APPLICATIONS OF GEIGER-MODE APDS IN ASTROPARTICLE PHYSICS

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OVERVIEW

- INTRODUCTION, THE MAIN AREAS OF ASTROPARTICLE PHYSICS(APP) RESEARCH
- PHOTON DETECTION, a key challenge in most astroparticle physics experiment
- AREAS WHERE G-APDS CAN REPLACE/IMPROVE PHOTON DETECTION
  - A) GROUND BASED GAMMA-RAY ASTRONOMY
  - B) THE HIGHEST ENERGY EXPERIMENTS
  - C) NEUTRINO EXPERIMENTS
  - D) UHE CR ARRAYS
- OUTLOOK/CONCLUSIONS where we might go and what improvements are needed/wanted

ASTROPARTICLE PHYSICS IS A RAPIDLY EXPANDING FIELD OF FUNDAMENTAL RESEARCH

AREAS OF ASTROPARTICLE PHYSICS (APP)

(IN THE US: PREFER THE NAME PARTICLE ASTROPHYSICS)

- GAMMA-RAY (γ) ASTRONOMY
- ν ASTRONOMY (LOW AND HIGH ENERGY)
- STUDY OF THE CHEMICAL COMPOSITION OF COSMIC RAYS ABOVE 10^{12} eV
- STUDY OF THE HIGHEST ENERGY (> 10^{19} eV) COSMIC PARTICLES
- DARK MATTER SEARCHES (WIMPS)
- NUCLEAR ASTROPHYSICS
- (GRAVITATIONAL WAVE PHYSICS)

BOUNDARIES NOT ALWAYS CLEARLY DEFINED
ULTIMATE GOAL: CONTRIBUTE TO UNDERSTAND OUR UNIVERSE COMPLETELY
PARTICLES AS INFORMATION CARRIERS FROM OUR UNIVERSE
SEARCH FOR PARTICLE PHYSICS (EXAMPLE WIMPS, NEUTRALINO. TOPOLOGICAL DEFECTS, RELIC PARTICLES.?GRAVITON?
LINKS TO CLASSICAL ASTRONOMY

SATELLITE BORNE DETECTORS: ONLY ONE COMMENT LATER. G-APDS ARE VERY PROMIZING FOR USE IN SATELLITES, STILL FAR AWAY DUE TO HIGH RELIABILITY REQUIREMENTS

THE EXPERIMENTAL CHALLENGES IN HIGH ENERGY ASTROPARTICLE PHYSICS

(as viewed from the instrument side)

- OBSERVATIONAL SCIENCE

- INITIAL PARAMETERS NOT UNDER CONTROL AS IN HEP
  ENERGY , TIME, (PATRICLE TYPE), (DIRECTION)

- FLUXES ARE VERY LOW -> NEEDS ULTRA-LARGE DETECTOR VOLUMES

- HIGH ENERGY -> CALORIMETRIC DETECTORS TO CONVERT INITIAL ENERGY INTO OBSERVABLE QUANTITIES

- INITIAL PARTICLE->INTERACTION IN CALORIMETER MATERIAL -> SHOWER->
- **-> OBSERVABLES -> PHOTONS, CHARGE CARRIERS IN SUITABLE MATERIALS**
- (-> RADIO WAVES ???)
- (->ACOUSTICAL SIGNALS ???)
- ->IONISATION -> TRACKING, COUNTING, (TAIL CATCHER) CALORIMETERS
  nearly all based on light detection in solid devices (gaseous detectors have operation probl.)

CALORIMETER MATERIAL COST AN ISSUE: USE FROM NATURE
(EXAMPLE: ν DETECTOR FOR ASTRONOMY MUST BE > 10^9 TONS,
FOR SUN ν LESS VOLUME)

POSSIBLE NATURAL CALORIMETER MATERIALS
(MUST BE TRANSPARENT FOR MEASURABLE QUANTITIES):

ATMOSPHERE, WATER, ICE

ALL HAVE THEIR SPECIFIC PROBLEMS

‘EXOTIC’ MATERIALS:
PURIFIED AND ACTIVATED OIL (LIQUID SCINTILLATOR)
LIQUID PURIFIED ARGON, (XENON)
(MAINLY IONISATION BUT ALSO SCINTILLATION, BECOMES IMPORTANT FOR LARGER VOLUMES)

PROCESSES GENERATING PHOTONS

A) SCINTILLATION IN AIR (N_2 FLUORESCENCE)
B) CHERENKOV RADIATION IN AIR, WATER, ICE

THE COSMIC RAY SPECTRUM

FRACTION OF γs UNKNOWN

< 10^{-4} from Galactic Plane

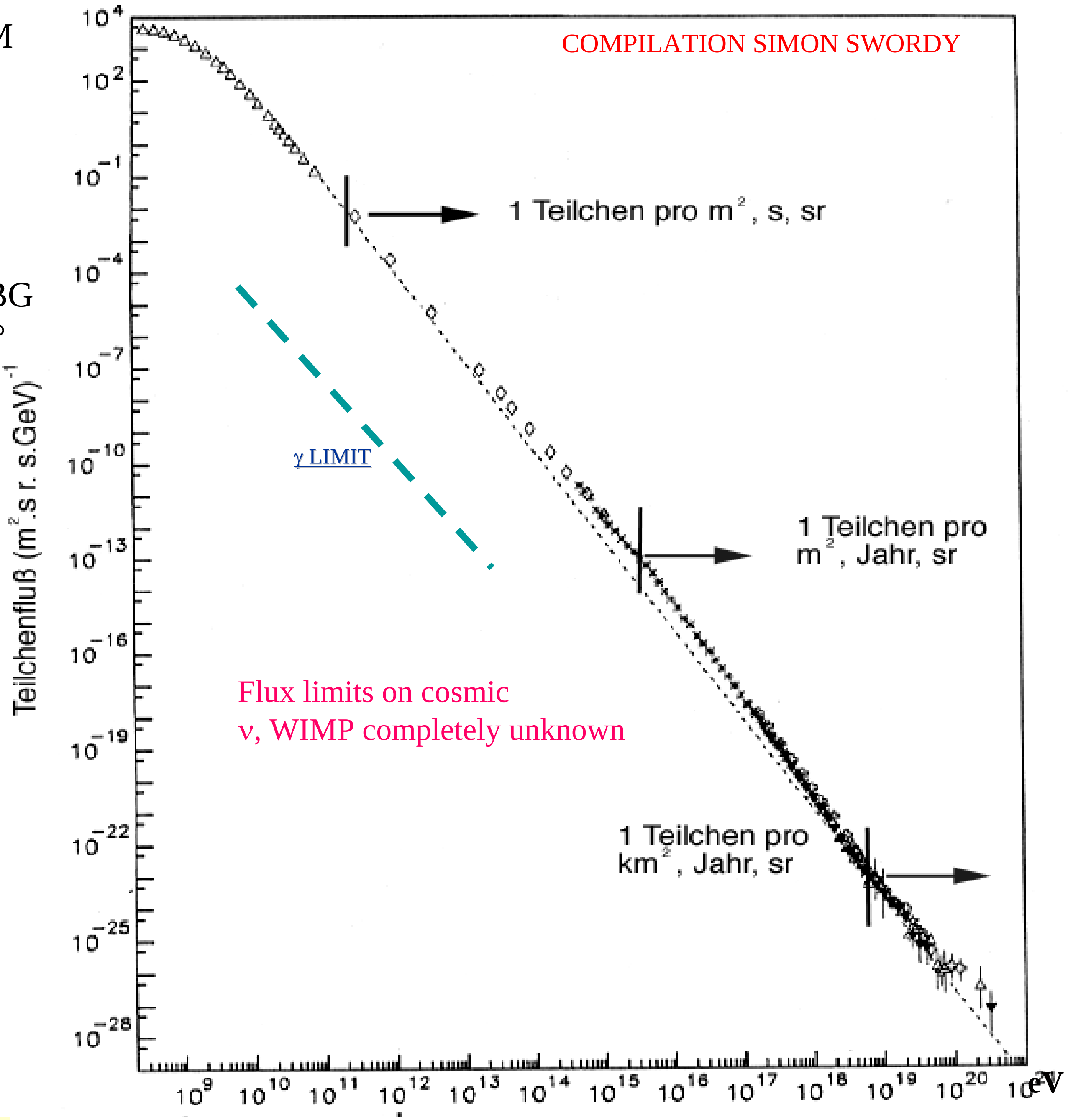
< 10^{-5} isotropic

Local γ emission spots(stars) can reach γ fluxes of a few % of CR BG

For typ. angular resolution of 0.1°

-> γ/hadron SEPARATION A BIG EXPERIMENTAL CHALLENGE

-> Detectors are only useful for 2-3 decades in energy



COMPILATION SIMON SWORDY

Flux limits on cosmic ν, WIMP completely unknown

NEARLY ALL EXPERIMENTS IN APP EXPERIMENTS ARE BASED ON PHOTON DETECTION

(QUITE DIFFERENT COMPARED TO THE NEEDS OF HEP EXPERIMENTS)

BETTER PHOTON DETECTORS WILL

a) MAKE BETTER PHYSICS
b) WILL ALLOW NEW EXPERIMENTS UP TO NOW IMPOSSIBLE

PMTS ARE THE ‚YARDSTICK‘ FOR NEW PHOTODETECTORS

APP IS NOW A DRIVER FOR NEW PHOTON DETECTORS

NEEDS LARGE AREA (UNO, HYPERK 50-100 K LARGE PMTS)

NEED LARGE NR (CTA 100-1000 K PIXELS)

ARTIST VIEWOF A PROTON INDUCED AIR SHOWER + OBSERVABLES

AIR MASS 1:
27 rad.length
11 hadronic abs. length

Zur Anzeige wird der QuickTime™
Dekompressor “Foto - JPEG”
benötigt.

SOME SPECIFIC PROBLEMS COMMON TO NEARLY ALL EXPERIMENTS

THE YIELD OF SCINTILLATION OR CHERENKOV LIGHT YIELD IS EXTREMELY LOW. ORDER 10^{-5} TO 10^{-3} OF TOTAL PRIMARY ENERGY (EXCEPTION IN L-Ar,Xe, LIQUID SCINTILLATOR)

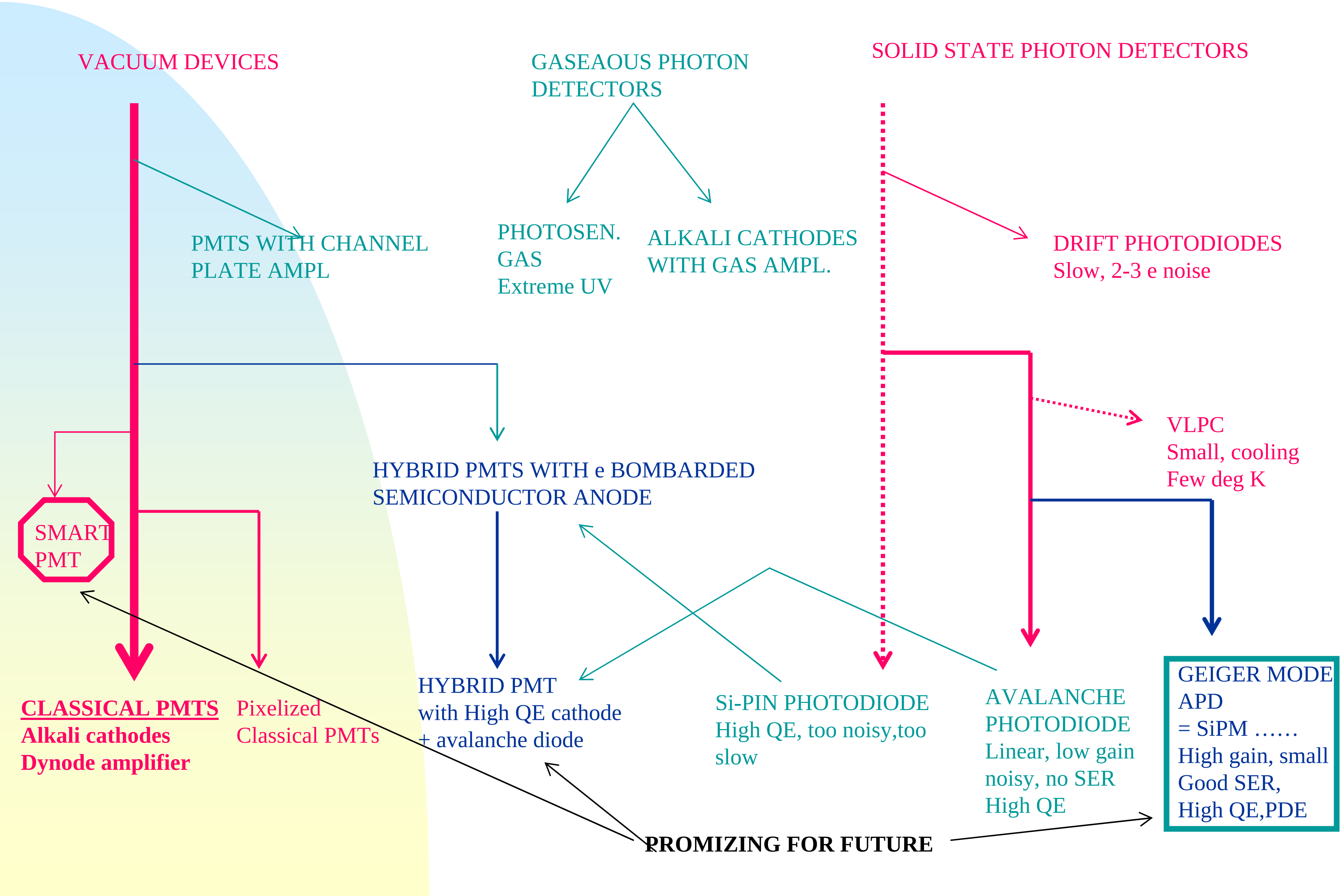
•-> THERE IS A NEED OF VERY LARGE PHOTON DETECTORS
OPTICAL CONCENTRATOR ELEMENTS HELP BUT ARE ALSO NOT CHEAP:
MIRRORS, FRESNEL LENSES, WINSTON CONE CONCENTRATORS
FLUORESCENT FLUX CONCENTRATORS

•NEED OF PIXELIZED SENSORS TO OVERCOME VARIOUS BACKGROUNDS
γ-HADRON SEPARATION IN γ ASTRONOMY
TO REJECT BACKGROUND LIGHT
TO DETERMINE DIRECTION OF SHOWERS

•NEED OF FAST PHOTON DETECTORS
nsec TIME RESOLUTION FOR CHERENKOV TYPE DETECTORS
10 - FEW 100 nsec TIME RESOLUTION FOR SCINT. LIGHT DETECTORS

EARTH ROTATES: CALORIMETER AND PHOTON DETECTORS MUST COPE WITH ROTATION (TELESCOPES, 4π UNIDIRECTIONAL READOUT..)

FAMILIES OF PHOTON DETECTORS



VACUUM DEVICES

GASEAOUS PHOTON DETECTORS

SOLID STATE PHOTON DETECTORS

PMTS WITH CHANNEL PLATE AMPL

PHOTOSEN.
GAS
Extreme UV

ALKALI CATHODES
WITH GAS AMPL.

DRIFT PHOTODIODES
Slow, 2-3 e noise

VLPC
Small, cooling
Few deg K

HYBRID PMTS WITH e BOMBARDED SEMICONDUCTOR ANODE

SMART
PMT

CLASSICAL PMTS
Alkali cathodes
Dynode amplifier

Pixelized
Classical PMTs

HYBRID PMT
with High QE cathode
+ avalanche diode

Si-PIN PHOTODIODE
High QE, too noisy,too slow

AVALANCHE
PHOTODIODE
Linear, low gain
noisy, no SER
High QE

GEIGER MODE
APD
= SiPM ……
High gain, small
Good SER,
High QE,PDE

PROMIZING FOR FUTURE

Motivation to replace PMTs by G-apds: G-apds have a number of advantages:

- Higher QE/PDE than PMT (60-80% possible)
- Good SER
- Low bias voltage, simpler power supplies
- Very robust- can be exposed to daylight under bias
- Eventually cheaper
- Extremely compact, extremely low in weight
- No shielding needed against earth magnetic field

Disadvantages

- New device, not yet mature, still under development
- Small sensor area
- Optical crosstalk
- High noise
- Larger elements problematic (rise-time, amplitude)
- Not yet large scale field tested
- More prone to radiation damage ??? What level??

TWO AREAS, WHERE G-APDS CAN ALREADY NOW MAKE IMPORTANT IMPROVEMENTS

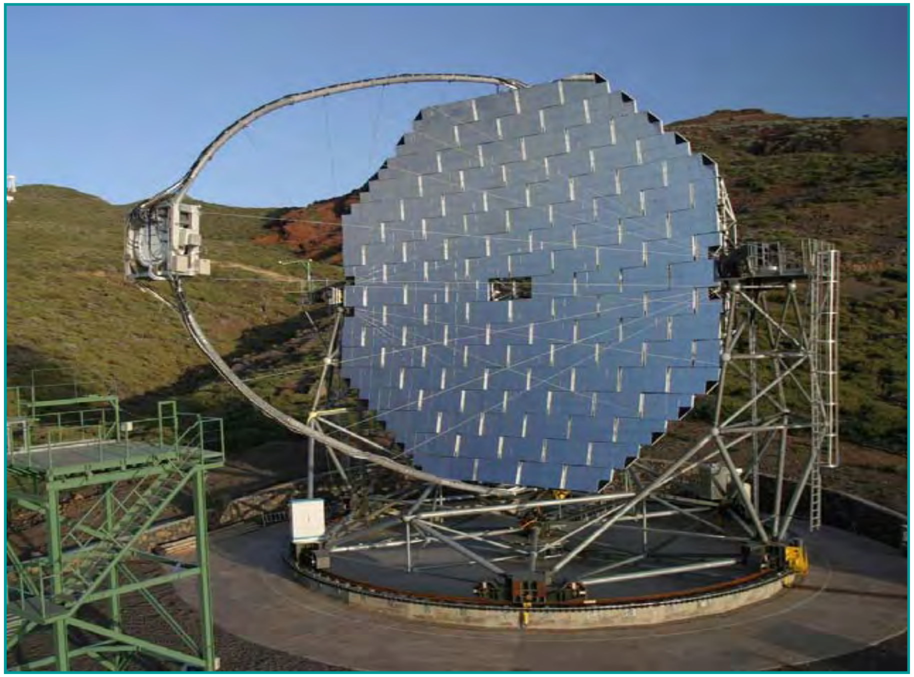
A) SMALL SENSORS (PIXELS, WHERE ALREADY HIGH BACKGROUND NOISE /LIGHT IS PRESENT -> DIRECT DETECTION OF LIGHT

A) SMART PMTS
(SECONDARY READOUT FOR LIGHT CONCENTRATORS/AMPLIFIERS
-> INDIRECT DETECTION

GROUND-BASED γ-RAY ASTRONOMY
A very successful new field (1989 1. TeV source found, Crab nebula)

Cosmic γ-rays create em air showers in the atmosphere
Observation of Cherenkov light, light ≈ energy, direction -> to source, complex analysis
Need of large mirrors
Need of high QE pixelized photon detector array as camera
Problem 1: rejection of hadronic CR bg
Problem 2: low light yield -> high threshold

Replacement of PMTs by higher QE/PDE photon sensors very much needed!
G-APD very promizing candidate
First tests end last year: A. Biland et al ETH-MPI-PSI group-> poster Vienna Inst. Conf.

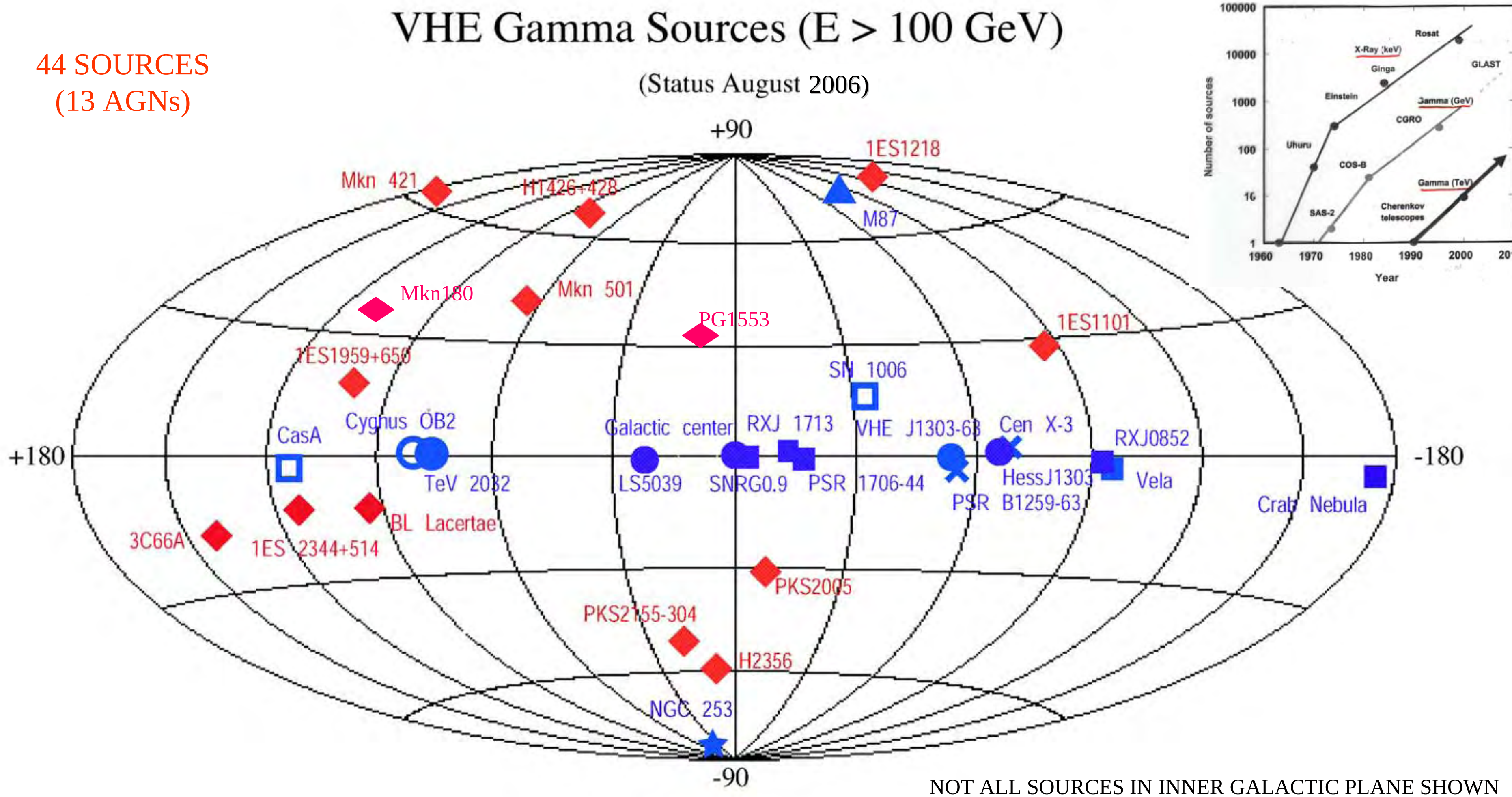


KIFUNE PLOT

VHE Gamma Sources (E > 100 GeV)

(Status August 2006)

44 SOURCES
(13 AGNs)



NOT ALL SOURCES IN INNER GALACTIC PLANE SHOWN

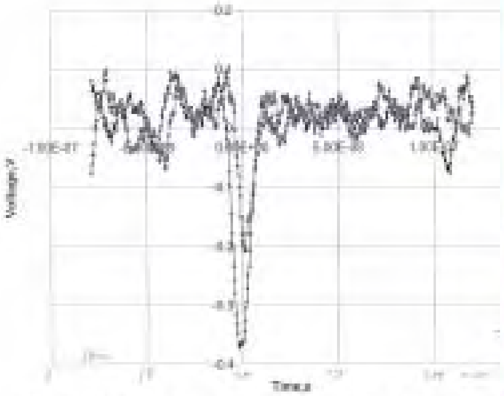
Galactic Coordinates

ALL SOURCES HAVE SPECTRA EXTENDING ABOVE 1 TEV, RARELY SPECTRA EXTEND ABOVE 10 TEV (CRAB->80 GEV)MANY AGNS HAVE A SOFT SPECTRUM

■ = Pulsar/Plerion
□ = SNR
★ = Starburst galaxy
○ = OB association
◆ = AGN (BL Lac)
▲ = Radio galaxy
✖ = XRB
● = Undetermined

Test 1

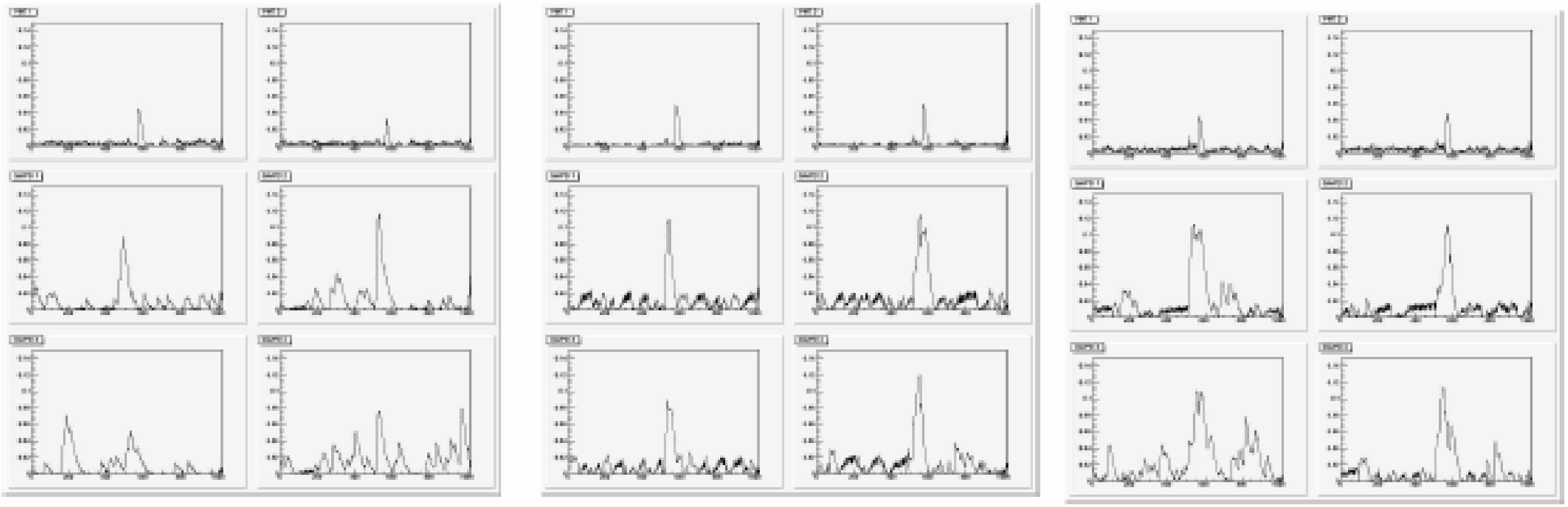
Arrangement of the detector he



Coincident pulses from 2 G-APD gro

Test 2

The solar concentrator at PSI and the detector assembly mounted in the focal plane.



3 recorded events: the 2 plots on top show the PMT signals, the 4 lower plots the signals from the G-APD groups. The horizontal scale is 0.5 ns/channel and the vertical scale is in Volt.

MPPC (Multi-Pixel Photon Counter)

S10362-11 series

Solid state photon counter using Geiger-mode APD and self-quenching resistance

The MPPC (Multi-Pixel Photon Counter) is a solid state photon counter using multi-pixel Geiger-mode APD of superior gain (10E5). The most notable feature is of segmented active area. Each pixel integrates quenching resistance, so that Geiger-mode is to function independently from photons illuminated to the segments. As a result, the MPPC's output is in proportion with the number of pixels, which are excited by incident light. Photon-counting is realized by digital-like output to the limited number of photons illuminated.

The MPPC is a new generation avalanche photodiode (APD) realized by Hamamatsu's cutting-edge semiconductor technology. This high performance will bring new photon counting applications in nuclear medicines, HEP, medical diagnosis, drug discovery, scientific instrument, measurement, analysis, etc.

■Features

- Stable operation with low voltage
- Insensitive to magnetic fields
- High gain (10E5)
- Low dark count
- Low power consumption

■Applications

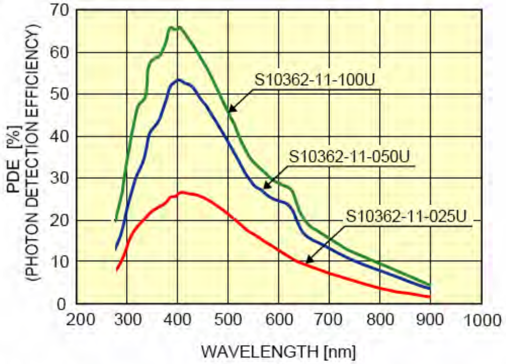
- PET (Positron Emission Tomography)
  Nuclear medicines
- HEP Calorimeter
- Fluorescence measurement
- DNA BIO-chip sequencer
- Environmental analysis

■ Electrical and optical characteristics (Ta=25 °C)

Parameter		S10362-11 series			Unit
		-025U, -025C	-050U, -050C	-100U, -100C	
Chip size		1.5 × 1.5			mm
Effective active area		1 × 1			mm
Number of pixels		1600	400	100	pixels
Pixel size		25 × 25	50 × 50	100 × 100	µm
Geometric efficiency		30.8	61.5	78.5	%
Sensitivity	λ=λp	400			nm
	Quantum efficiency	70 Min.			%
	PDE *1	25	50	65	%
Operating voltage		77 ±10	70 ±10	70 ±10	V
Gain		2.75E+05	7.50E+05	2.40E+06	-
Dark count		100	270	400	Kcps
Terminal capacitance		35			pF
Time resolution (FWHM)		250	220	250	ps
Temp coefficient of bias voltage		50			mV/°C

The MPPC is developed by HAMAMATSU PHOTONICS K. K. and it is one of the products of Si-PM (Silicon Photomultiplier) family which was originally developed in Russia.

■ Spectral response



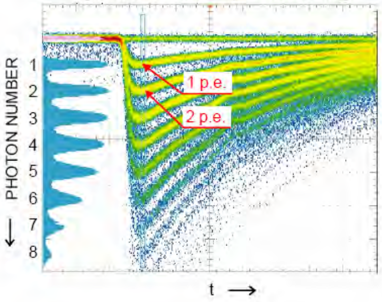
Photon Detection Efficiency

$$= \text{Geom. Factor} \times \text{Q.E.} \times \text{Avalanche probability}$$

$$= \frac{\text{Effective pixel size}}{\text{Pixel Size}} \times \text{Q.E.} \times \frac{\text{Geiger Mode Operating Pixel No.}}{\text{Total Pixel No.}}$$

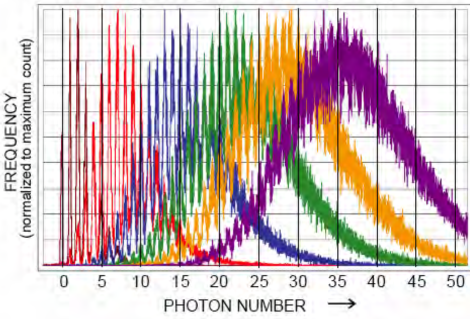
■Pulse height spectrum (linear amp. X 120)

[S10362-11-050U (M=7.50E+05)]



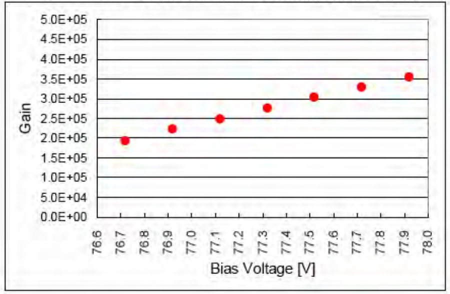
■Pulse height spectrum (charge amp.)

[S10362-11-025U (M=2.75E+05)]



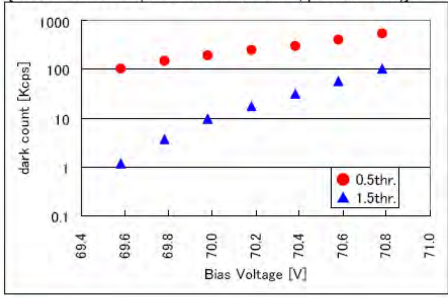
■ Gain vs. bias voltage

[S10362-11-025U (Active area: 1 x 1 mm, pitch: 25 µm)]



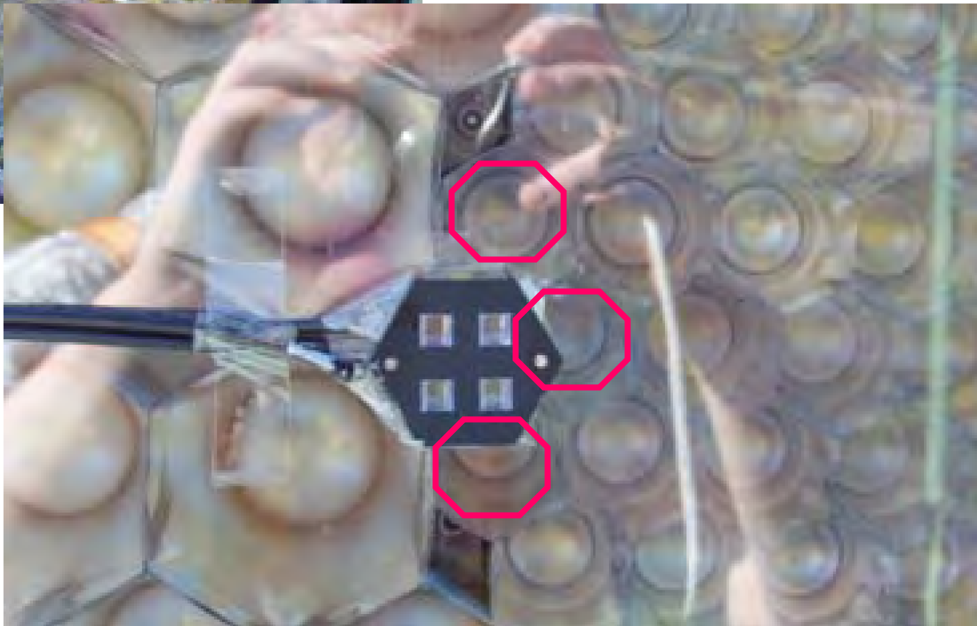
■ Dark count vs. bias voltage

[S10362-11-050U (Active area: 1 x 1 mm, pitch: 50 mm)]



3. Test

Installation of 4 MPPC in front
Of the MAGIC camera
Trigger by air shower C-light
Comparison of signal in neighbor
Pmt cells (9 cm**2)
With 4 g-apd pixels (0.36 cm**2)
Readout by 2 Ghz F-ADC



PMT signal

Zur Anzeige wird der QuickTime™
Dekompressor „TIFF (Unkomprimiert)“
benötigt.

PMT signal

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Dekompressor „TIFF (Unkomprimiert)“
benötigt.

PMT signal

Zur Anzeige wird der QuickTime™
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4 g-apd signals

Zur Anzeige wird der QuickTime™
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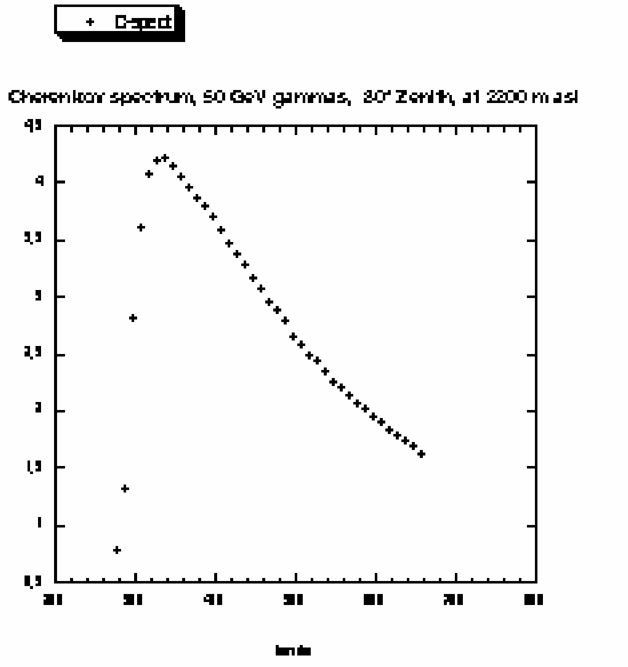
SIGNALS FROM AN EVENT

GATE SPIKES FROM MULTIPLEXER

PARAMETERS OF OPTICAL ELEMENTS FOR COMPARISON OF DIFFERENT LIGHT SENSORS



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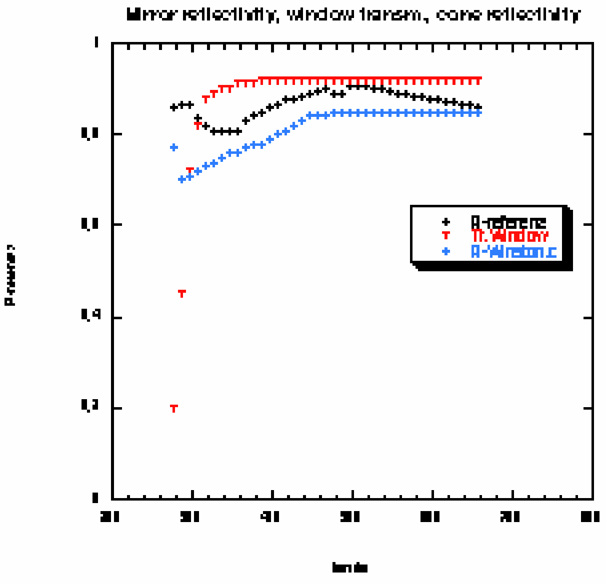
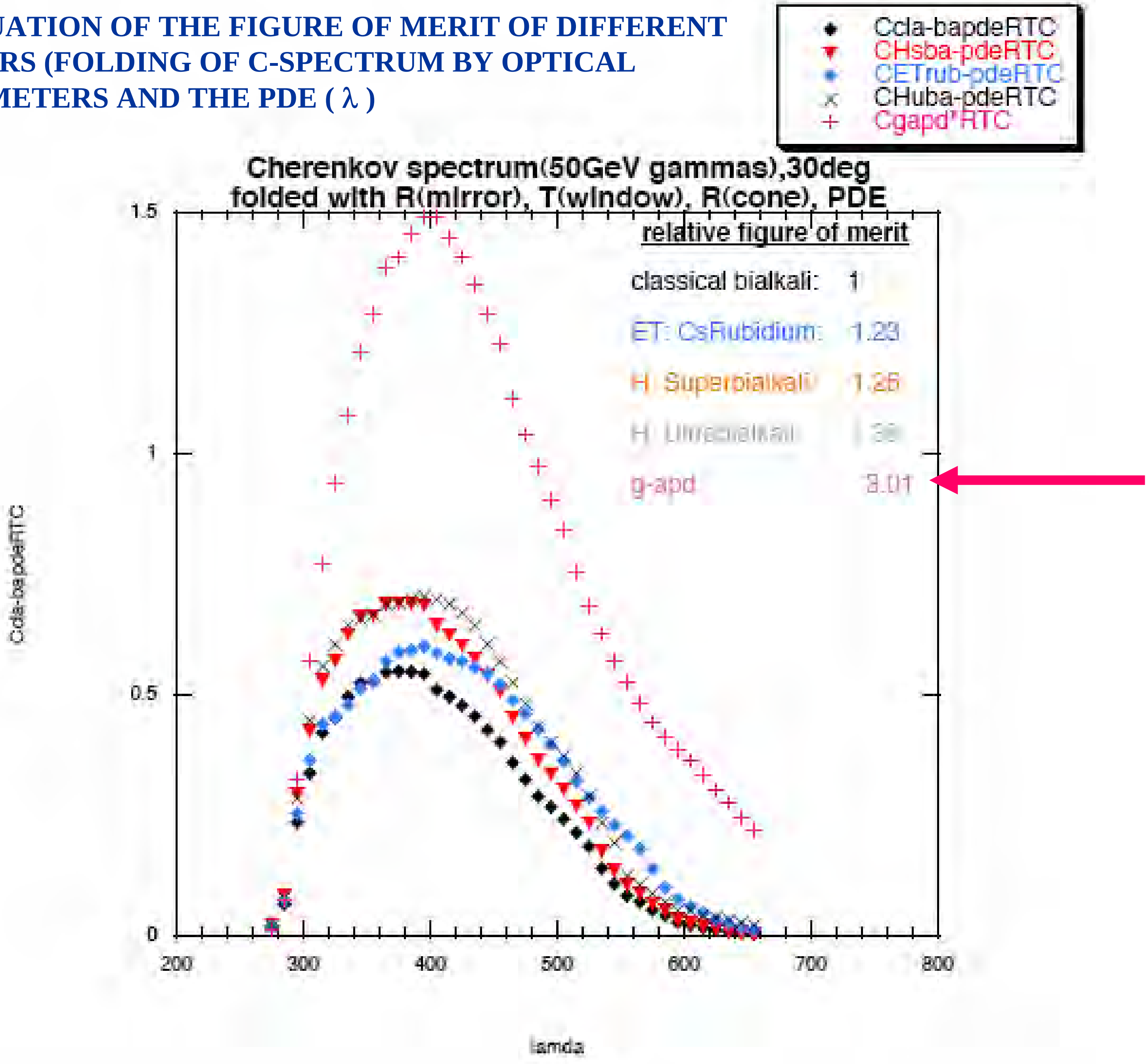


EVALUATION OF THE FIGURE OF MERIT OF DIFFERENT SENSORS (FOLDING OF C-SPECTRUM BY OPTICAL PARAMETERS AND THE PDE (λ)



- The tests have confirmed that Cherenkov light from air showers can be detected

- Tests confirmed 2.5 x gain compared to flat window, standard bialkali PMTs
  about a factor 2 improvement compared to advanced hemispherical pmts with diffuse lacquer
- coating and special light collectors as in the MAGIC camera (for 50x50μ cell MPPC)
- No cooling necessary: intrinsic noise < night sky illumination rate
- Clip cable or diff. Amplifier allows to shorten pulse width

Further improvements of G-APDs for γ-ray astronomy possible:

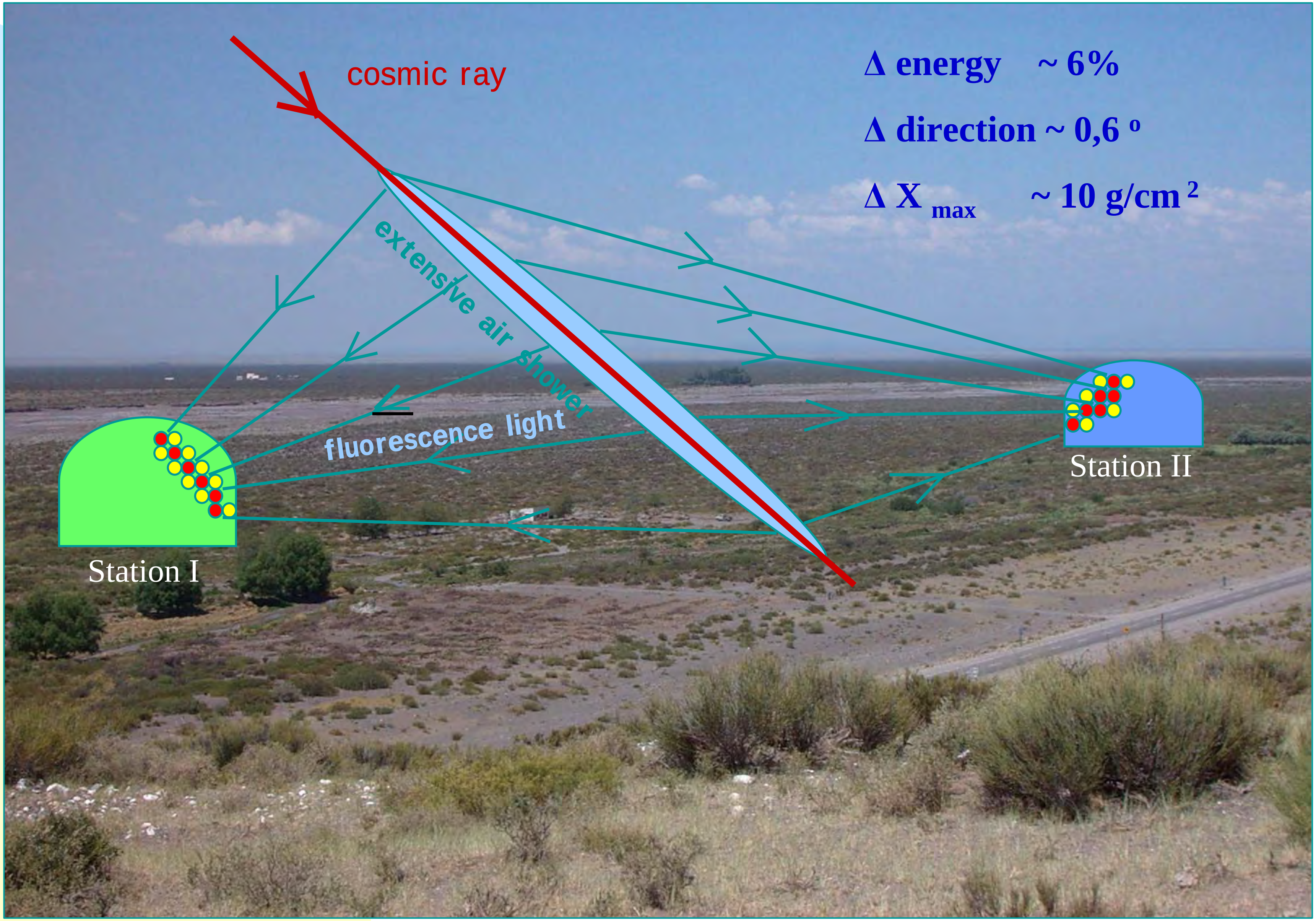
- Widening of high PDE spectral range
- Adding WLS in plastic coating to enhance UV sensitivity
- Rise-time of < 1 nsec
- Faster recovery time
- Use of microlenses or micro light-catchers to overcome dead area between cells- > higher PDE
  - > further increase in PDE by 20-30% (needed if grooves are used)
- Optical filters with transmission between 300 and 700 nm for cutting out IR night sky light
- 5x5 or 10x10 mm MPPC with 100x100 μ cell size but no degradation in rise time

An important issue:Calibration

- Timing calibration: relatively easy by means of test pulsers
- Gain calibration (drift due to temperature, voltage): steady (50Hz) light pulsers of low and high
  Intensity. Modest temperature regulation. Semiautonomous Voltage controllers

OBSERVATION OF HIGHEST ENERGY COSMIC RAYS BY FLUORESCENCE LIGHT

Fluorescence Telescopes – Stereo Measurement



Δ energy ~ 6%

Δ direction ~ 0,6 ^{o}

ΔX_{max} ~ 10 g/cm ^{2}

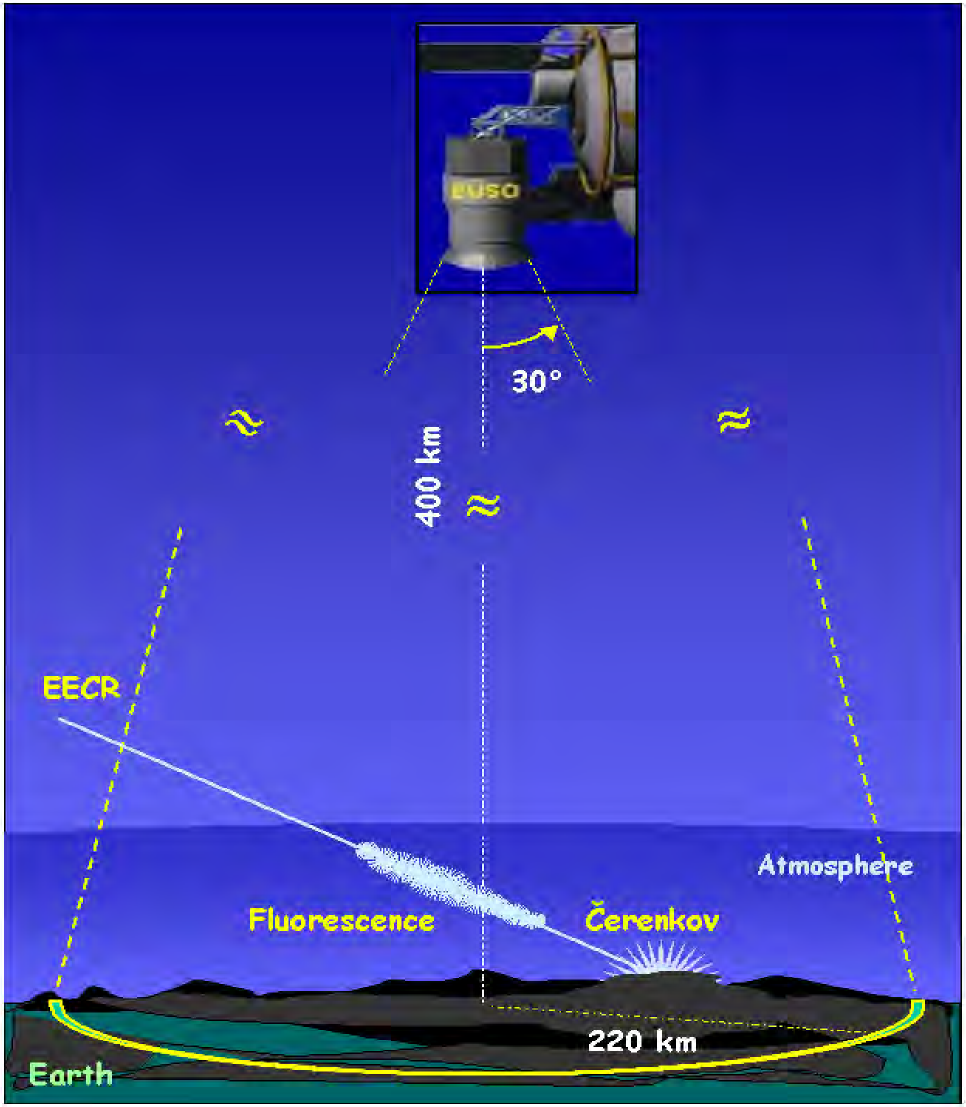
EECR detection

EUSO will detect EAS light from above:

Fluorescence photons isotropically produced at different depths image the shower longitudinal profile

Cherenkov photons collimated with the shower are detected when reflected/diffuse in a surface

Both types of photons contain information on the energy, direction and nature of the incoming particle



The Earth atmosphere is both the detector and the propagation medium. It affects the signal production, propagation and the Acceptance

SOME COMMENTS ON USING G-APDS IN RESEARCH SATELLITES

- IN STATELLITES : WEIGHT, RELIABILITY, COMPACTNESS, LOW VOLTAGE AT A PREMIUM
  ALSO VIBRATION RESISTANCE, ROBUSTNESS IMPORTANT

- IN PRINCIPLE G-APDS ARE VERY INTERSTING CANDIDATES, NEARLY IDEAL DETECTORS FOR SATELLITE BORNE INSTRUMENTS

- G-APDS NEED TO BE SPACE QUALIFIED: LONG USER HISTORY, SPECIAL RELIABILITY TESTS
  -> NEWEST (BEST) TYPES WILL NOT CONSIDERED

- IMPORTANT:
  RADIATION RESISTANCE (SOLAR FLARES, VAN ALLEN BELT, GENERAL COSMIR RAY BG)

- FIBER GLAST. EUSO, JEM-EUSO, S-EUSO

NEUTRINO ASTRO PHYSICS, NEUTRINO ASTRONOMY

ν's :

- OCCUR IN MANY HIGH ENERGY PROCESSES

- MESSENGERS OF LEPTONIC PROCESSES

- FLY STRAIGTH-> CAN BE EXTRAPOLATED TO ORIGIN,
  IF ENERGY HIGH ENOUGH

- BASICALLY UNABSORBED (NOT LIKE γ's OF CERTAIN ENERGY)
- CAN SEE(IN PRINCIPLE) THROUGH ENTIRE UNIVERSE

- FLUX OF HIGH ENERGY ν's VERY SMALL
- INTERACTION CROSS SECTION VERY SMALL
- -> NEEDS ULTRA-LARGE DETECTORS

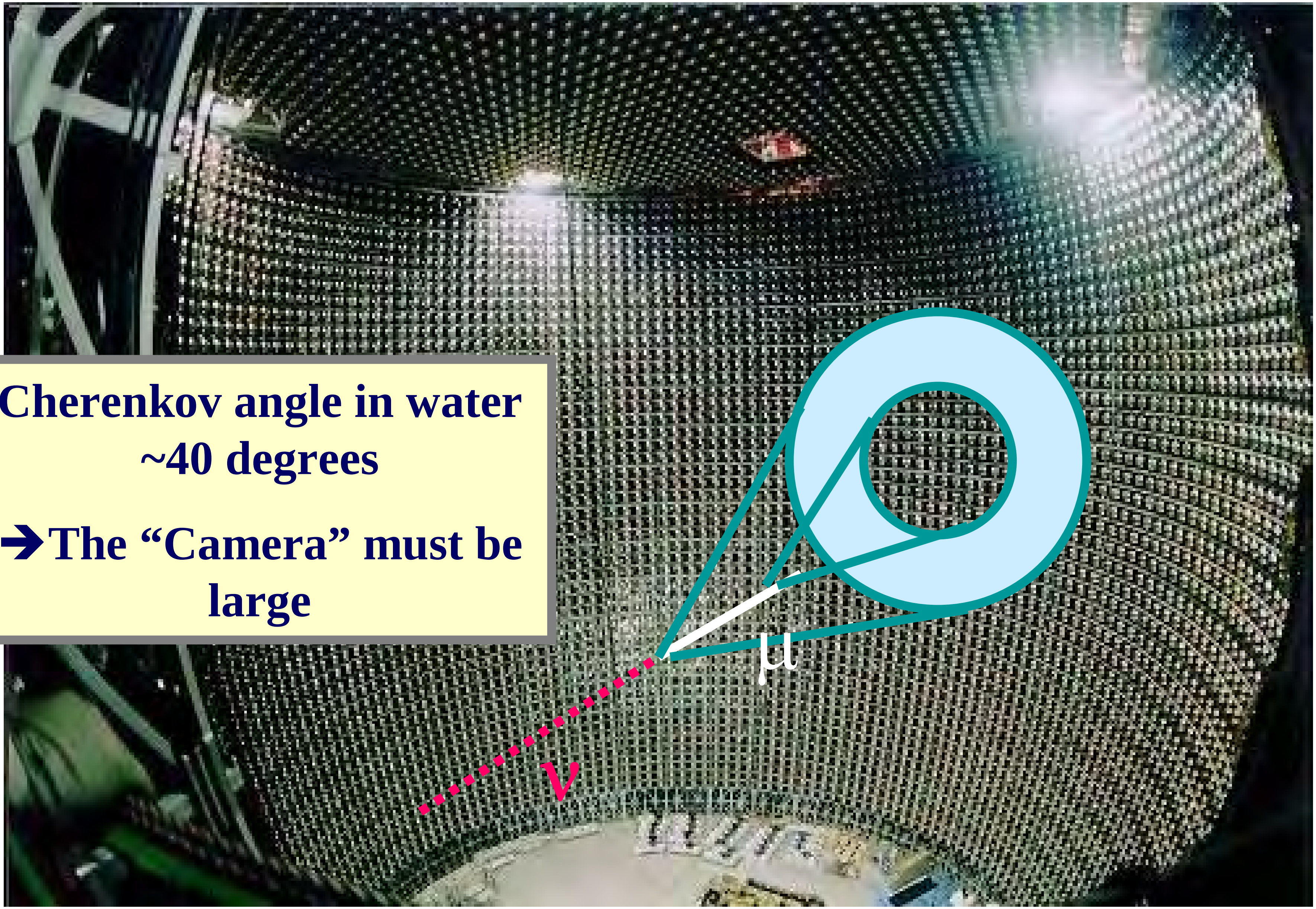
- NOT ALL ν PARAMETERS KNOWN: MASSES…

- FIRST DETECTED ν SOURCES: SUN, SN 1987 A.
  FIRST HINTS FROM AMANDA OF AN AGN (1ES1959)

REQUIREMENTS, PROBLEMS OF ν-DETECTION FROM COSMIC SOURCES

- ULTRA-LARGE DETECTOR VOLUMES NEEDED
  RATES NEVERTHELESS VERY SMALL
- INDIRECT DETECTION THROUGH NEUTRAL /CHARGED CURRENT REACTIONS
- USE OF CHERENKOV LIGHT IN LARGE WATER VOLUMES
- SCINTILLATION LIGHT IN LARGE LIQUID SCINTILLATOR DETECTORS
- SHIELDING PROBLEMS -> DETECTORS DEEP UNDERGROUND
  FOR LOWER ENERGY: NEED OF LOW BACKGROUND MATERIALS
- DUE TO EARTH ROTATION 4π LIGHT DETECTOR COVERAGE
- CALIBRATION A PROBLEM
- DETECTORS ALSO USEFUL FOR OTHER FUNDAMENTAL PHYSICS STUDIES

THE TEMPLATE DETECTOR FOR ALL LARGE VOLUME WATER DETECTORS SUPERKAMIOKANDE

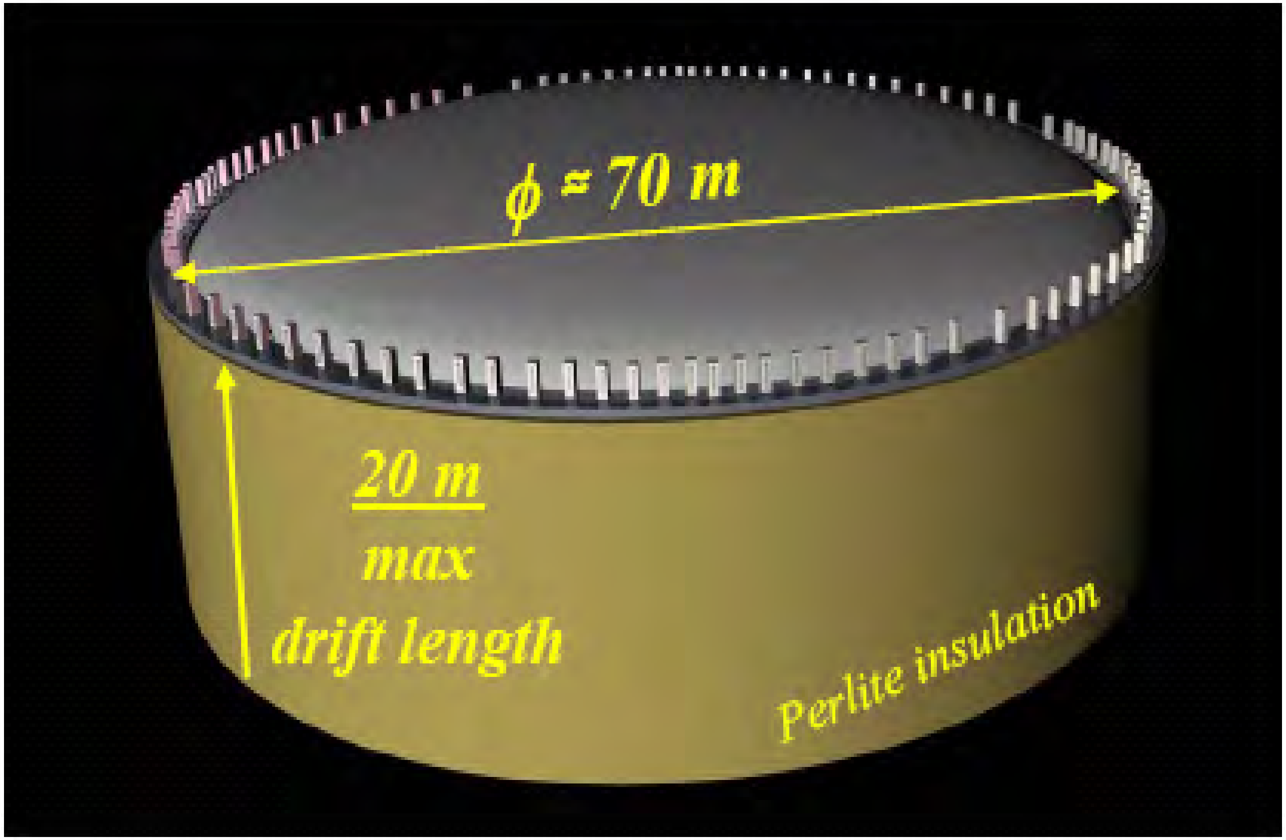


Cherenkov angle in water ~40 degrees

➔The “Camera” must be large

Next generation ～100 kton liq. Ar detector

Rubbia

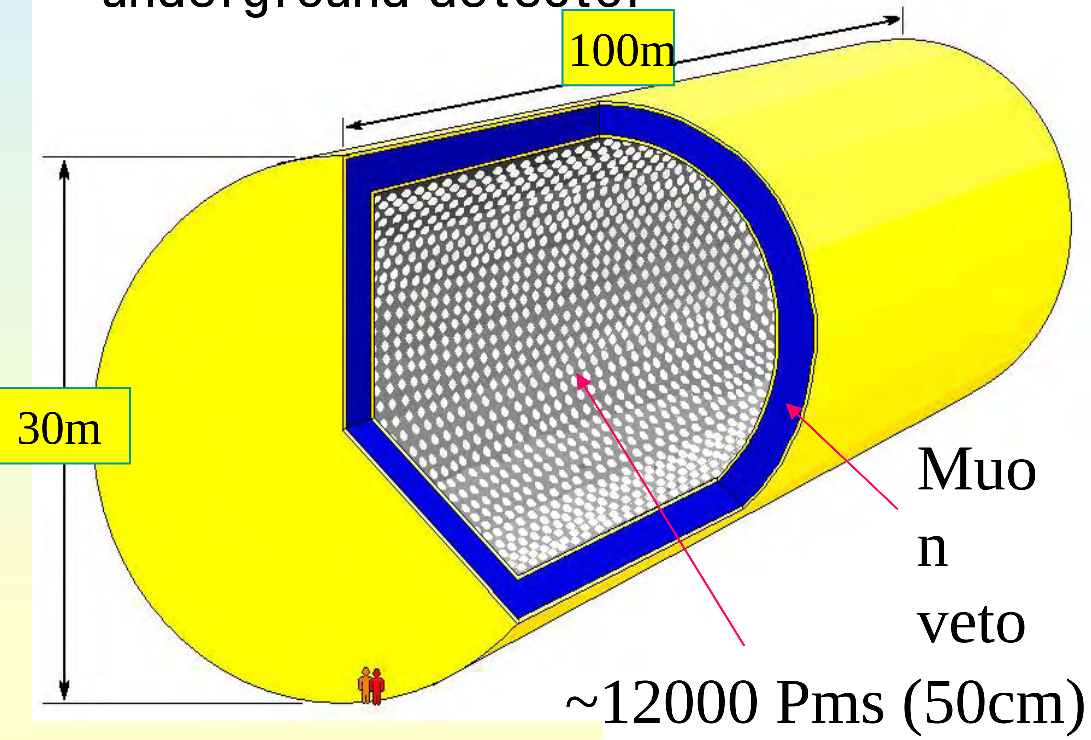


Next-generation liq. Scintillator detector

Possible locations

LENA

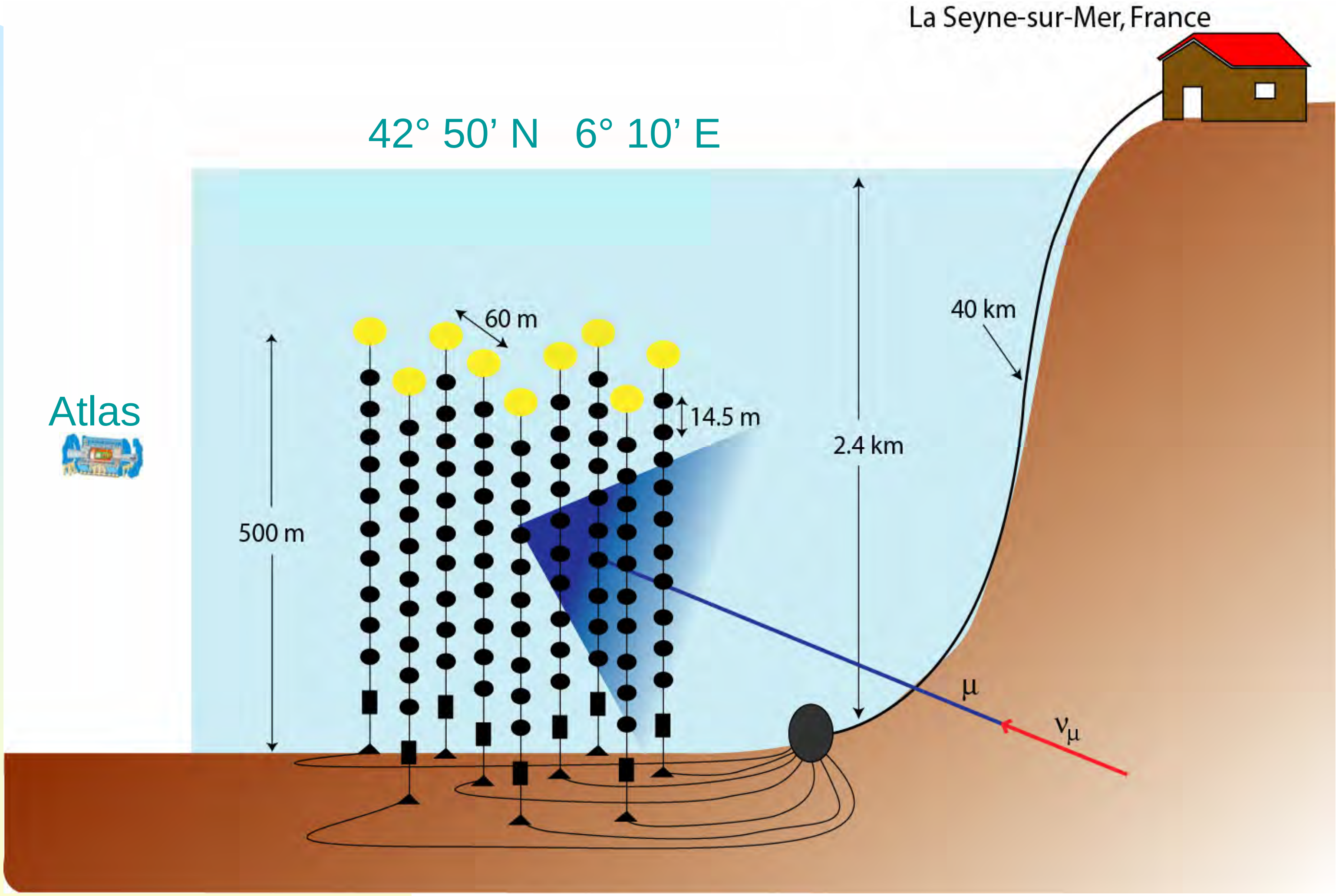
A large (～50 kton) liquid scintillator underground detector




CENTRE FOR UNDERGROUND PHYSICS IN PYHÄSALMI MINE

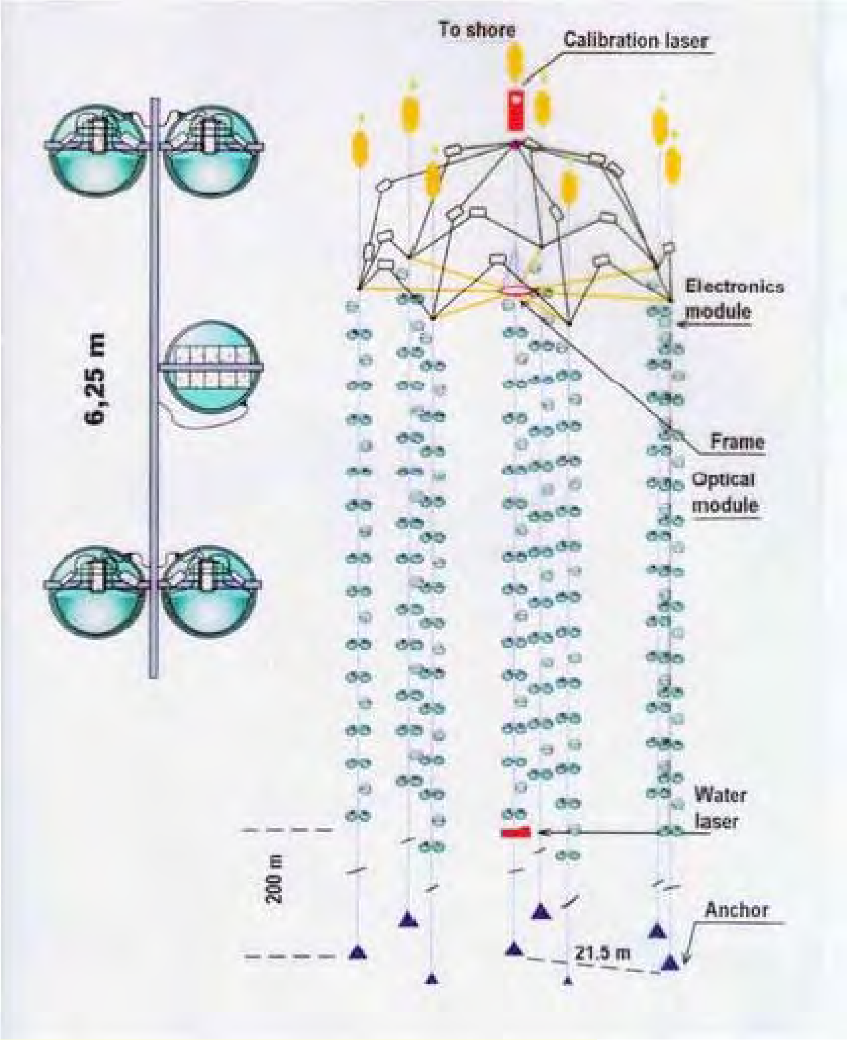
DETECTORS FOR HIGH ENERGY ν ASTRONOMY

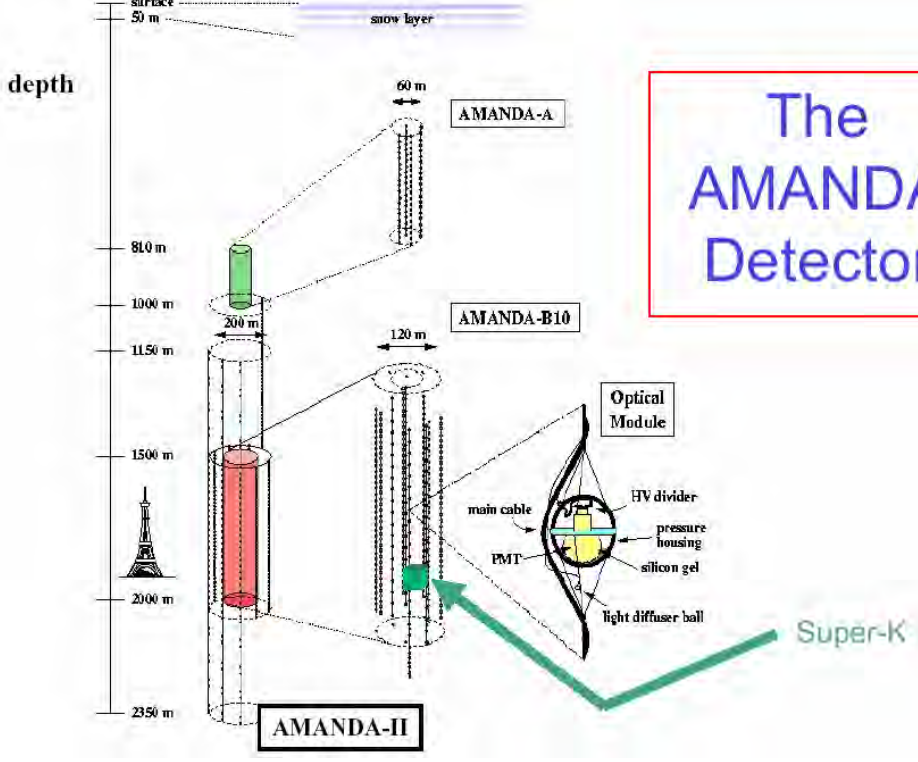
Antares detector



Equipped volume 0.1 km^2 x 0.4 km (=800 x SuperK)

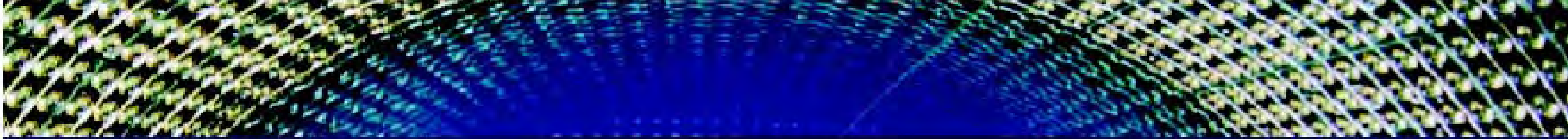
THE LAKE BAIKAL DETECTOR





The AMANDA Detector

The Optical Module



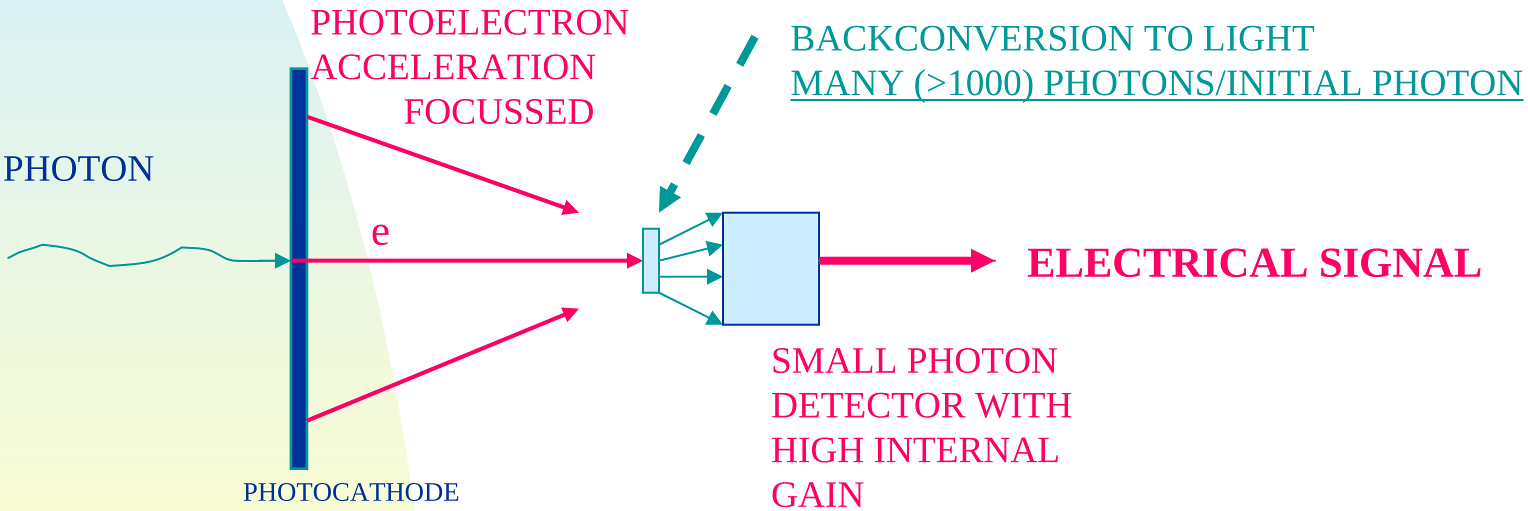
Can PMT's be manufactured at a much lower cost?
A challenge to the photo-detector/PMT manufacturers

AIM $1500 FOR A 20” PMT, FULLY AUTOMATED PRODUCTION ???

THE LIGHT CONCENTRATOR/AMPLIFIER APPROACH

THE BASIC IDEA: A LIGHT AMPLIFIER WITH STRONG FOCUSSING OF THE PHOTOELECTRONS AND A NEW SECONDARY PHOTON READOUT

REVIVAL OF THE OLD IDEA OF THE SMART PMT (PHILIPS)/QUASAR PMT COMBINED WITH THE NEW GEIGER-MODE APD SENSORS



PHOTOELECTRON
ACCELERATION
FOCUSSED

BACKCONVERSION TO LIGHT
MANY (>1000) PHOTONS/INITIAL PHOTON

PHOTON

e

ELECTRICAL SIGNAL

SMALL PHOTON
DETECTOR WITH
HIGH INTERNAL
GAIN

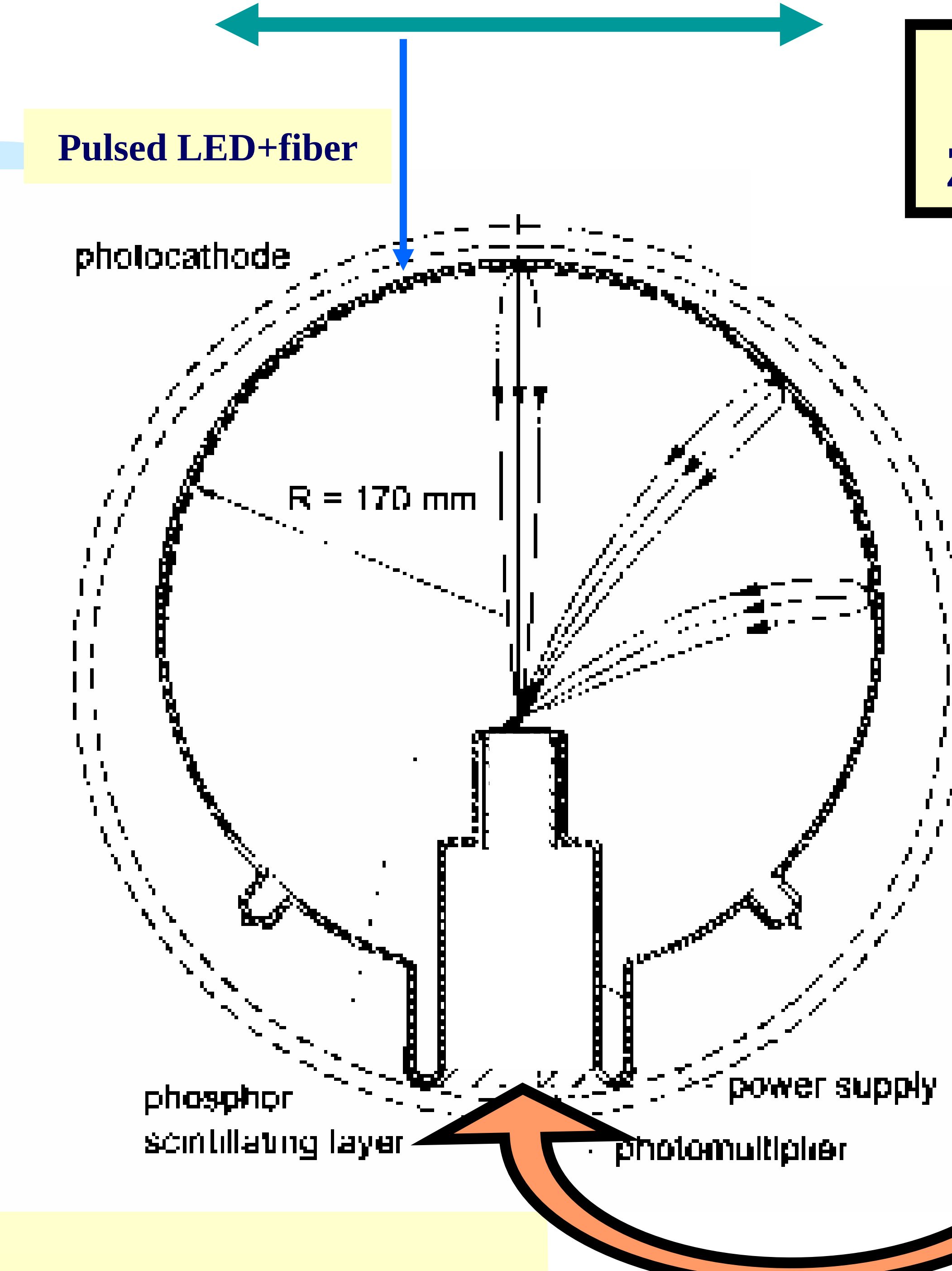
PHOTOCATHODE

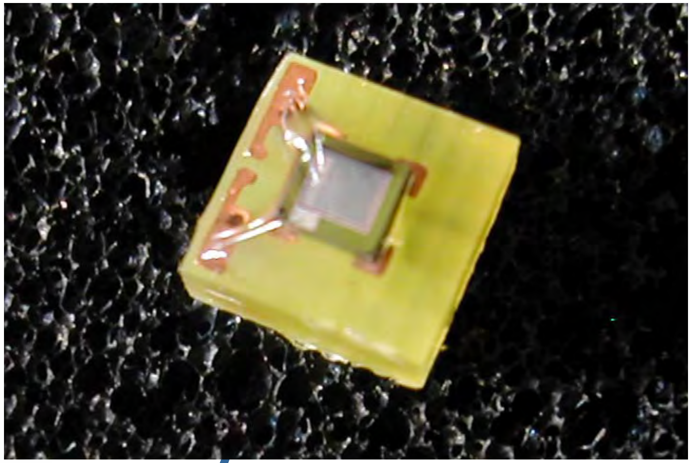
IN THE ORIGINAL CONCEPT ANOTHER PMT WITH EXTRA POWER SUPPLY WAS NEEDED.FOR THE SECONDARY LIGHT DETECTION, PMT COULD HAVE MODEST GAIN (PROBLEMS: LOW LIGHT YIELD OF CONVERTER, DECAY TIME OF LIGHT CONVERTER)

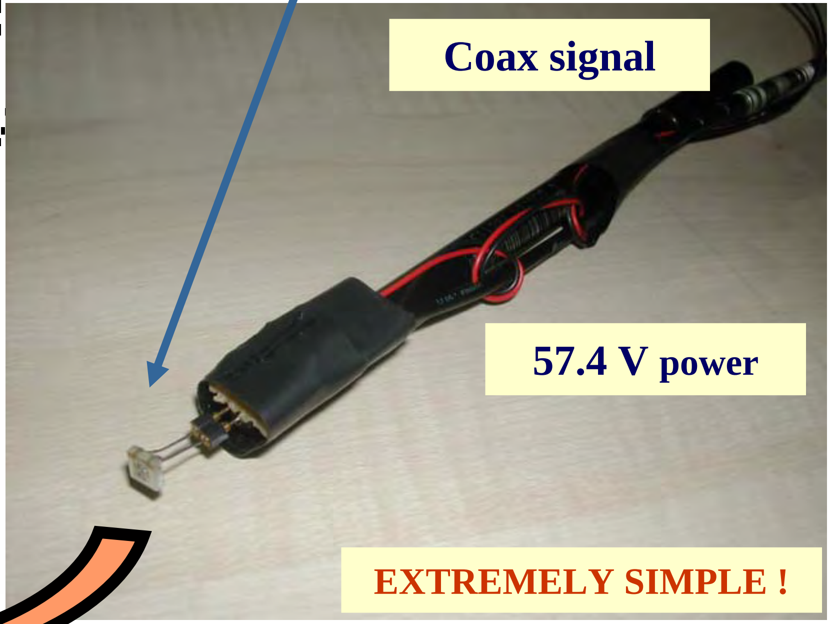
Geiger-mode APD

ZS-2 from Sadygov, MICRON

Pulsed LED+fiber



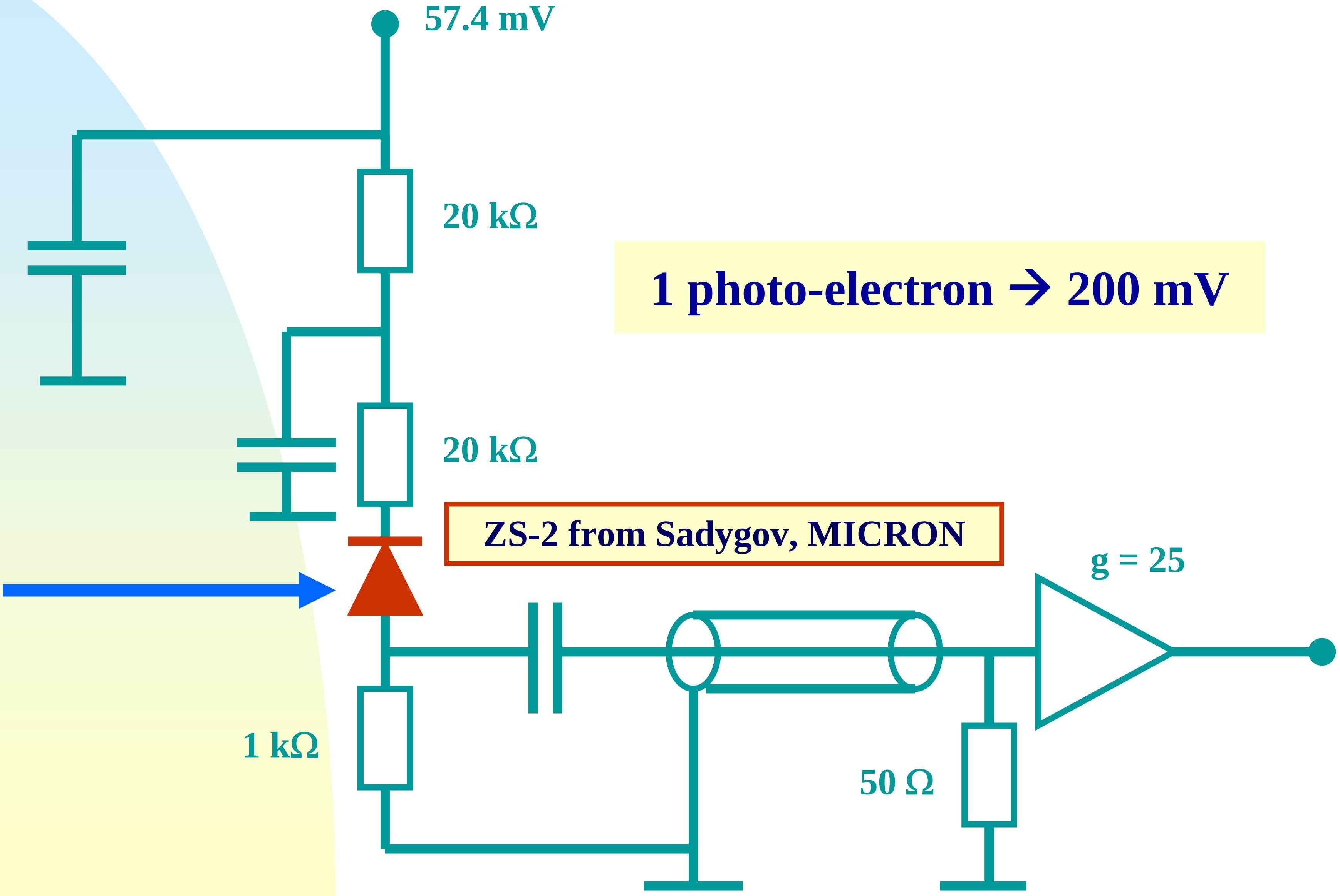




Coax signal

57.4 V power

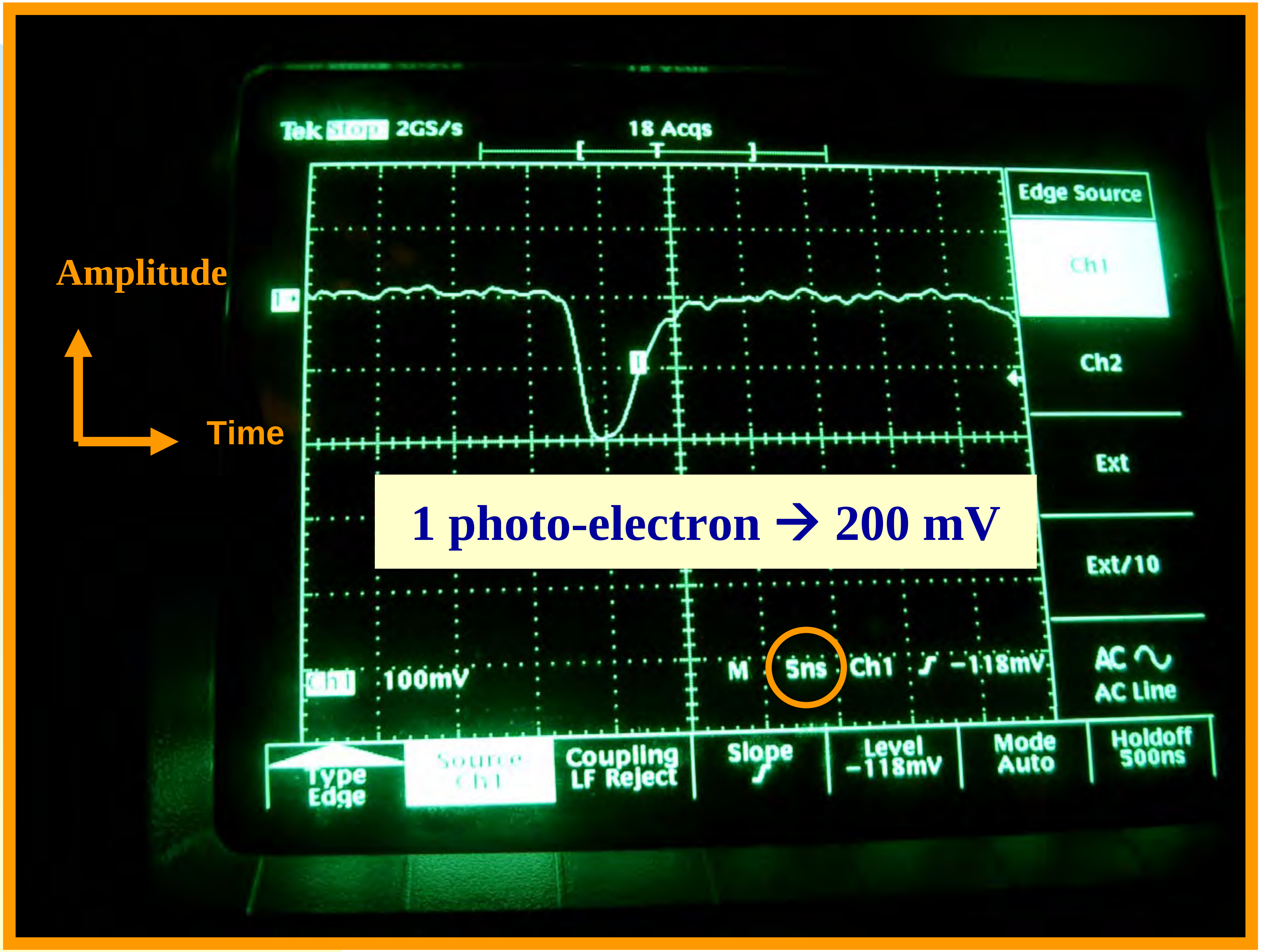
EXTREMELY SIMPLE !



1 photo-electron → 200 mV

ZS-2 from Sadygov, MICRON

A Typical Single-Photon Signal in the Geiger-mode APD

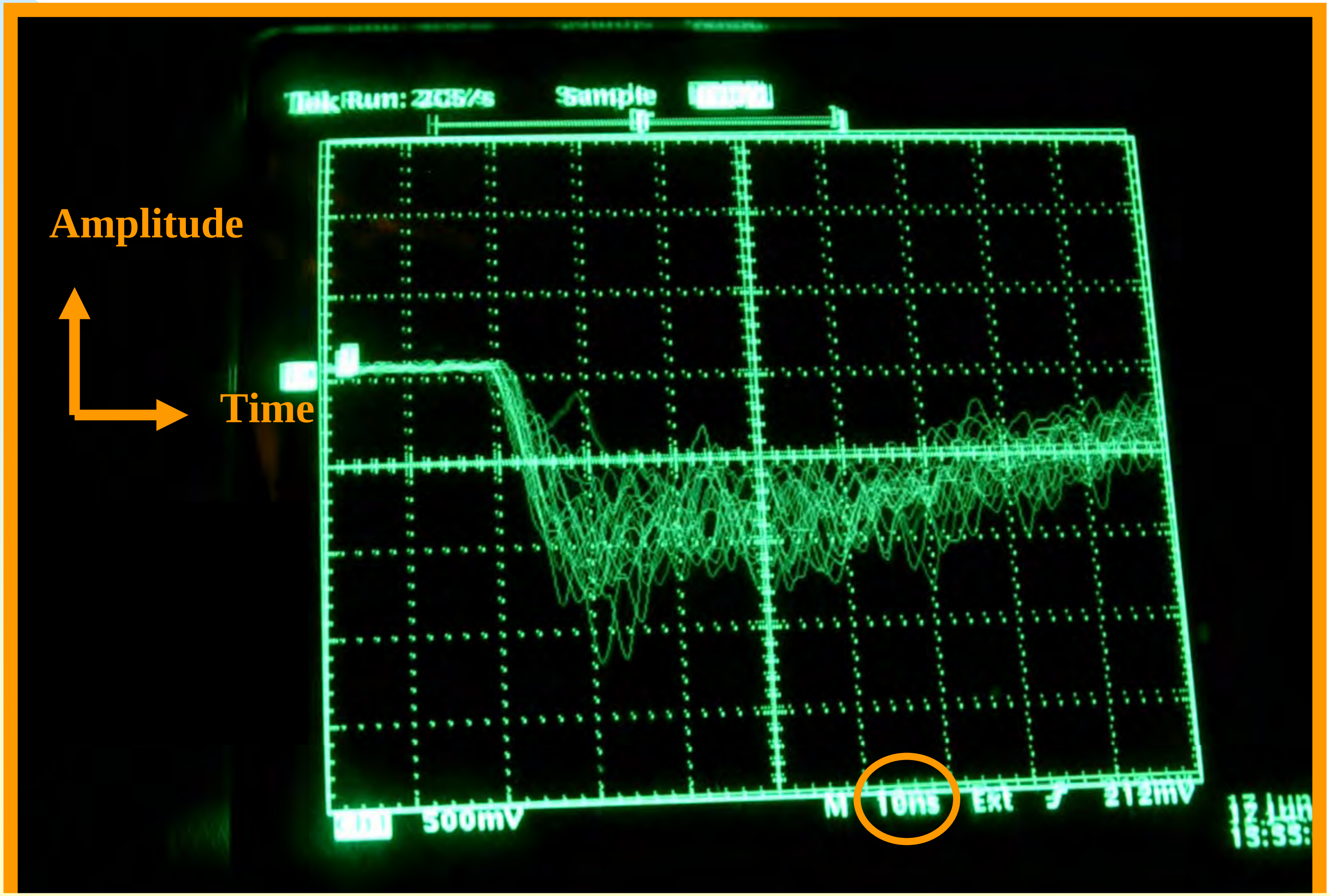


Amplitude

Time

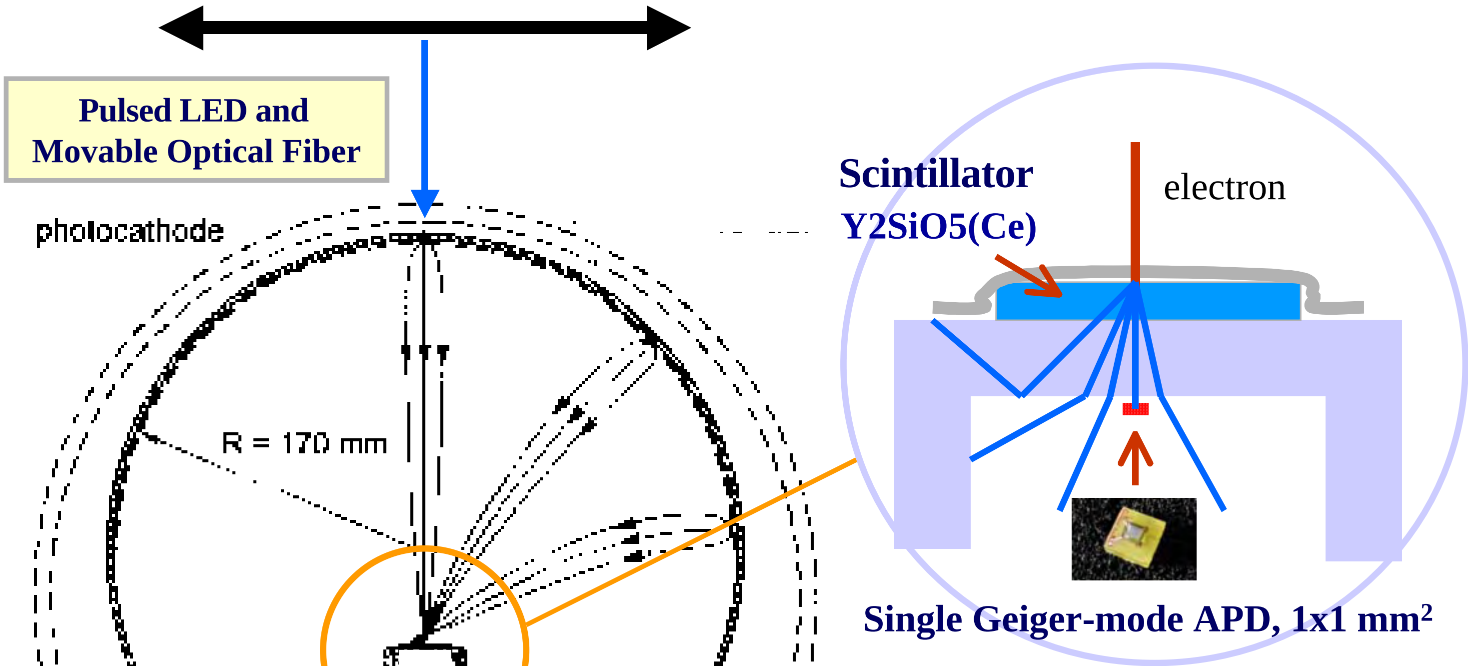
1 photo-electron → 200 mV

Superposition of many light pulses in the Geiger-mode APD (full bandwidth)



Note the individual photon structure and decay spectrum of the scintillator

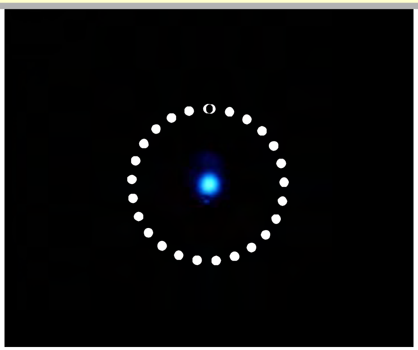
Pulsed LED and Movable Optical Fiber



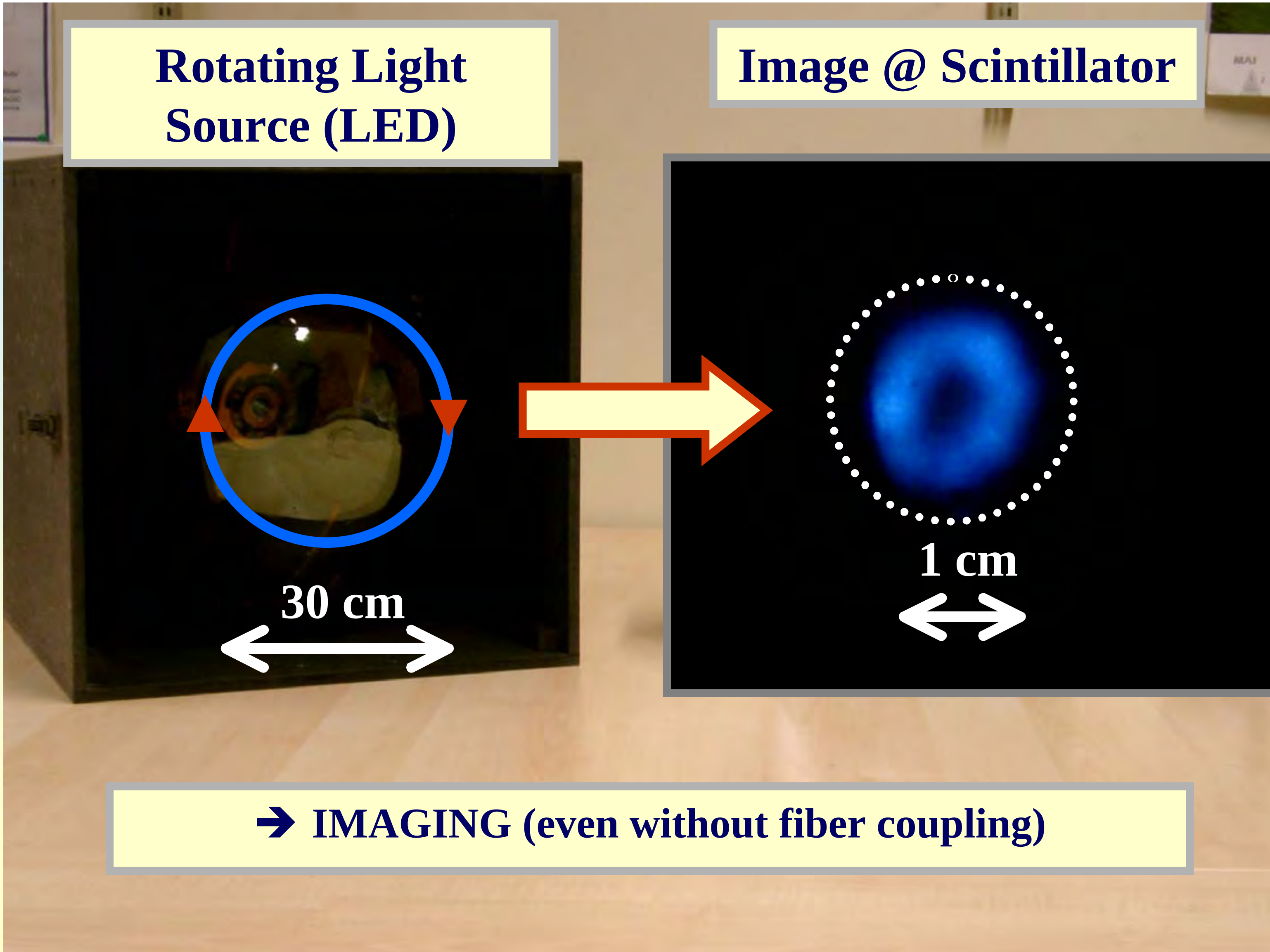
SMART PMT, QUASAR

Single Geiger-mode APD, 1x1 mm^2

No fiber plate → low light collection efficiency (~1/150)



EVEN THE QUASAR HAS SOME MODEST IMAGING QUALITY: USE OF A SMALL G-APD ARRAY ALLOWS TO SELECT SIGNALS FROM CERTAIN REGIONS -> PARTIAL NOISE SUPPRESSION IS POSSIBLE



Rotating Light Source (LED)

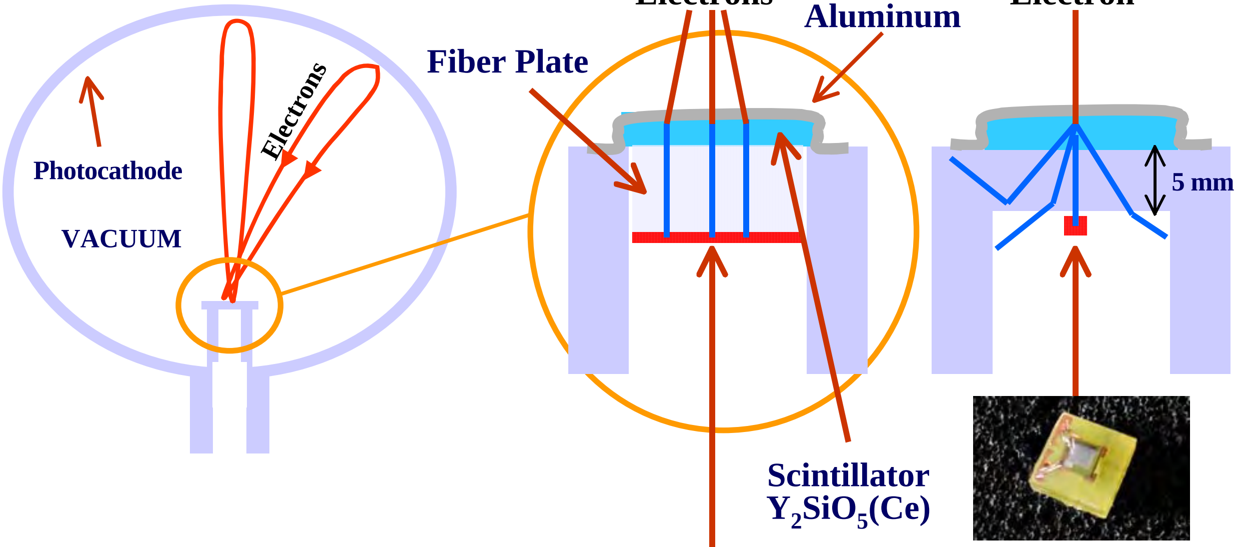
Image @ Scintillator

→ IMAGING (even without fiber coupling)

HEMISPHERICAL LIGHT AMPLIFIER

THE ULTIMATE DESIGN

CURRENT PROTOTYPE SETUP



Electrons

Photocathode

VACUUM

Fiber Plate

Electrons

Aluminum

Electron

5 mm

Scintillator
$Y_2SiO_5(Ce)$

Geiger-Mode APD Array

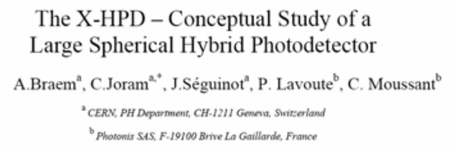
Single Geiger-Mode APD (1x1 mm^2)

ADVANTAGES

- PRODUCTION SIMPLER BECAUSE NO DYNODE SYSTEM WITH COATING TEMPERATURE CAN BE OPTIMIZED FOR CATHODE PRODUCTION
- NO BLEEDER CURRENT NEEDED: ULTRALOW POWER HT GENERATOR SPARK PLUG HT UNIT ?….
- NO HT FOR SECONDARY PMT
- COST OF G-APD (C-MOS) SHOULD BE VERY LOW
- VOLTAGE (50-80V) + POWER FOR G-APD BIAS VERY LOW
- COMBINED GAIN CAN BE MADE VERY HIGH 10^7 EASILY POSSIBLE
- PRACTICALLY INSENSITIVE TO THE EARTH MAGNETIC FIELD
- EASY TO INSTALL NEW VERY POWERFUL GETTER PUMP AND TO ACTIVATE IN SITU
- G-APD NOT BE DAMAGED BY EXCESSIVE LIGHT (EVEN IN DAYLIGHT NOT DAMAGED)

A SPHERICAL SOLUTION WITH SPHERICAL SCINTILLATOR, SIMPLE PRODUCTION 5 STERAD, MINIMAL TIME JITTER, ELECTRONICS CAN BE LOCATED IN STEM MAY BE EVEN PRODUCED INSIDE BENTOS SPHERE

See also CERN PH-EP2006-025



The X-HPD – Conceptual Study of a
Large Spherical Hybrid Photodetector

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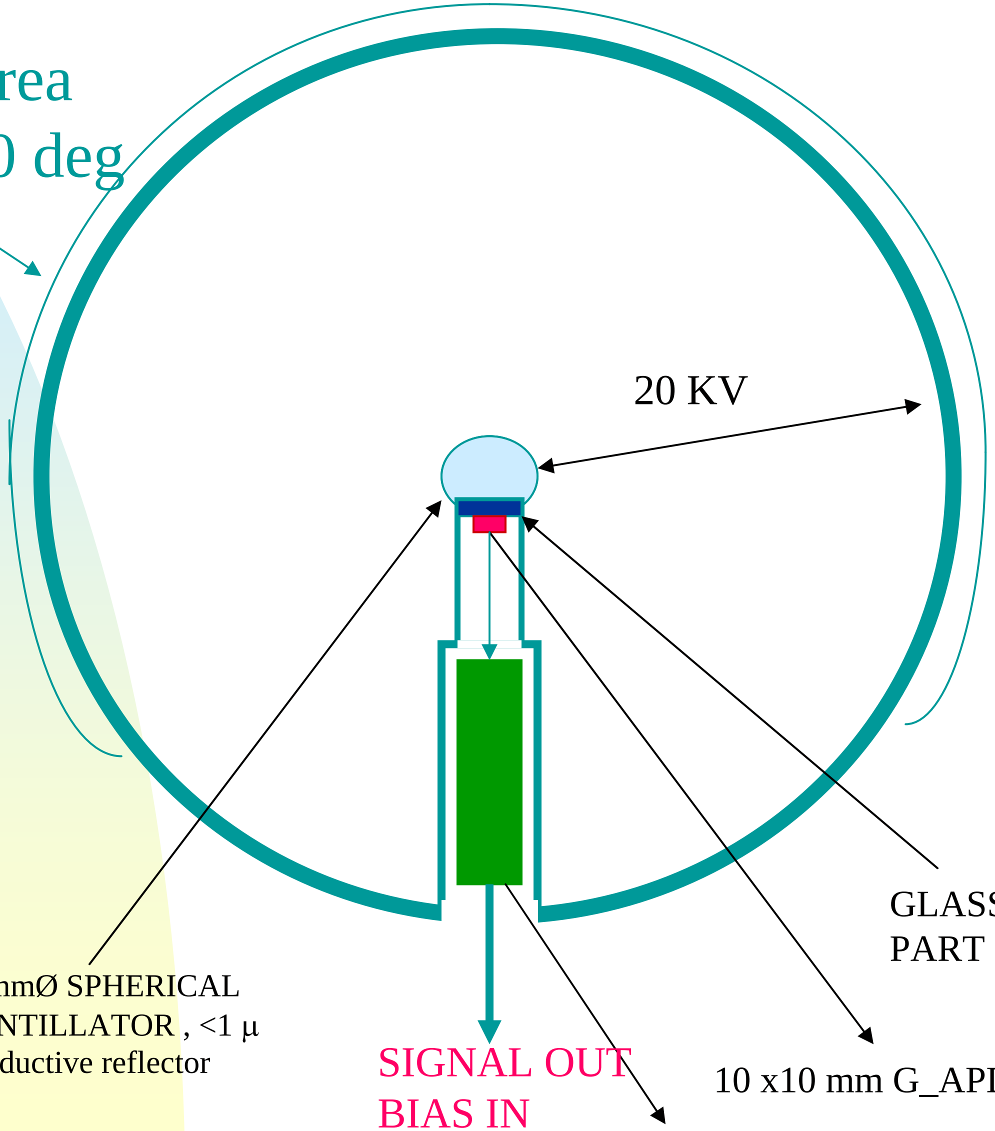


Cathode area covers 270 deg

20 KV

GLASS LIGHT GUIDE
PART OF VACUUM SEAL

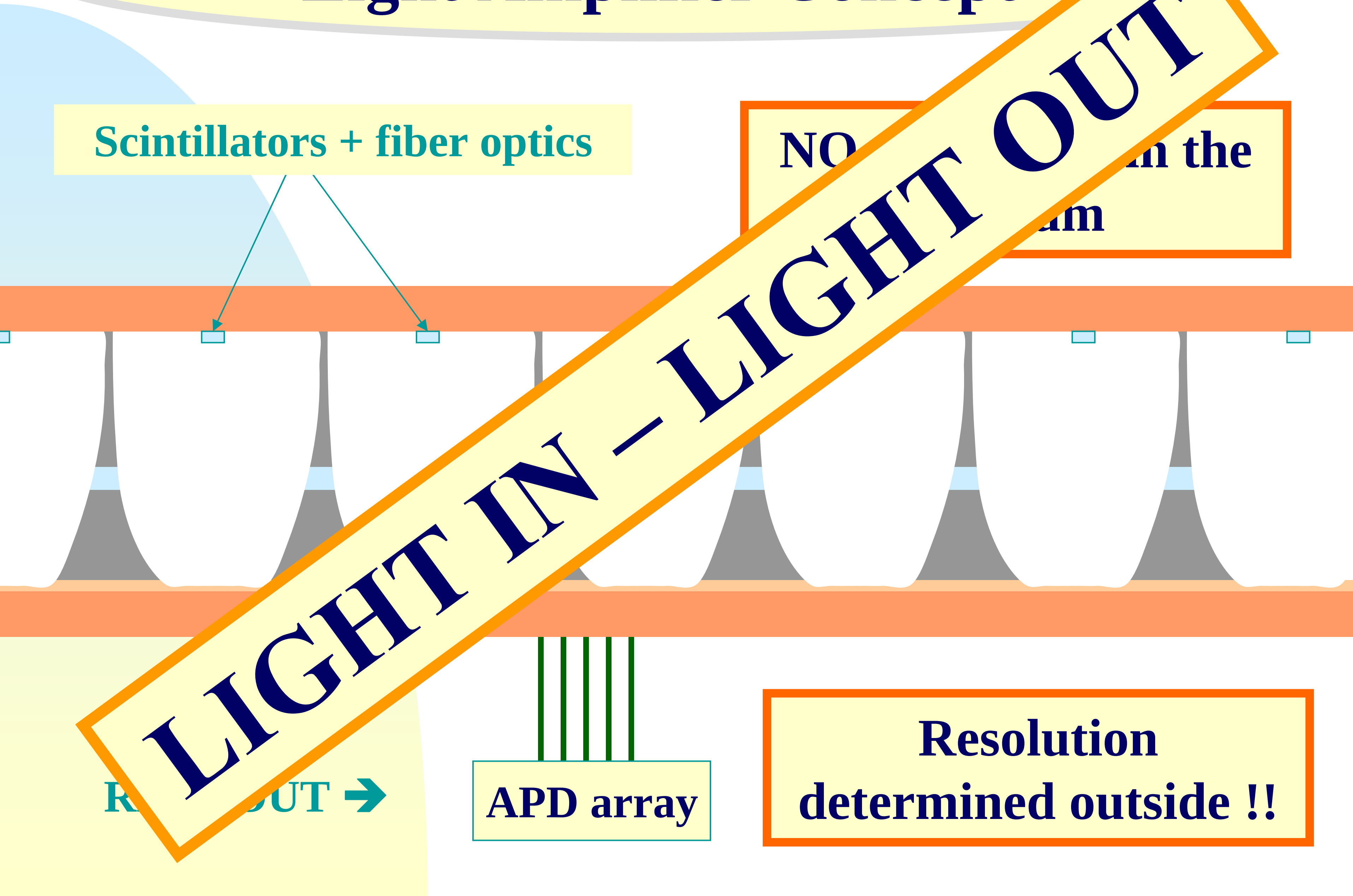
10 mmØ SPHERICAL
SCINTILLATOR , <1 μ
Conductive reflector

SIGNAL OUT
BIAS IN

10 x10 mm G_APD

HT. ELECTRONICS

Light Amplifier Concept



Scintillators + fiber optics

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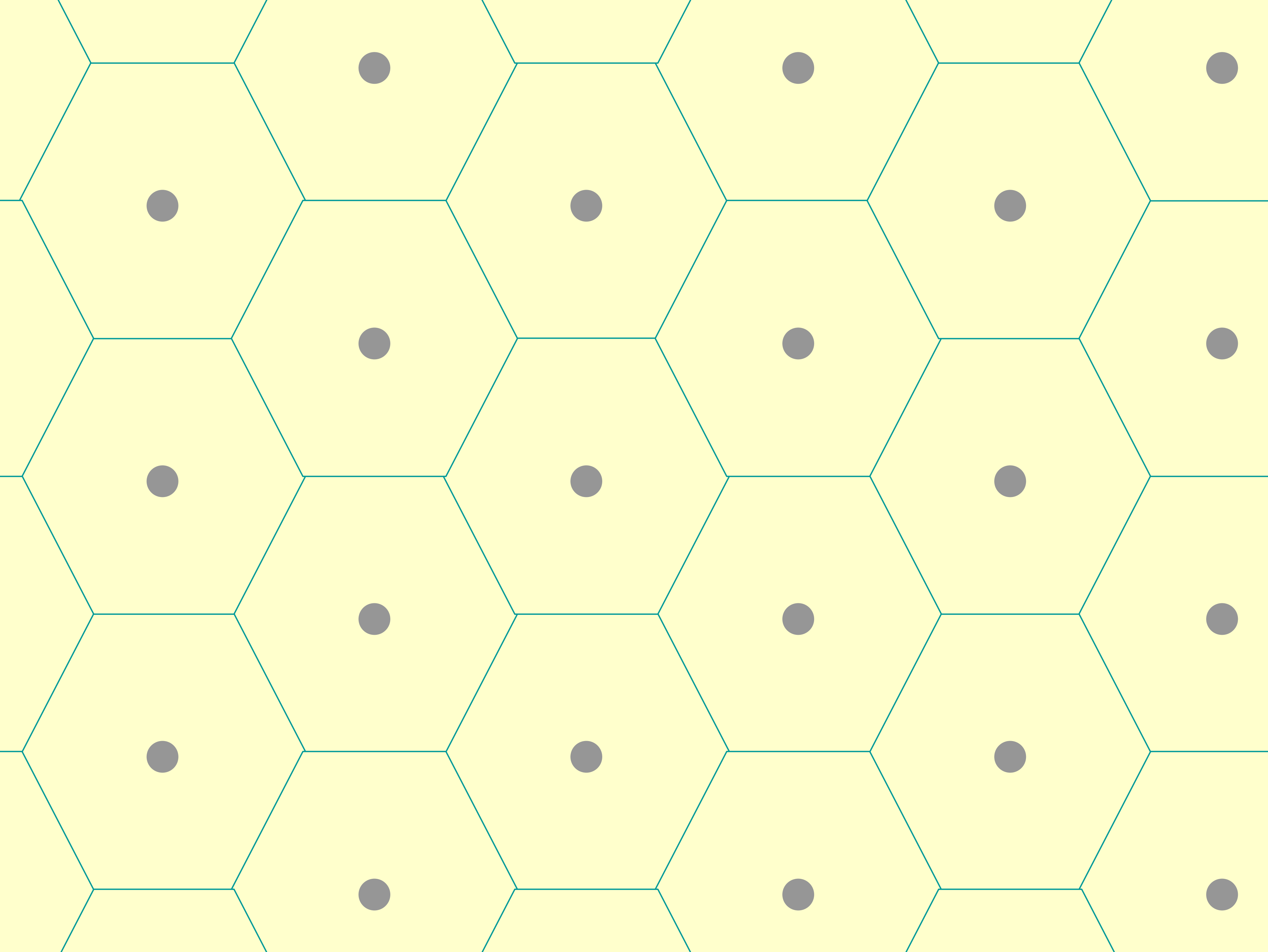
LIGHT IN – LIGHT OUT

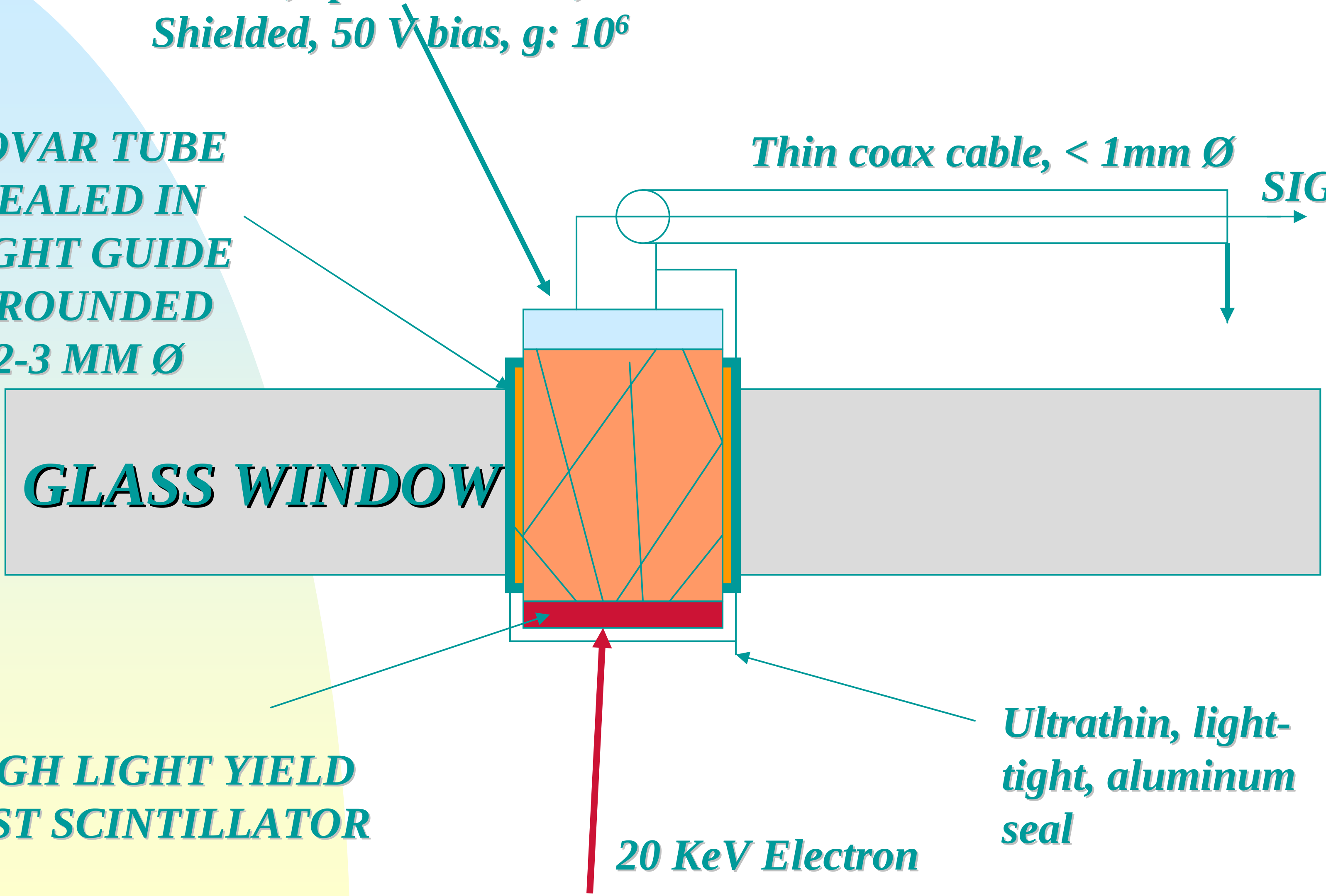
R OUT ➔

APD array

Resolution determined outside !!



DETAILS OF THE READOUT



G-APD, optical contact,
Shielded, 50 V bias, g: 10^6

KOVAR TUBE
SEALED IN
LIGHT GUIDE
GROUNDED
2-3 MM Ø

Thin coax cable, < 1mm Ø

SIGNAL

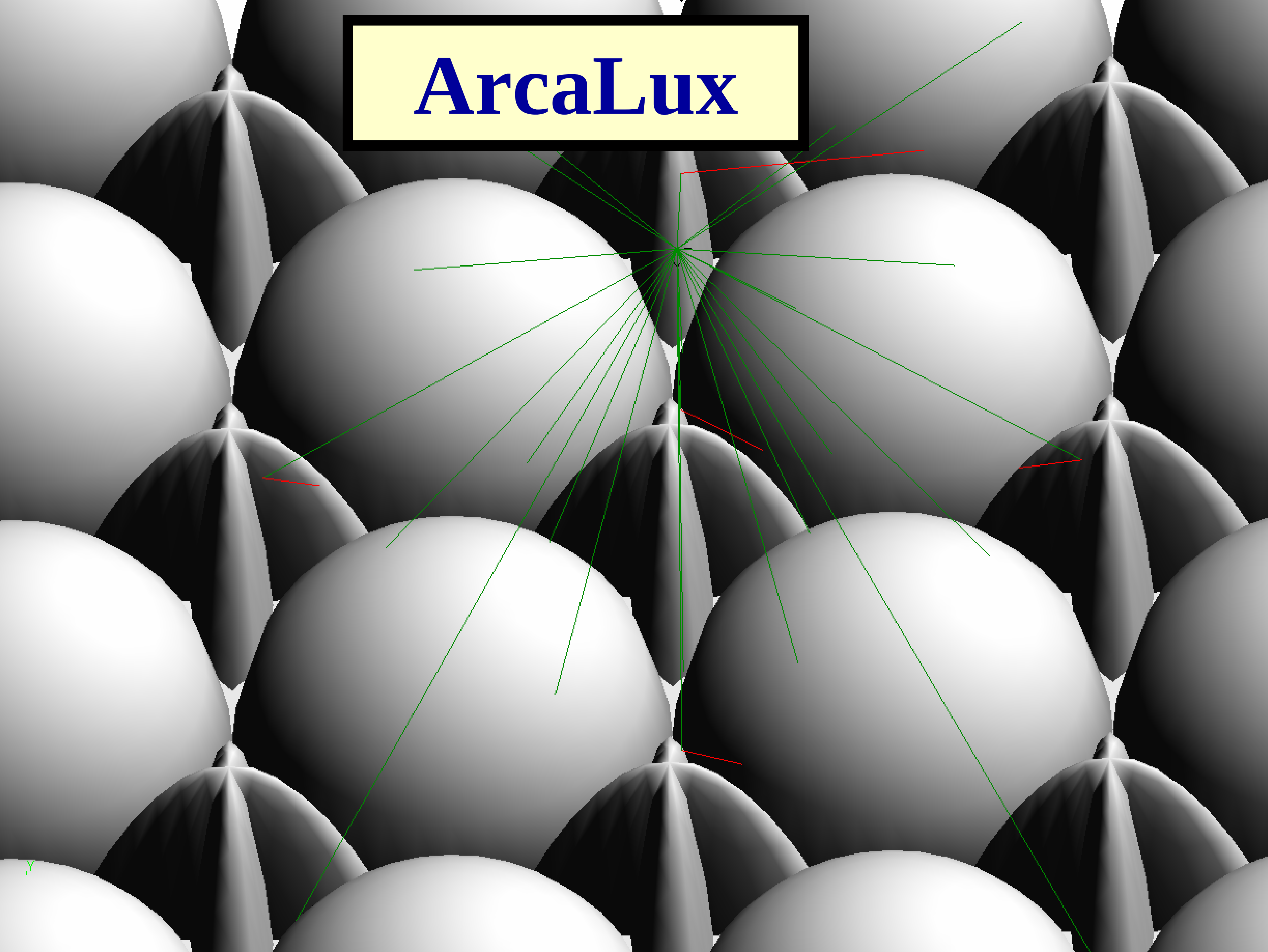
GLASS WINDOW

HIGH LIGHT YIELD
FAST SCINTILLATOR

20 KeV Electron

Ultrathin, light-tight, aluminum seal

ArcaLux



WHERE DO WE STAND, WHERE WILL WE GO AND CONCLUSIONS

FOR DIRECT LIGHT DETECTION:

- G-APDs ready in next 1-2 years for large scale tests in C-Telescopes for ground-based γ-astronomy but we want 5x5 or 10x10 mm g-apds (not sacrifying fast risetime)

- G-APDs soon ready (3-5 years) for γ-ray astronomical observations with large telescopes for example for the CTA (Cherenkov Telescope Array, ≈ 100 large telescopes)

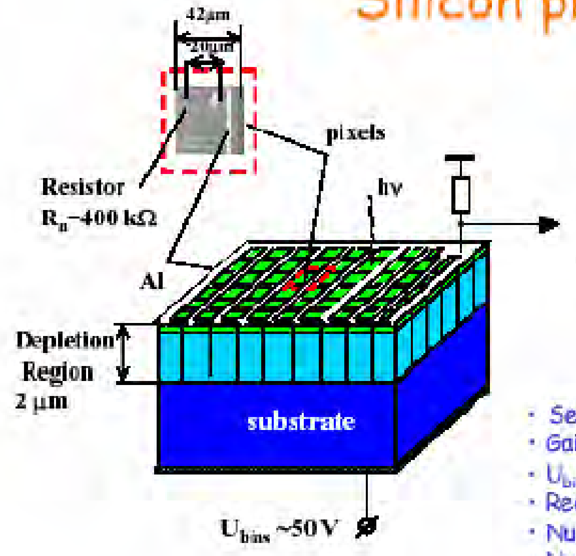
FOR INDIRECT LIGHT DETECTION (WLS FIBERS OR XTALS)

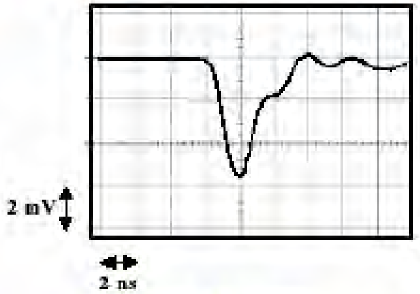
- G-APDs work already for fiber calorimeters or scintillation counters using wls fibers
  in APP detectors the radiation damage is normally no problem

- G-APDs for SMART PMT secondary readout
  g-apds soon ready (3x3, 5x5, 10x10 mm**2 area, matrices -> work related to PET dev.)
  development of SMART tubes still pending (large volumes, fast, high light yield Xtals)

G-APDS LOOK VERY PROMIZING FOR APP DETECTORS, MIGHT RESULT IN STRONG EVOLUTION OF PERFORMANCE AND SENSITIVITY (FOR SATELLITE DETECTORS IT MIGHT TAKE LONGER)

Silicon photomultiplier (SiPM)





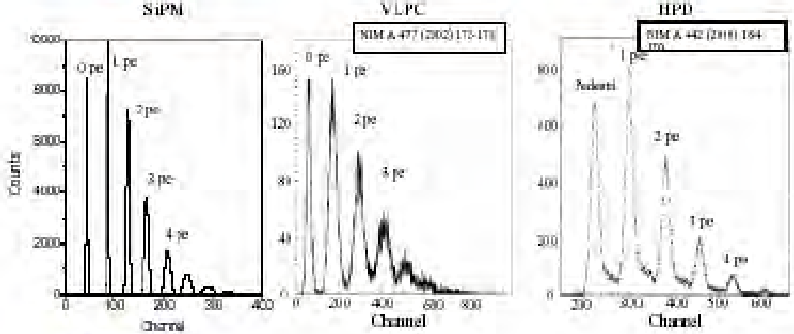
SiPM main features:

- Sensitive size 1x1mm^2 on chip 1.5x1.5 mm^2
- Gain $2 \cdot 10^6$
- U_{bias}~50V
- Recovery time ~ 100 ns/pixel
- Number of pixels: 576
- Nuclear counter effect: negligible (due to Geiger mode
- Insensitive to magnetic field
- Dynamic range ~10^3/mm^2

For further details see:
«Advanced study of SiPM»
http://www.slac.stanford.edu/pubs/icfa/fall01.html

B.Dolgoshein "SiPM possible applications"

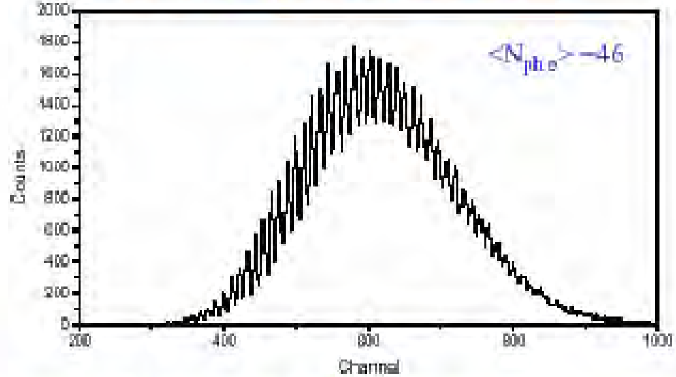
Single photoelectron (single pixel) spectra



SiPM:
- excellent single photoelectron resolution
- low ENF expected

B.Dolgoshein "SiPM possible applications"

More about pixel signal resolution: tens of photoelectrons

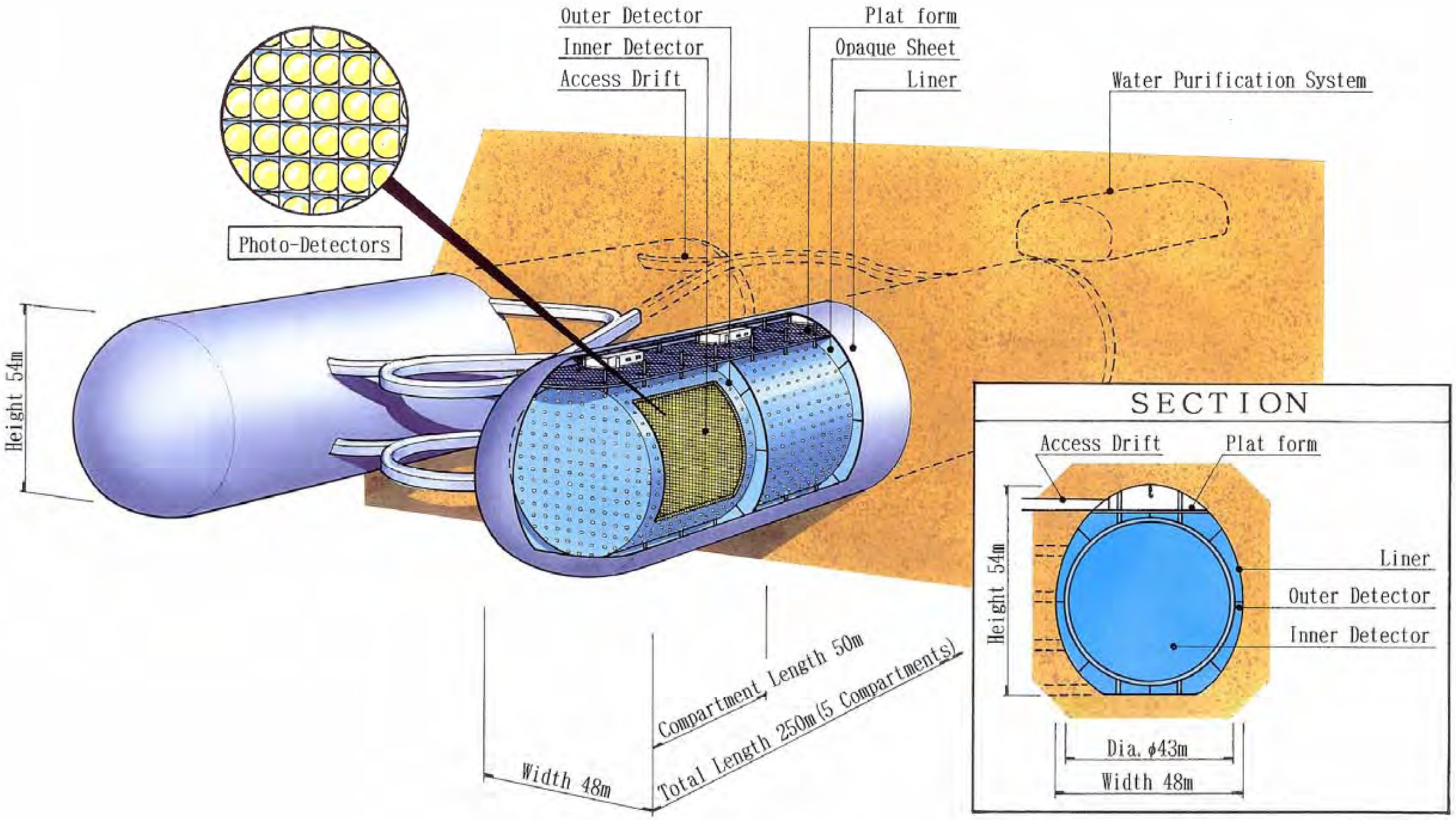


- SiPM consists of a large number of pixel photoelectron counters with binary readout for each pixel, working as analogue device
- signal uniformity from pixel to pixel is quite good

B.Dolgoshein "SiPM possible applications"

Hyper-Kamiokande

~1 Mton water Cherenkov detector at Kamioka



Comparison of 3Generations of Kamioka Nucleon Decay Experiments

	Kamiokande	Super-Kamiokande	Hyper-Kamiokande
Mass	3,000 t (+1,500 t)	50,000 t	1,000,000 t
Photosensitive Coverage	20 %	40 % (SK-I and -III) 20 % (SK-II)	?
Observation Started	1983	1996	?
Cost (Oku-Yen)*	5	100	500?**

* 1 Oku-Yen ≈ 1M$

** Target cost; No realistic estimate yet

UNO Detector Conceptual Design

A Water Cherenkov Detector

optimized for:

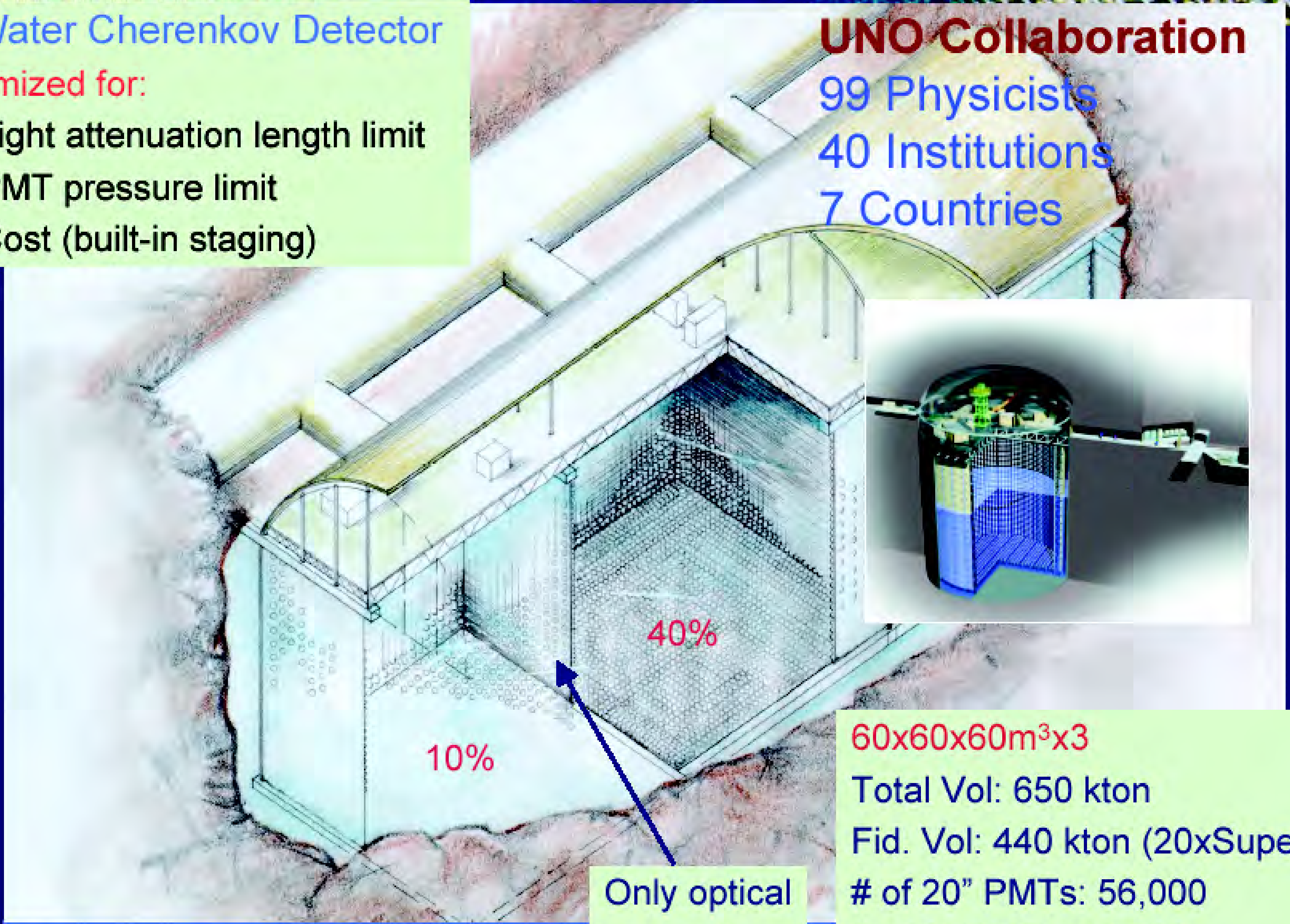
- Light attenuation length limit
- PMT pressure limit
- Cost (built-in staging)

UNO Collaboration

99 Physicists

40 Institutions

7 Countries



Only optical separation

60x60x60m^{3}x3

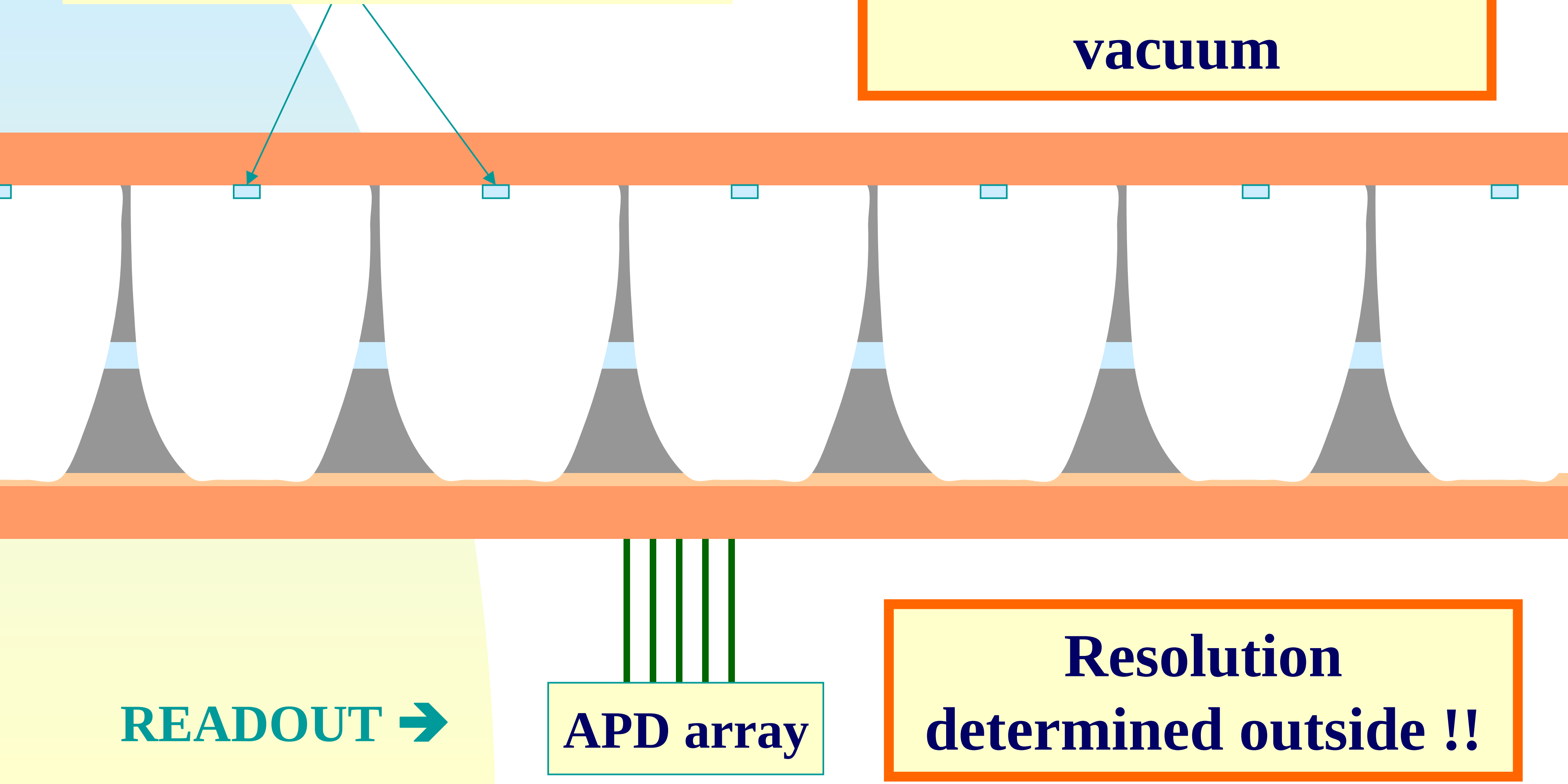
Total Vol: 650 kton

Fid. Vol: 440 kton (20xSuperK)

# of 20” PMTs: 56,000

# of 8” PMTs: 14,900

Light Amplifier Concept



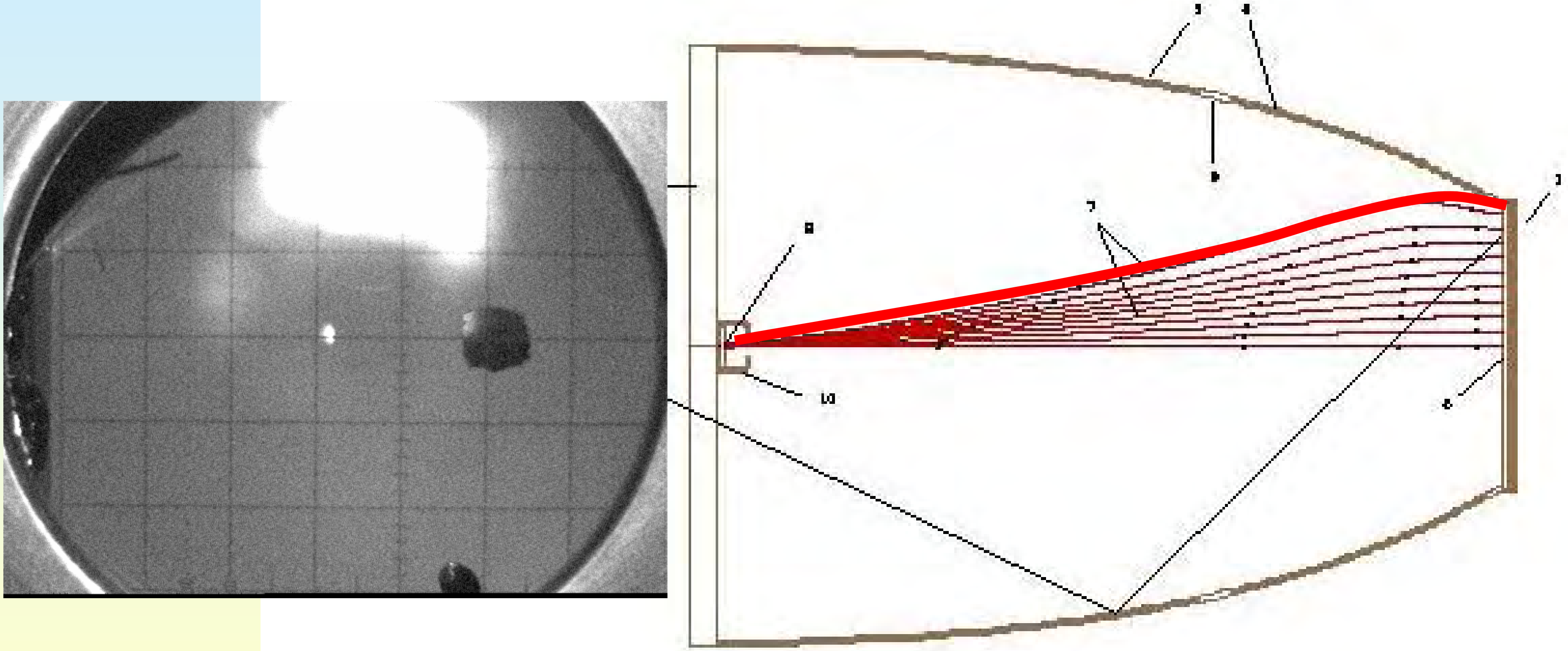
Scintillators + fiber optics

NO electronics in the vacuum

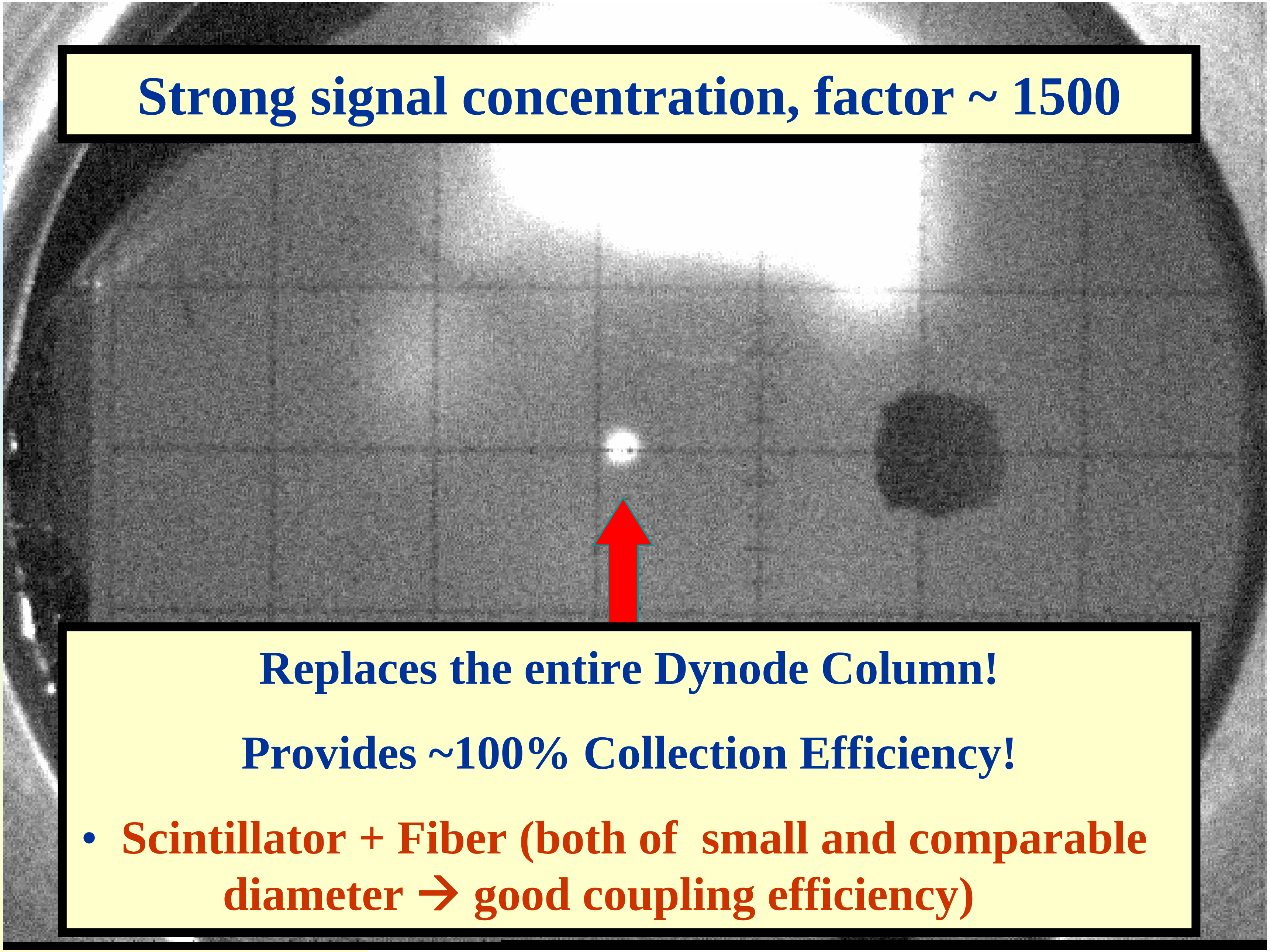
READOUT →

APD array

Resolution determined outside !!


5
4
9
3
7
8
10
6

Strong signal concentration, factor ~ 1500



Replaces the entire Dynode Column!

Provides ~100% Collection Efficiency!

- **Scintillator + Fiber (both of small and comparable diameter → good coupling efficiency)**

POSSIBLE NEW SCINTILLATORS

a)BrilLanCe from Saint-Gobain

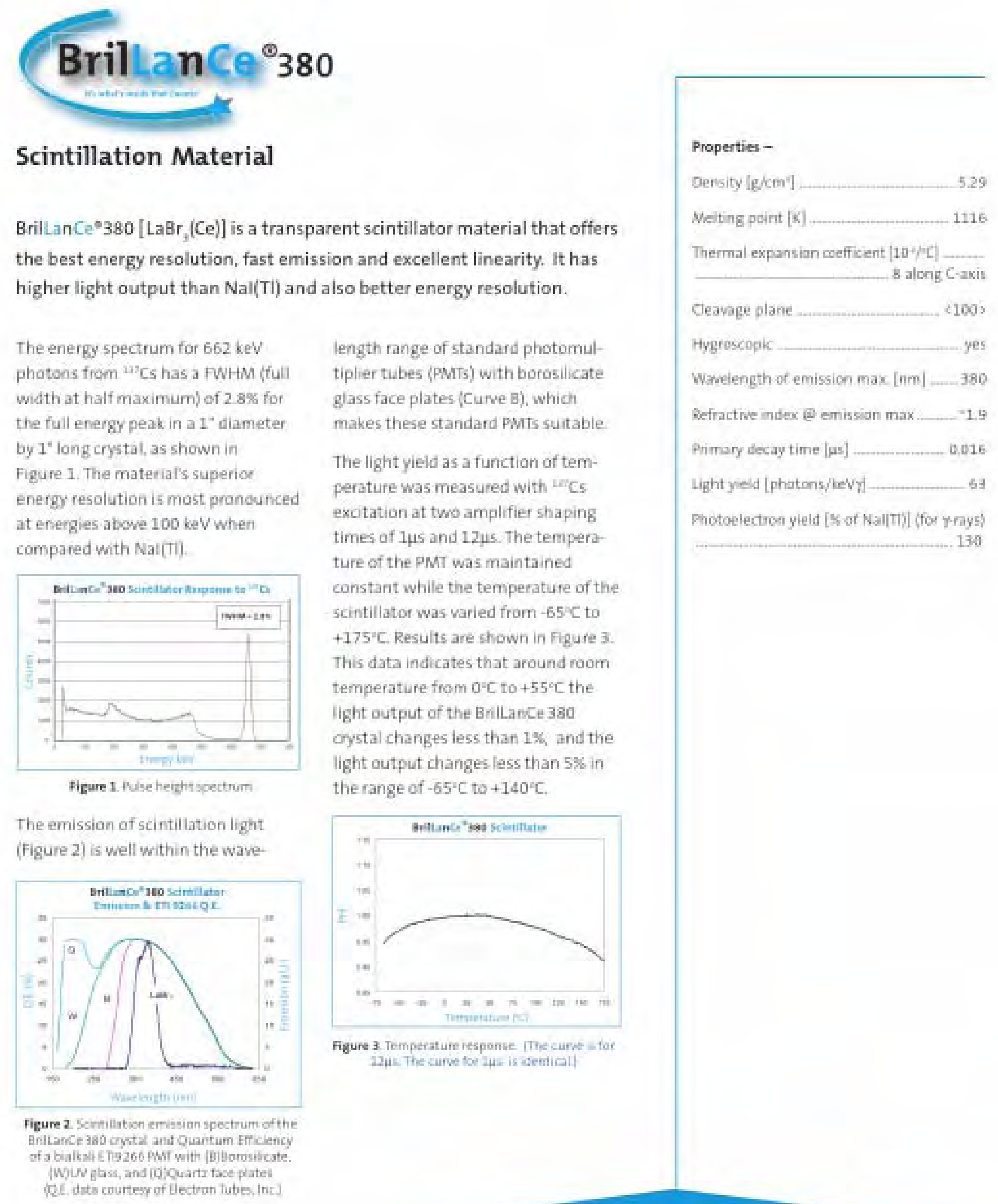
- **High light yield > 60phots/KeV**
- **Fast τ : 16 nsec**
- **Caveat: extremely hygroscopic**

b) LSO,LYSO

- **High light yield. 25-30phots/KeV**
- **Fast 35-40 nsec**
- **Easy to handle**

C) ZnO

- **Medium light yield, 10 phots/kEV**
- **Ultrafast ≈ 1 nsec**
- **Exotic material**
- **No commercial production**
- **Small xtals**



BrilLanCe®380

Scintillation Material

BrilLanCe®380 [$LaBr_3$(Ce)] is a transparent scintillator material that offers the best energy resolution, fast emission and excellent linearity. It has higher light output than NaI(Tl) and also better energy resolution.

The energy spectrum for 662 keV photons from ^{137}Cs has a FWHM (full width at half maximum) of 2.8% for the full energy peak in a 1" diameter by 1" long crystal, as shown in Figure 1. The material's superior energy resolution is most pronounced at energies above 100 keV when compared with NaI(Tl).

BrilLanCe®380 Scintillator Response to ^{137}Cs

Figure 1. Pulse height spectrum

The emission of scintillation light (Figure 2) is well within the wavelength range of standard photomultiplier tubes (PMTs) with borosilicate glass face plates (Curve B), which makes these standard PMTs suitable.

BrilLanCe®380 Scintillator Emission & ETI 9266 Q.E.

Figure 2. Scintillation emission spectrum of the BrilLanCe 380 crystal and Quantum Efficiency of a bialkali ET9266 PMT with (B)Borosilicate, (W)UV glass, and (Q)Quartz face plates (Q.E. data courtesy of Electron Tubes, Inc.)

The light yield as a function of temperature was measured with ^{137}Cs excitation at two amplifier shaping times of 1µs and 12µs. The temperature of the PMT was maintained constant while the temperature of the scintillator was varied from -65°C to +175°C. Results are shown in Figure 3. This data indicates that around room temperature from 0°C to +55°C the light output of the BrilLanCe 380 crystal changes less than 1%, and the light output changes less than 5% in the range of -65°C to +140°C.

BrilLanCe®380 Scintillator

Figure 3. Temperature response. (The curve is for 12µs. The curve for 1µs is identical.)

Properties –

Density [g/cm^3]	5.29
Melting point [K]	1116
Thermal expansion coefficient [10^{-6}/°C]	8 along C-axis
Cleavage plane	<100>
Hygroscopic	yes
Wavelength of emission max. [nm]	380
Refractive index @ emission max	~1.9
Primary decay time [µs]	0.016
Light yield [photons/keVγ]	63
Photoelectron yield [% of NaI(Tl)] (for γ-rays)	130

SOME SIMPLE, LOW COST SECONDARY IMPROVEMENTS:

- IMPROVING THE EFFECTIVE QE (THE G-APD COMMUNITY USES THE WORD PHOTON DETECTION EFFICIENCY=PDE)
  LARGE PMTS HAVE NORMALLY A POOR EFFECTIVE QE

- INCREASE IN QE BY DIFFUSE LACQUER COATING
  MULTIPLE CROSSING OF SEMITRANSPARENT CATHODE BY LIGHT TRAJECTORY

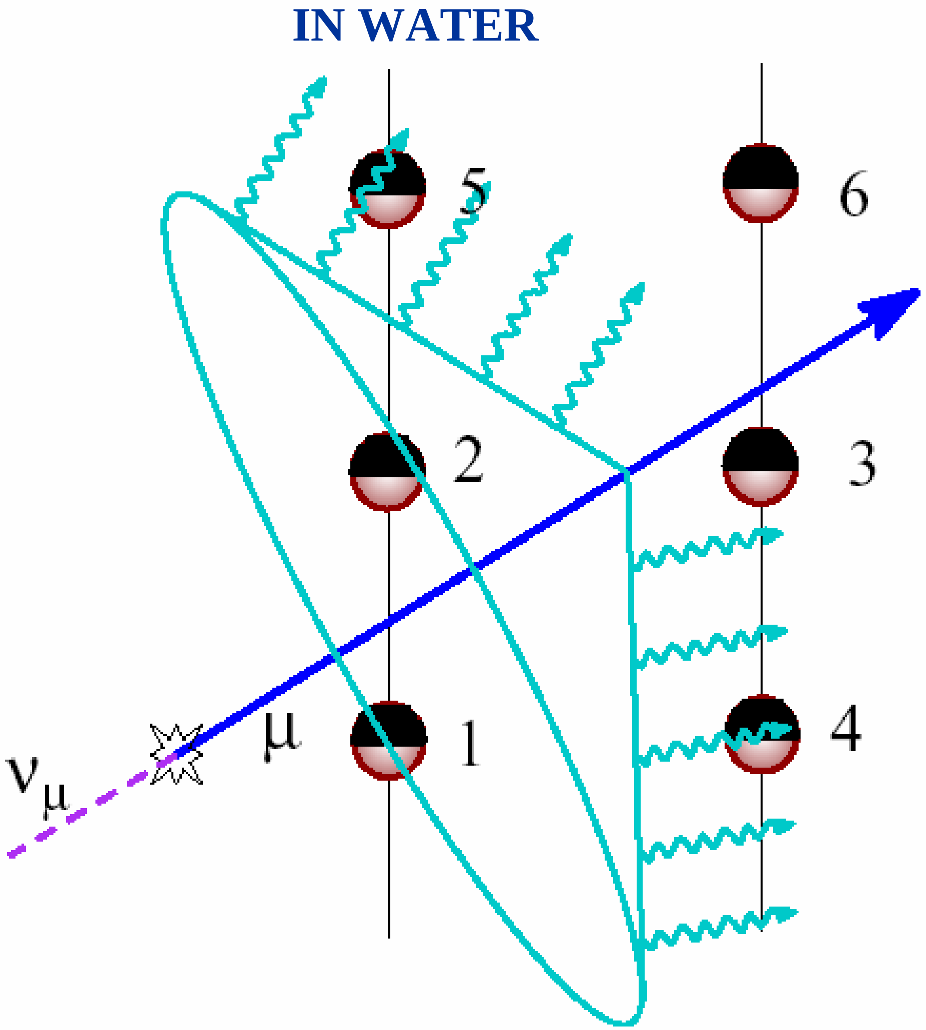
- INCREASE OF QE BY INTERNAL BACKREFLECTION (ALREADY PARTLY IN USE)

Physics motivation

- Astrophysics
  - Neutrino astronomy
  - Composition of jets
  - Engine of cosmic accelerators
- Particle physics
  - Origin of UHE cosmic rays
  - Massive particles (GUT)
  - Dark matter
  - Neutrino properties (ν_τ, σ)

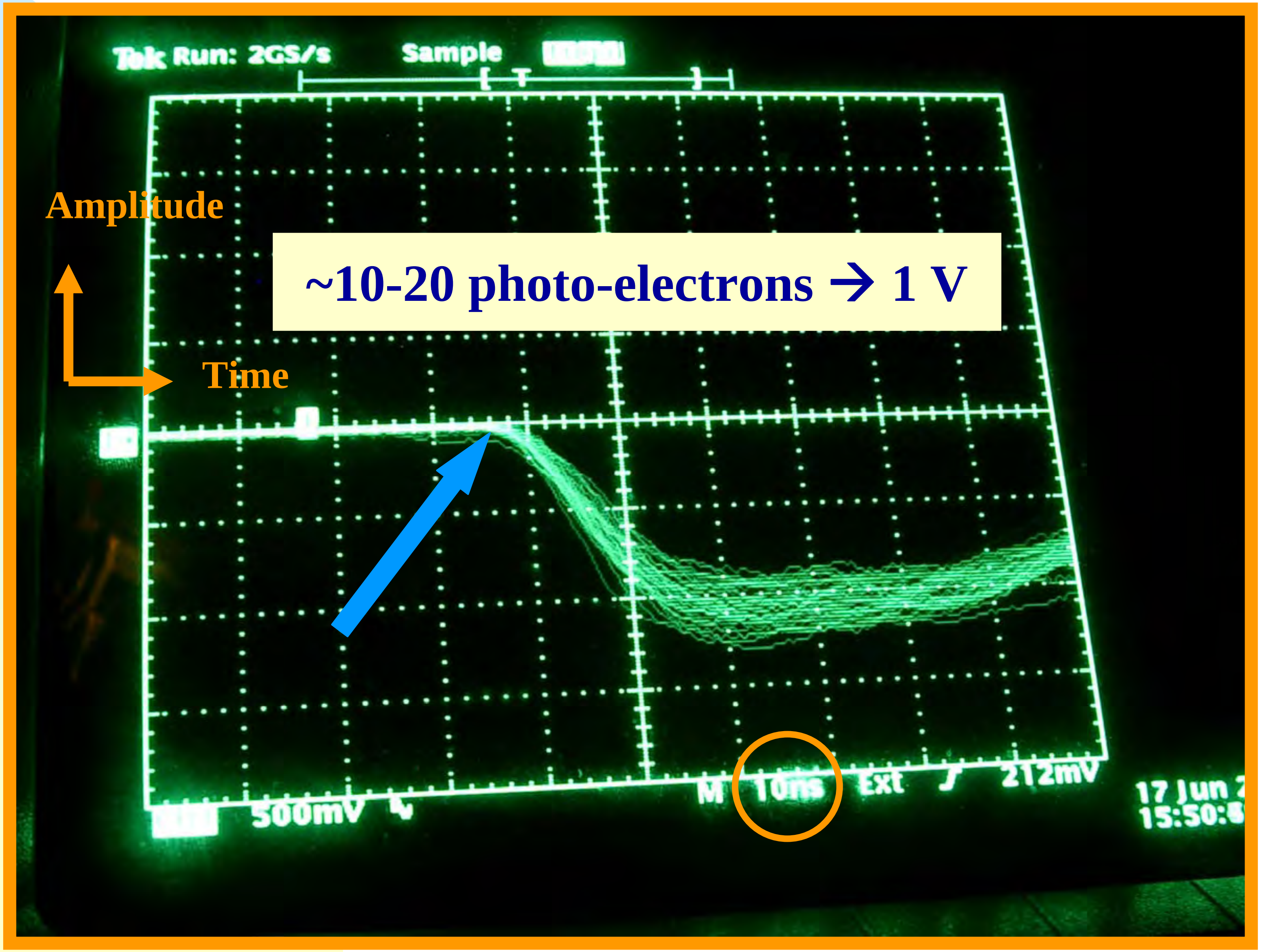
Detection Method for ν_μ

- Cherenkov photons are detected by array of PMTs
- Tracks are reconstructed by *maximum likelihood* method of photon arrival times.



Superposition of many light pulses in the Geiger-mode APD

(signal integrated)



Amplitude

Time

~10-20 photo-electrons → 1 V