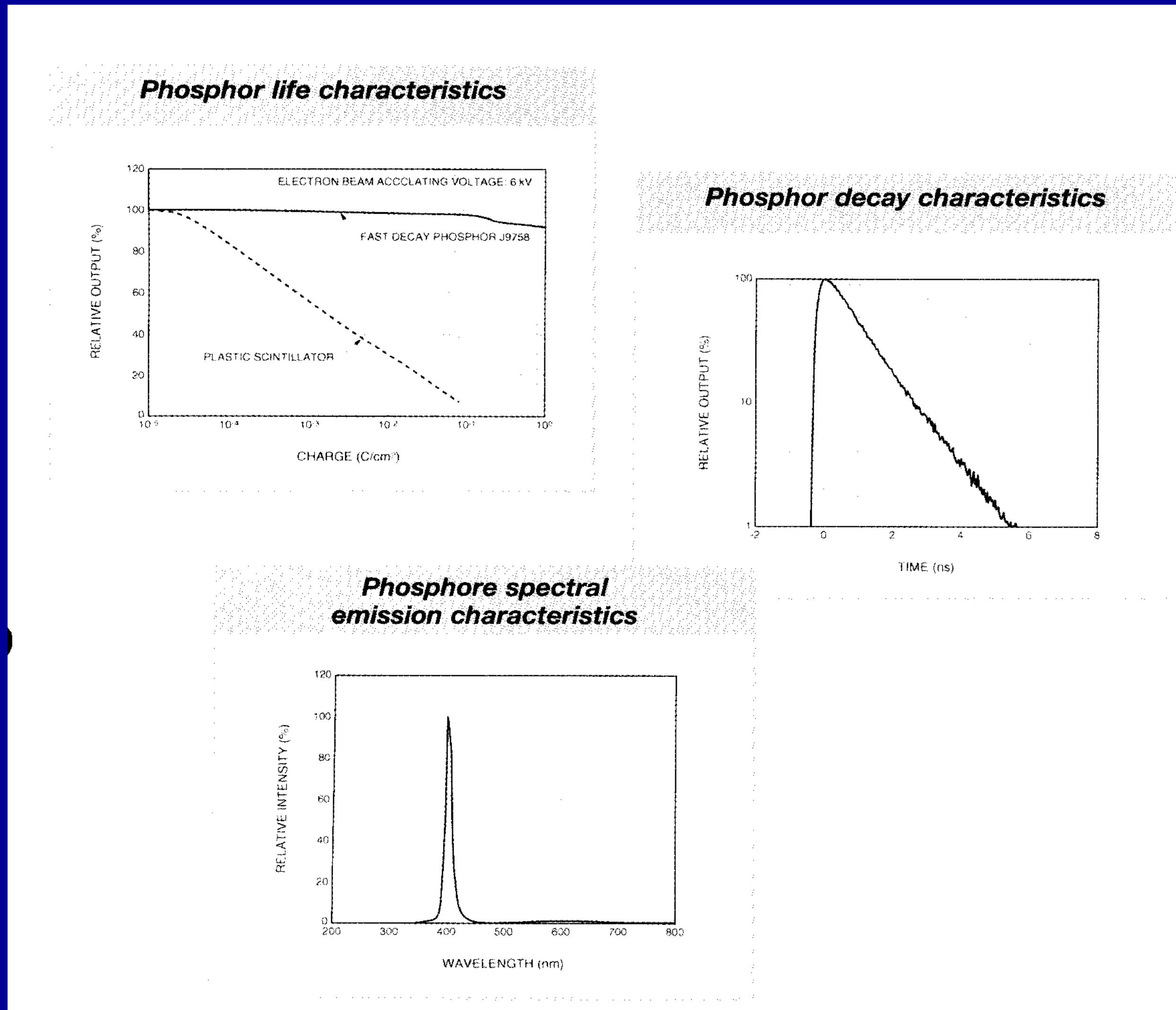
ZnO:Ga

F1 = F2 = 250!

Challenge:

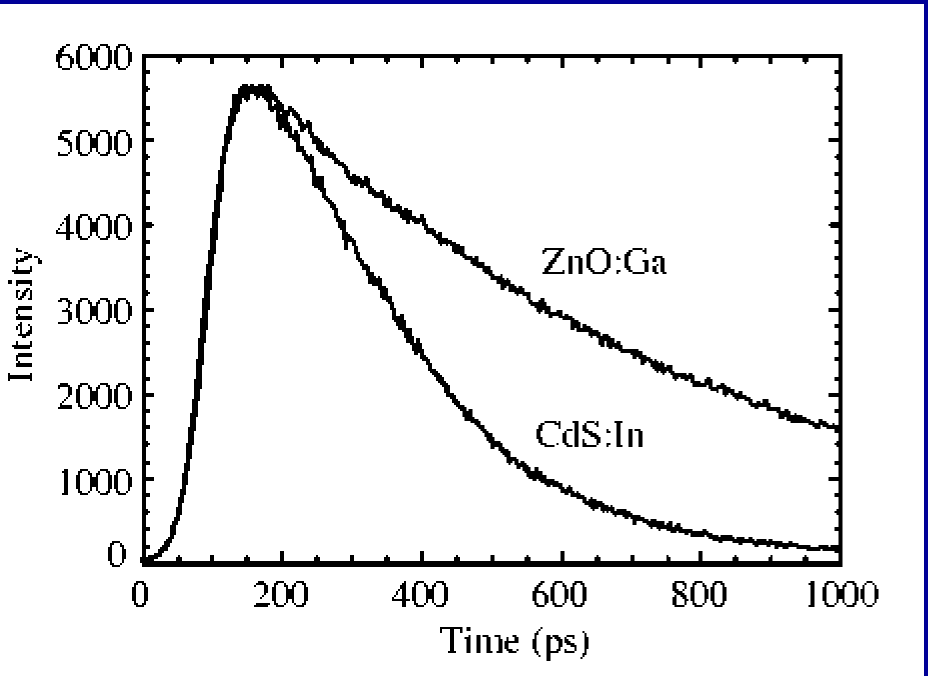
- the material should be extremelly pure
- problems with monocrystal growth but phosphor will be O'K for luminescent screen

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



Hamamatsu news 2006, pp18-19

ZnO:Ga



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

W.Moses. NIMA (LBNL-50252)

Hypothetical QUASAR-370 with ZnO:Ga and high QE fast small PMT would be a fantastic photodetector with <1ns jitter (FWHM) and <1ns anode pulse width!

More details on scintillators in *B.Lubsandorzhiev and B.Combettes TNS 2008*

Problems

- Luminescent screen (new highly efficient, fast, inorganic scintillators, not only crystals but phosphors too!)
- HV compound (like foam poly-urethane, …...)
- HV power supply (cheap, compact …..)
- HV connectors (no connectors, HV powersupply fully integrated into phototubes electro-optical preamplifier, only low DC voltage input!? (like Hamamatsu’s small PMT modules) ………..)
- Photocathode (higher sensitivity to Ch. light …..)
- We need the 21st century technology for the 21st century photodetector (E.Lorenz)

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
- Immunity to Earth‘s magnetic field

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

Quasar-370 hybrid phototube is very close to the ideal photodetector

Quasar-370 hybrid phototube is very good prototype of a photodetector for the next generation of neutrino telescopes and/or other giant neutrino projects like LENA, Hyper-Kamiokande, etc.