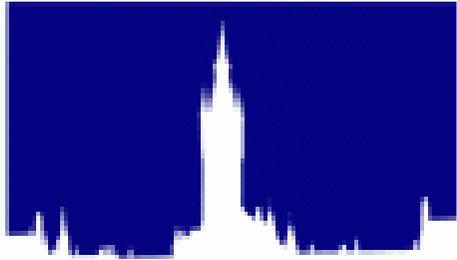


PSD8



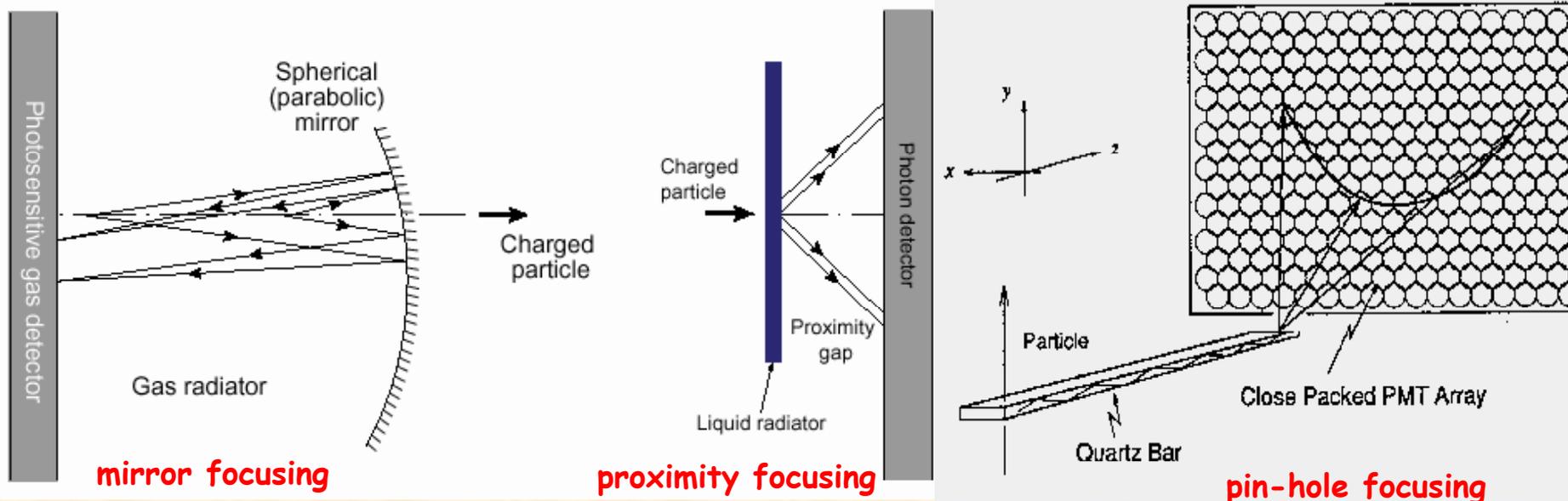
8TH INTERNATIONAL CONFERENCE ON
POSITION SENSITIVE DETECTORS

Advances in the photon detection technologies for Cherenkov light imaging applications

OUTLINE

- Cherenkov Light Imaging Techniques
- Properties of photon detectors for Cherenkov Imaging
- The "state of the art" in Cherenkov photon detection
- On-going developments
 - MCP-PMT
 - G-APD
 - THGEM and S-RETGEM
- Prospects for a new generation of photon detectors based on Multiwall Carbon Nanotubes
- Concluding remarks

A powerful approach to particle identification



Imaging of photons emitted through the Cherenkov effect is a unique tool to identify charged particles over an impressive range in momentum, from a few hundred MeV/c up to several hundred GeV/c

The performance of this approach has yet to be matched by competing methods especially when the physics objectives require excellent separation power

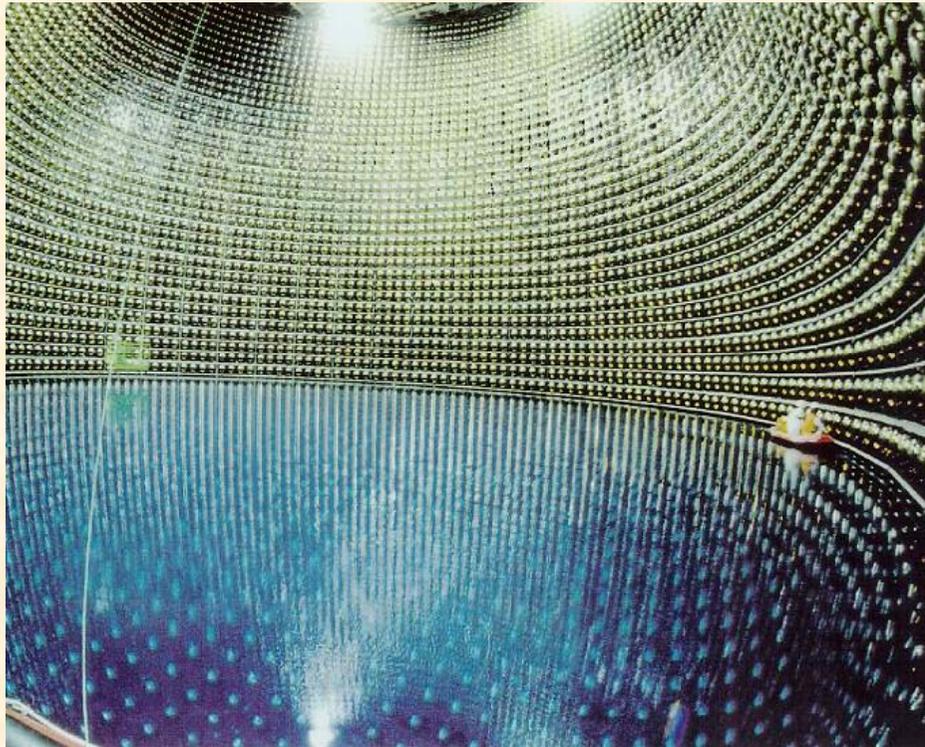
Examples

Past: OMEGA and DELPHI (CERN), SLD and BaBar (SLAC), SELEX (FNAL), HERA-B and HERMES (DESY)

Present: COMPASS (CERN), PHENIX (BNL), Hall-A (TJNAF)

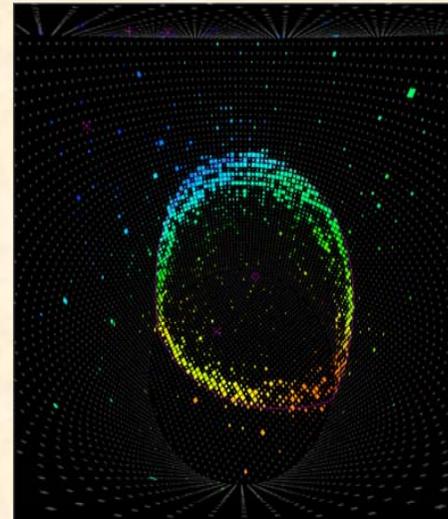
Future: ALICE, LHCb and NA62 (CERN), SuperB Factories, PANDA and CBM (FAIR)

Cherenkov Light Imaging in Astroparticle Physics

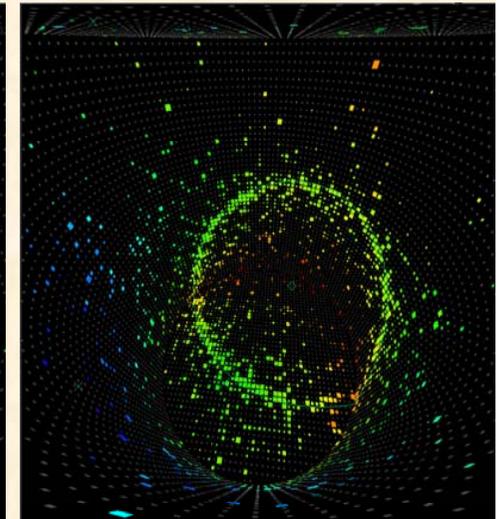


Super-Kamiokande

μ fully contained



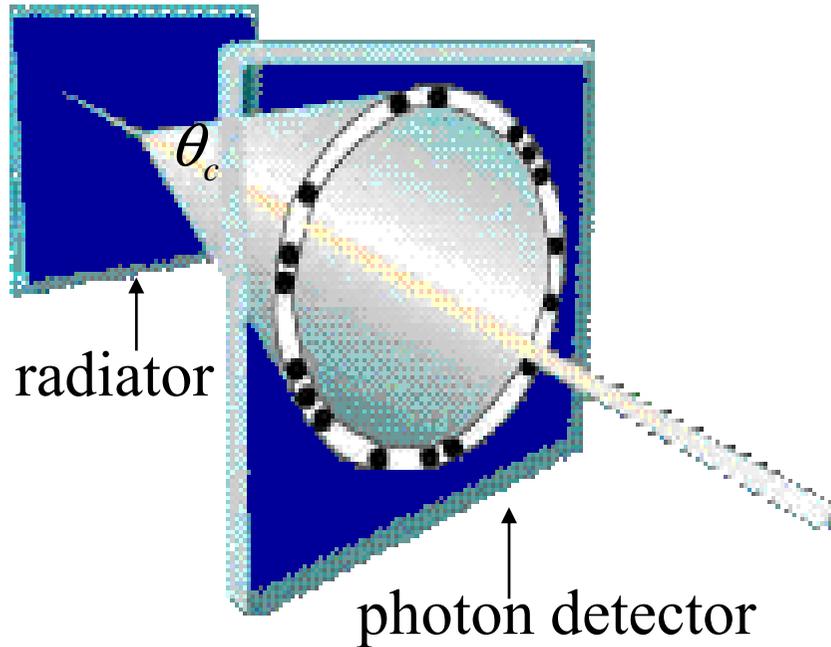
e fully contained



50 000 ton water ~11k PMTs, 50cm \varnothing

Costs of Cherenkov devices scale with surface rather than with volume
-> neutrino physics experiments and air shower detectors exploit huge (and inexpensive) water, air or ice targets that are also Cherenkov radiators

Photon detector properties



- Cherenkov light emitted in the radiator is detected by a position-sensitive photon detector.
- The particle mass is deduced by combining the Cherenkov angle measurement with momentum.

$$\theta_c = \arccos \frac{1}{n(\lambda) \beta}$$

$$m = \frac{p}{\beta\gamma} = p \sqrt{n^2 \cos^2 \theta_c - 1}$$

main photon detector property:
 detecting single photons (UV+visible)
 with high efficiency and low noise

$\left. \begin{array}{l} \text{minimize } \sigma_\theta \\ \text{maximize } N_{p.e.} \end{array} \right\} \Rightarrow \sigma_\theta$
 $\xrightarrow{\text{high granularity}}$
 $\xrightarrow{\text{high packing density}} \Rightarrow N_{p.e.}$
 $\xrightarrow{\text{high geometry (fill factor)}}$

High Photon Detection Efficiency

$$\text{PDE} = \epsilon_{\text{geometry}} \cdot \text{QE} \cdot \epsilon_{\text{ph.electron}}$$

QE characterizes photocathodes

PDE characterizes photon detector

"Well mastered" Photon Detectors - 1

Cherenkov light imaging has been made possible by the development of two types of photon detectors:

1°) GASEOUS AMPLIFICATION

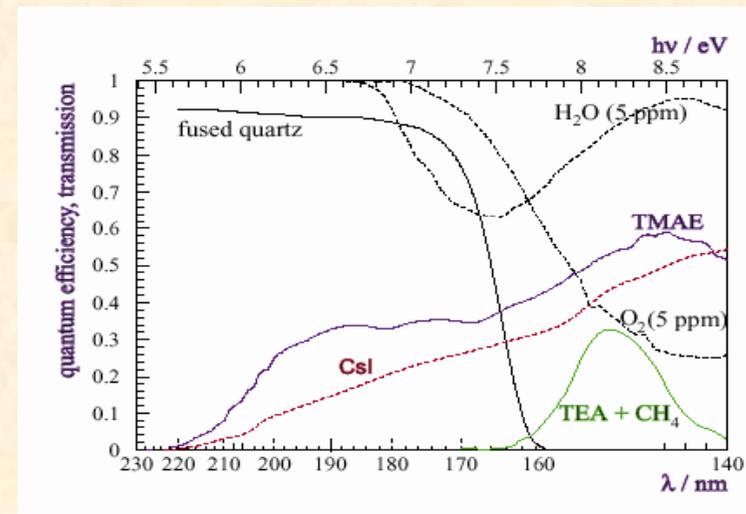
(Drift Chambers, MWPCs, MSACs)

PRO

- cost effective solution for large area coverage
- operation in magnetic fields
- $PDE \cong QE$
- custom design

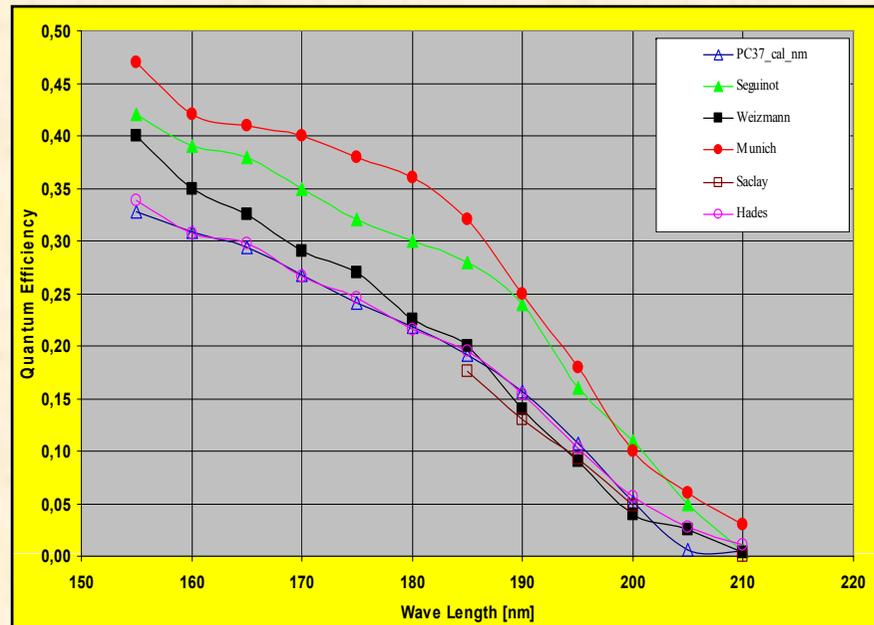
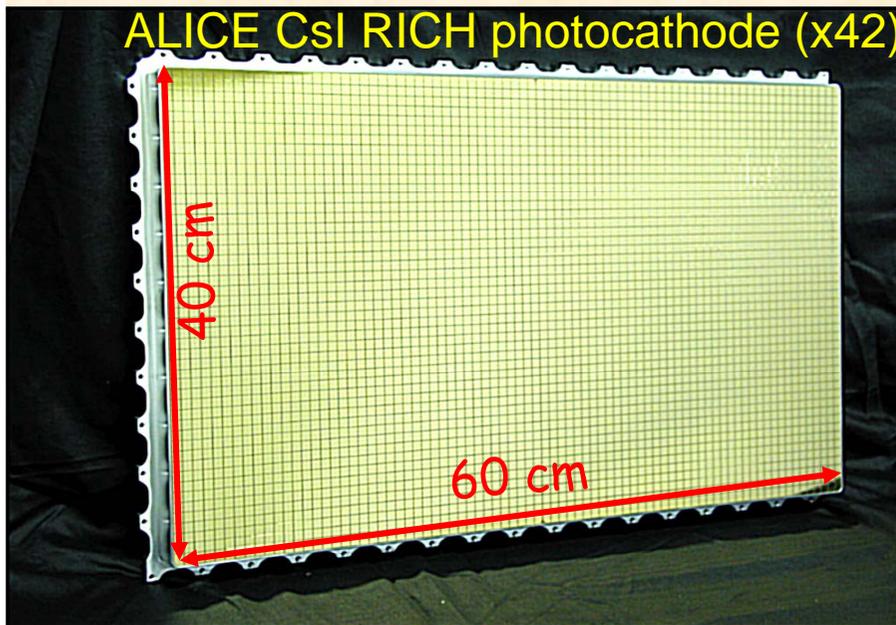
CONTRA

- detector bandwidth in the UV region, difficult to work in (cleanliness, outgassing pollution, etc)
- optical materials are difficult to make and are expensive (less transparent windows and less reflective mirrors)
- **rate limitation and ageing**



"State of the Art" in gaseous amplification

ALICE CsI RICH photocathode (x42)



CsI-RICHs:
ALICE, COMPASS, HADES,
Hall-A at TJLAB



**ALICE RICH: 12 m²,
160 kch, 0.5 Tesla**

"Well mastered" Photon Detectors - 2

2°) VACUUM-BASED PHOTON DETECTORS

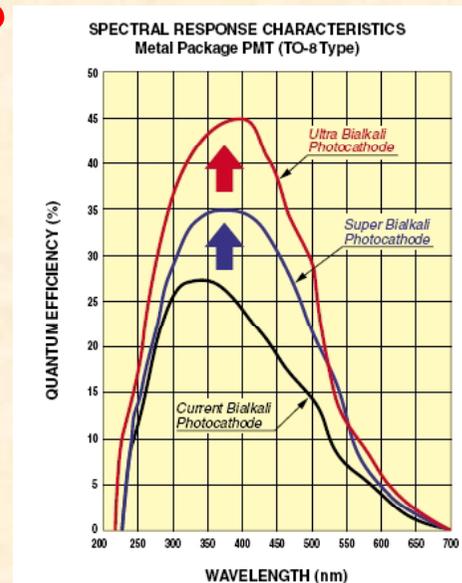
(PMT arrays, MaPMTs, HPDs)

PRO

- greatly increasing QE (> 40% peak value) in the visible:
 - larger choice of materials for the radiator (ex. silica aerogel)
 - improved performance because of the larger detector bandwidth (more photons) and modest chromatic dispersion $(dn/dE)_{vis} < (dn/dE)_{UV}$
- good timing resolution (≤ 1 ns)

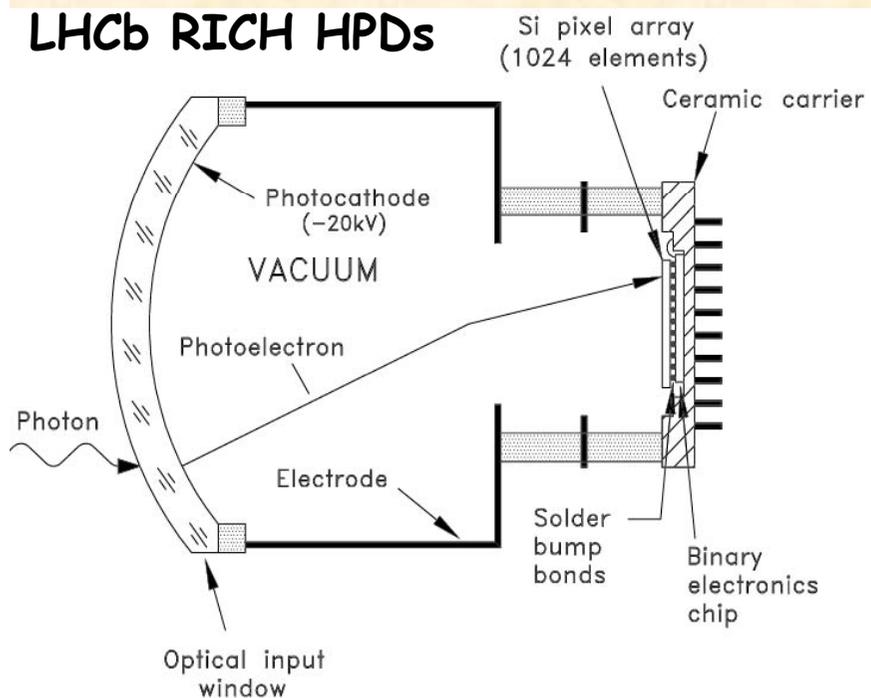
CONTRA

- Sensitive to magnetic field
- low fill factor -> low PDE
 - use of a lens arrangement to increase the active area
- **Difficult to manufacture in HEP labs**



"State of the Art" in vacuum-based photon detectors

LHCb RICH HPDs

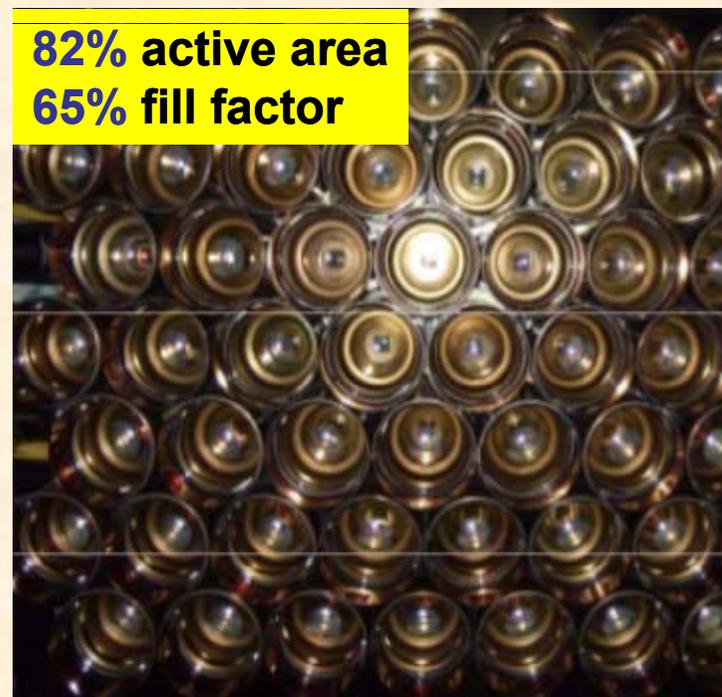


Developed in collaboration with industry
(Photonis-DEP)

484 HPDs
active area = 3.3 m²

83 mm diameter
72 mm photocathode diameter

82% active area
65% fill factor



- quartz window with S20 photocathode
- cross-focusing optics
- space resolution 2.5 × 2.5 mm²
- low noise (dark count rate < 5 kHz/cm² i.e. 1% probability of 1 spurious hit /event)
- 0.5 Mchannels read-out at 40 MHz

Two posters at this conference:
L. Carson & A. Pickford

New challenging requirements

Future experiments at Super-B factories ($\times 100$ KEK B-Factory luminosity)
 PANDA and CBM experiments at FAIR (interaction rates up to 20 MHz)

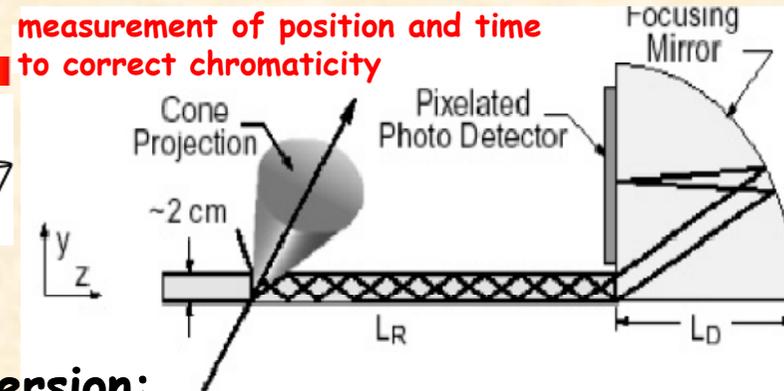
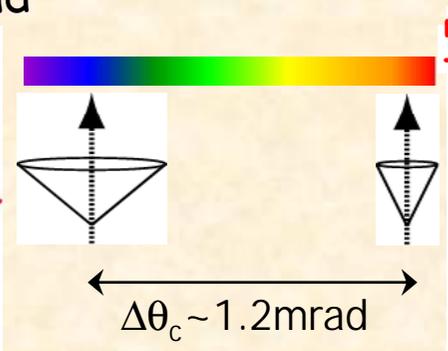
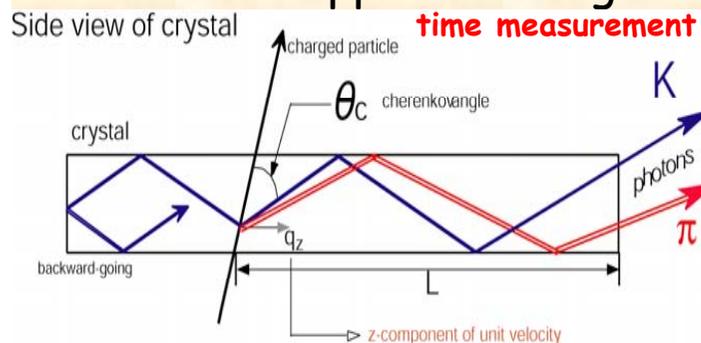
- Harsh radiation environment (up to 10 Mrad)
- High photon rates (up to 1 MHz/channel)
- Immunity to magnetic field of 1-2 Tesla

New direction in Cherenkov light imaging at low momentum:

- Time Of Propagation (TOP) detector (T. Ohshima, 2000)
- Focusing DIRC (B. N. Ratcliff, 2003)

Photon detector features:

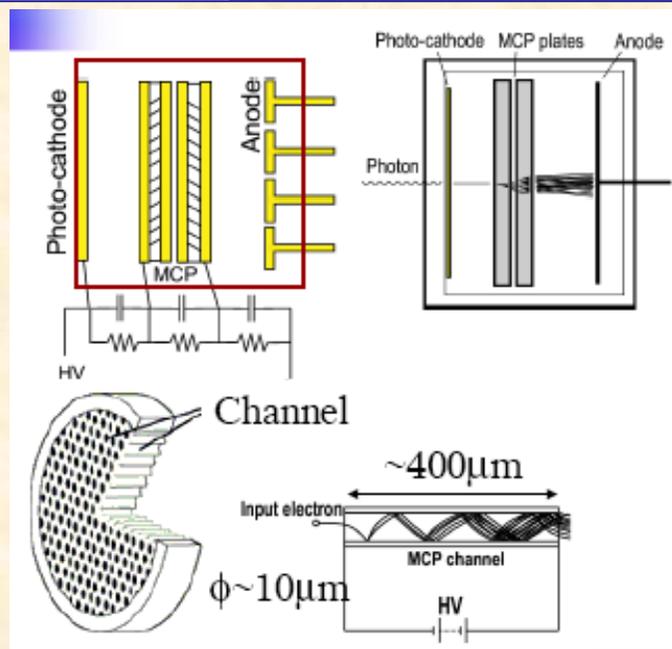
- small pixels (< 5 mm)
- fast timing ($\sigma_t \sim 50$ ps)
 - measurement of photon flight time
 - to suppress background



$t_K - t_\pi(3 \text{ GeV}/c) = 75 \text{ ps}$
 for 1 m flight path

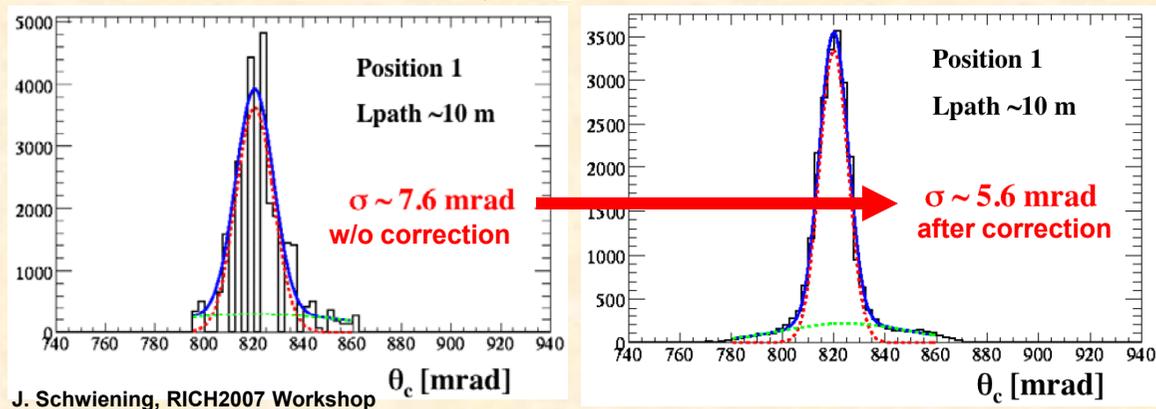
Chromatic time dispersion:
 $\sim 100 \text{ ps}$

MCP-PMTs



Correction of chromatic dispersion proved thanks to the fast timing properties of MCP-PMTs

Burle/Photonis MCP-PMT 85012-501
(64 pixels, 10 μm pore diameter)

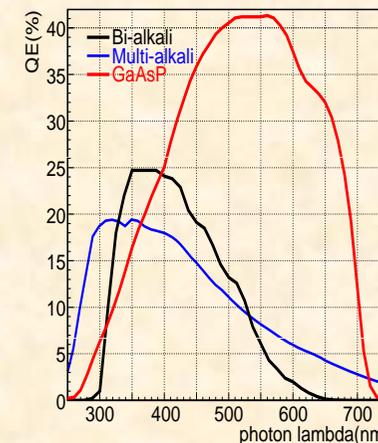
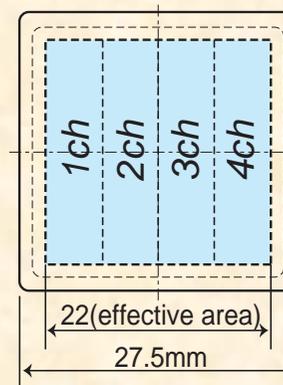


J. Schwiening, RICH2007 Workshop

CUTTING EDGE R&D IN COLLABORATION WITH INDUSTRY FOR TOP COUNTER AT BELLE/KEK-B

Square-shape MCP-PMT with GaAsP photo-cathode (advantages: higher QE than bi-alkali and, at longer wavelengths the group velocity spread is smaller than in bi-alkali bandwidth)

- 2 MCP layers, 10 μm holes
- 4ch anodes
- time resolution= 35 ps for single p.e. (gain= 0.6×10^6)



Response of MCP-PMTs to Magnetic Fields

**PANDA-DIRC
STUDIES**

Characteristics of the investigated MCP-PMTs

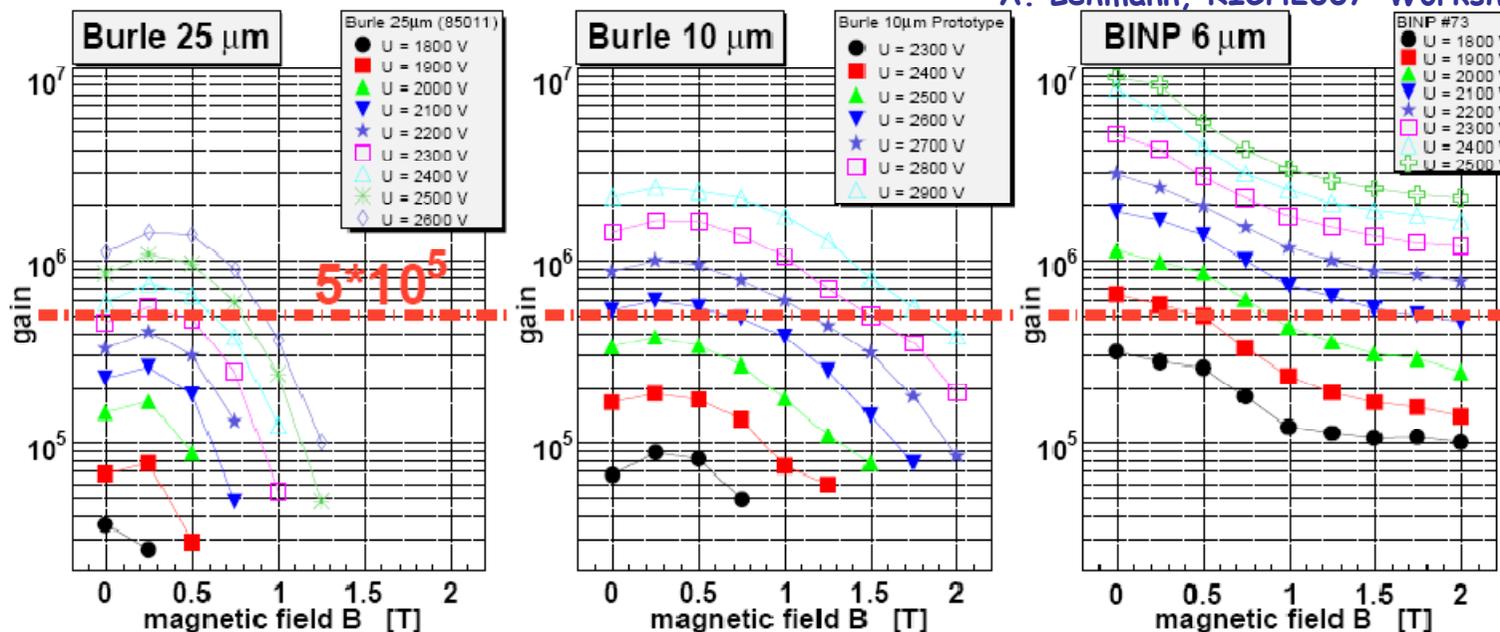
	Burle25	Burle10	BINP
pore diameter (μm)	25	10	6
active area (mm^2)	51x51	51x51	$9^2 \pi$
number of pixels	8x8	8x8	1
pixel size (mm^2)	5.9x5.9	5.9x5.9	$9^2 \pi$
cathode protection	none	none	5 nm Al_2O_3
active area ratio	0.44	0.47	0.34

collection efficiency $\sim 60\%$

Low PDE

Protect photocathode against ion feedback

A. Lehmann, RICH2007-Workshop



Burle 10 μm pores and BINP can be operated up to 2 Tesla, BINP also up to 45° tilt

Solid State Photon Detectors: G-APD

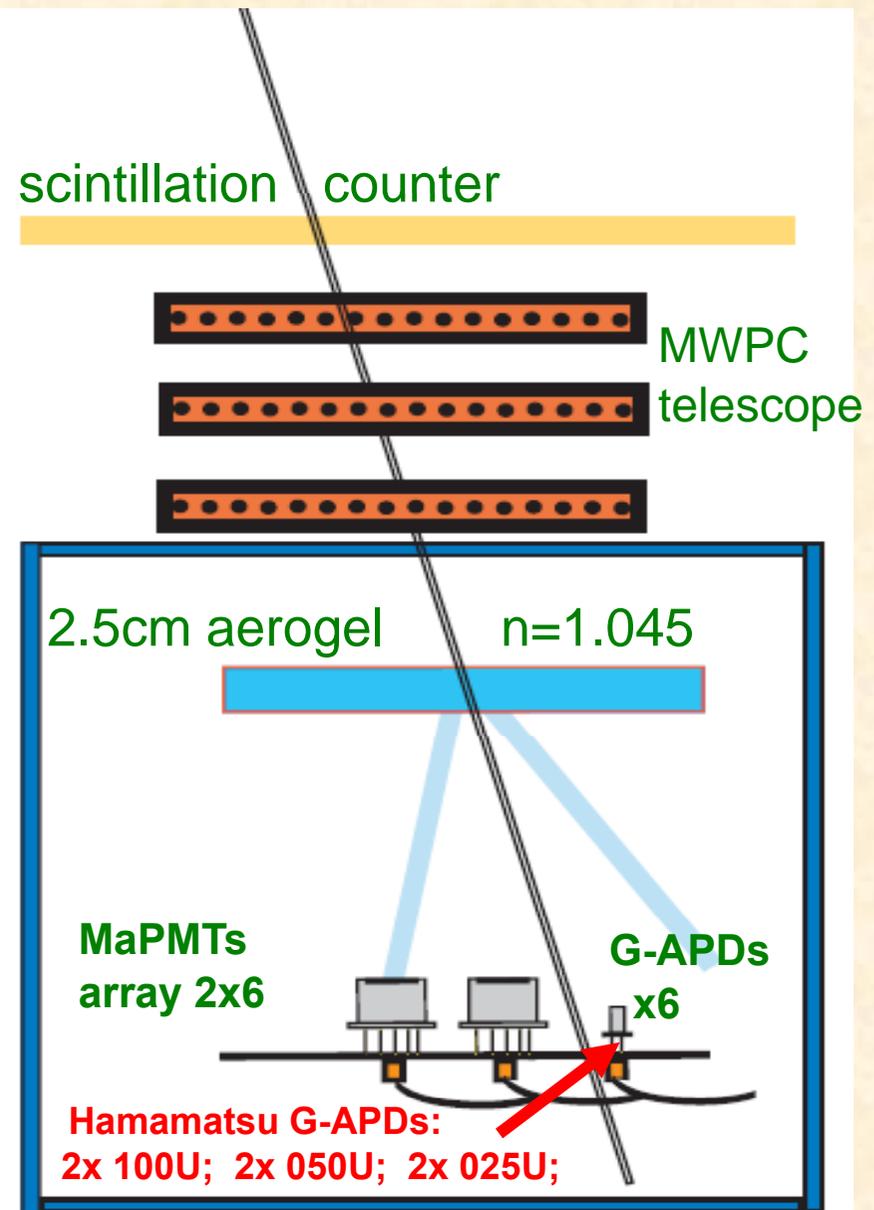
G-APD (also called SiPMT, PPD, MPPC, etc) has many interesting properties for Cherenkov Imaging applications
(talk by M. Danilov)

- Insensitivity to magnetic fields
- Excellent photon counting capability
- Very good timing (≤ 100 ps)

First Cherenkov photons observed by Belle teams (P. Krizan, Instr08 Workshop)

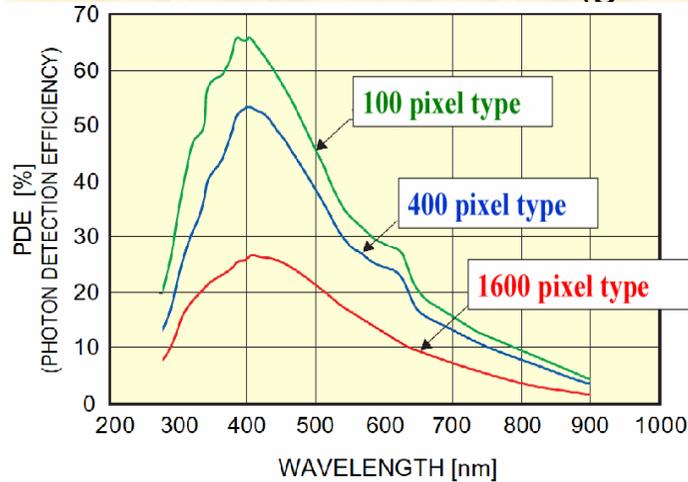
G-APDs provided 4 x more photons than MaPMTs per photon detector area – in agreement with expectations

First detection of Air Shower Cherenkov Light by G-APDs (MAGIC Collaboration)
p-on-n MPPC 3×3 mm², 100×100 μ m² cells
Figure of merit improved by a factor 3 wrt bialkali PMTs (E. Lorenz, RICH2007)



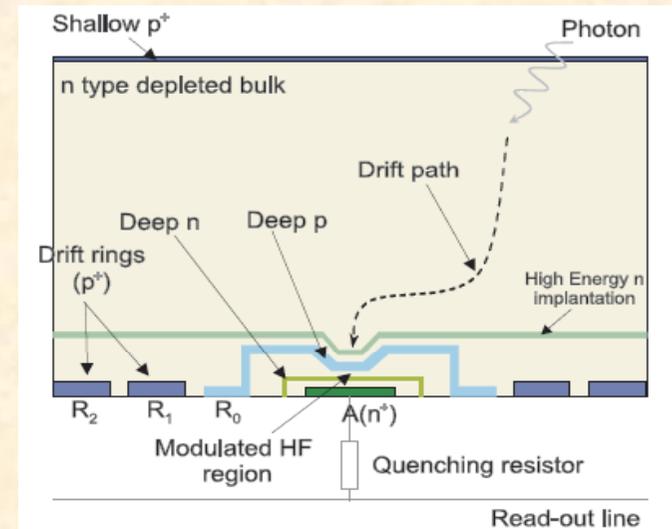
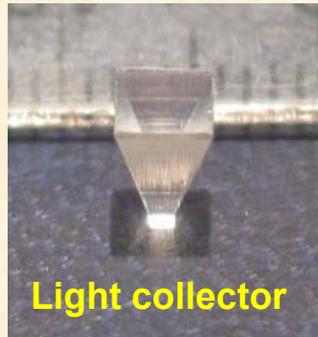
Drawbacks and limitations

- **Low fill factor** due to the structures present around each micro-cell (guard ring, trench)



=400nm, including the cross-talk and after pulse

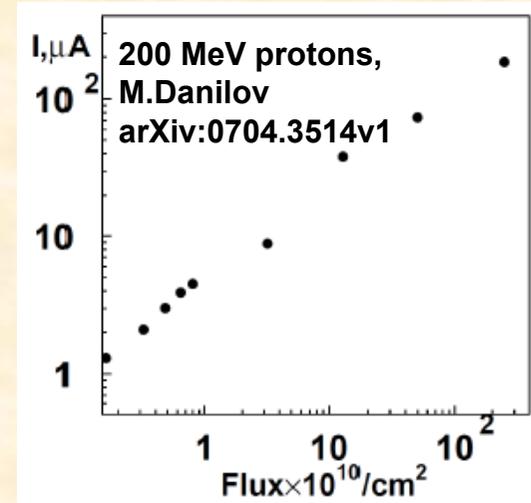
Fill Factor increases as cell size increases:
 $40 \times 40 \mu\text{m}^2 \Rightarrow \sim 40\%$
 $50 \times 50 \mu\text{m}^2 \Rightarrow \sim 50\%$
 $100 \times 100 \mu\text{m}^2 \Rightarrow \sim 76\%$



MPI approach to increase PDE (low rate applications)

K. Yamamoto, PD07, Kobe

- **Noise**
 - **afterpulse** (trapping and delayed release of carriers) + **crosstalk due to emission of photons triggering Geiger discharges during an avalanche formation ~20%**
 - **Dark Count Rate** (thermal generation in the depleted region): **100 kHz to several MHz/mm² at 25°C**
- **Operational issues (Gain vs temperature)**
- **Radiation Damage -> increase of dark current**



Recent Advances in Gaseous Photon Detectors

ISSUES OPERATING GASEOUS PD AT HIGH RADIATION RATES

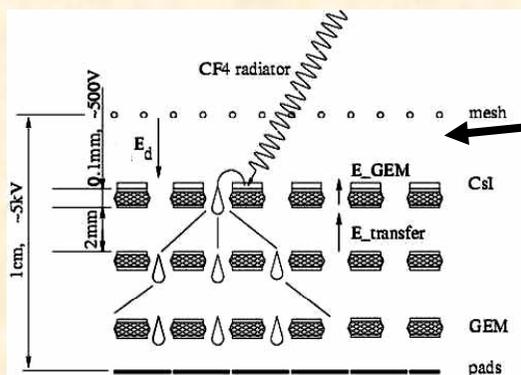
MWPC & PPAC (open geometry)

The formation of photon and ion-mediated secondary-avalanches limit the performance (gain, signal timing and spatial resolution) and operation stability

GEM (Closed geometry)

Photon-feedback effects are suppressed but photocathode is damaged by ions flowing back from the amplification region. Cascaded GEMs with CsI reflective photocathodes feature a **IBF** (fraction of avalanche-generated ions **back-flowing** to the photocathode) $>10\%$

Hadron Blind Detector
(1 m²) of the PHENIX
experiment at RHIC at
Brookhaven



reversed field to suppress
background from particle's
ionization

AIM:

To develop gaseous PMTs featuring $IBF < 10^{-5}$, equipped with photocathodes sensitive to single photons in the visible range, capable to operate at high magnetic fields and photon fluxes exceeding 1 MHz/mm²

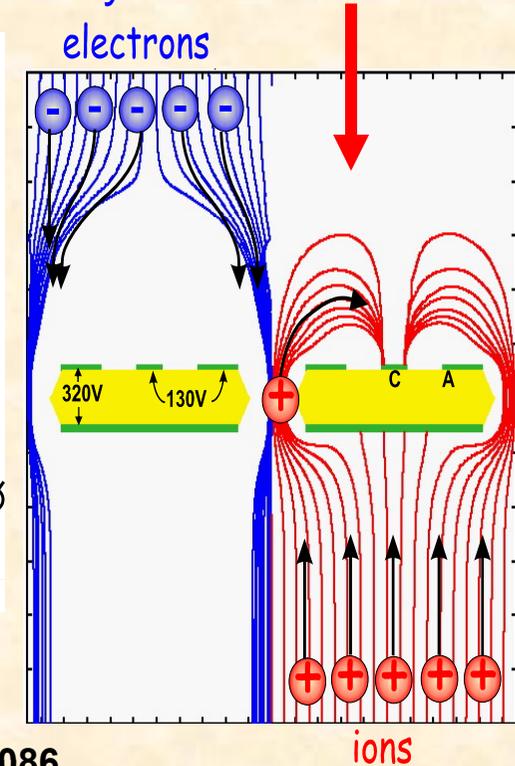
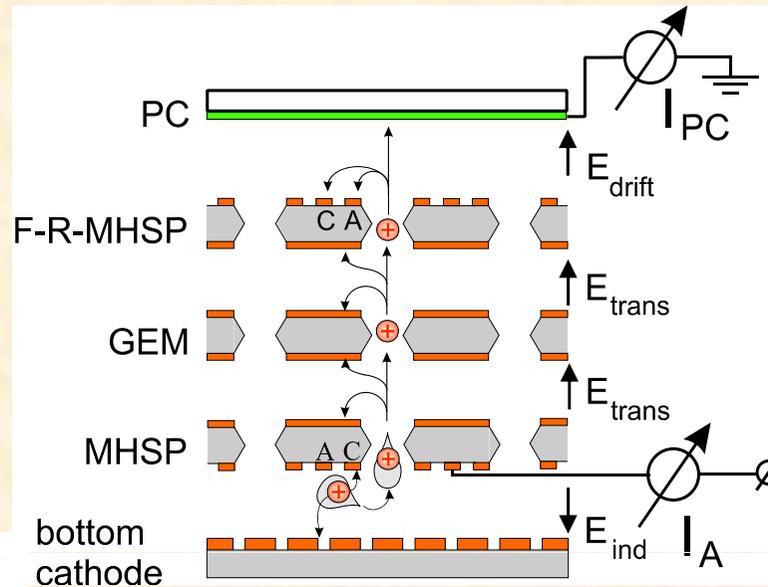
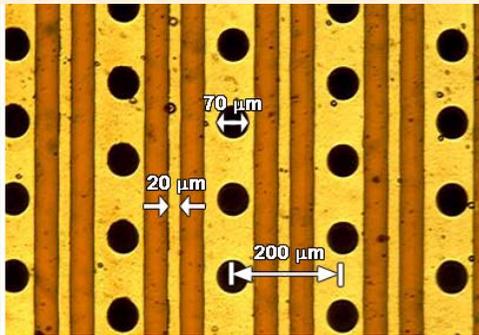
Innovative ion blocking geometries

R&D by Weizmann & Coimbra

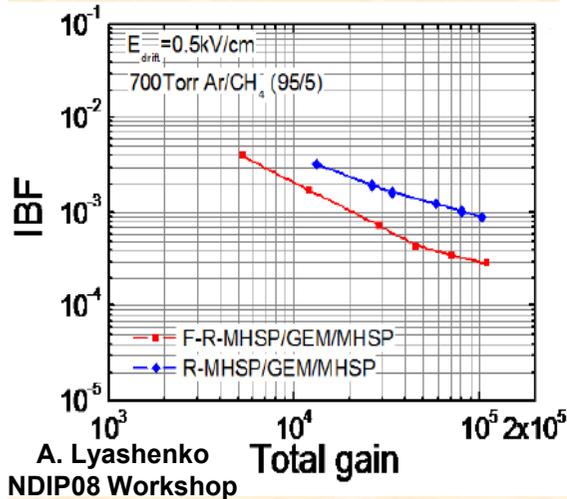
Micro-hole + Flipped reverse-bias strip plates (to deviate avalanche ions)

ions are trapped by negatively biased cathode strips

MHSP



recent results from other geometries in
R. Chechik and A. Breskin arXiv:0807.2086



- short multiplication times -> fast signals [width 10 ns, time resolution below 2 ns]
- high gain [$>10^5$]
- high rate capability ($> 10^6$ particles/mm²)

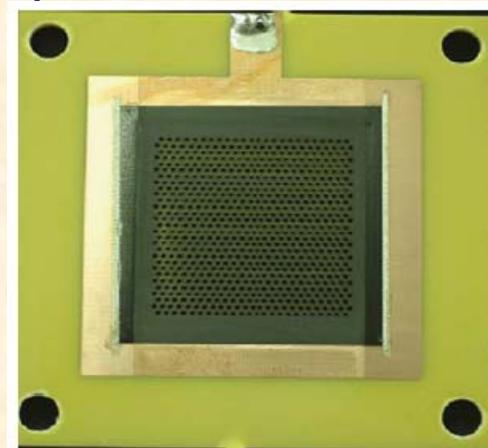
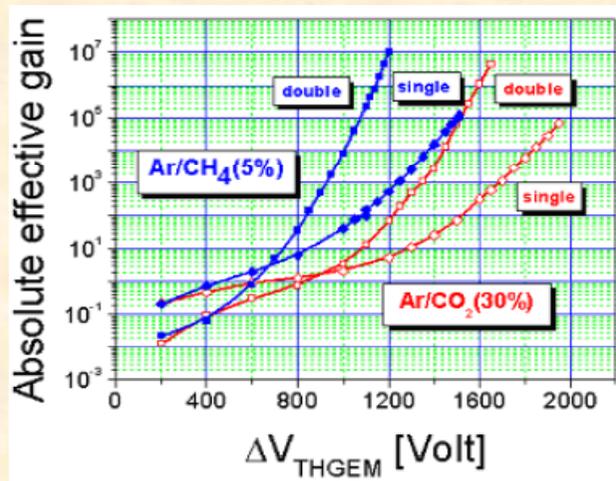
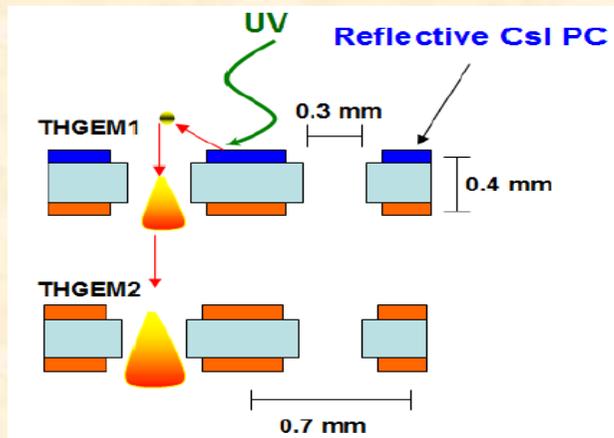
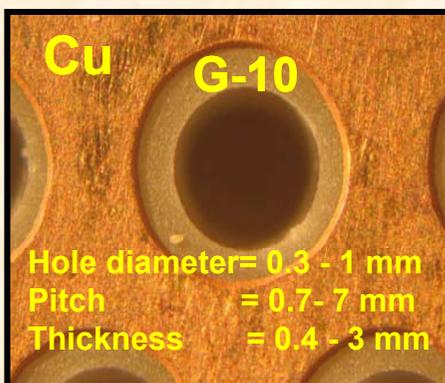
THGEM and S-RETGEM

L. Periale et al., NIM A478,2002,377, Chechik et al. NIM A535 (2004) 303

10^3 - 10^4 gain in single GEM

10^5 gain in single-THGEM

- Manufactured by standard PCB techniques of precise drilling in G-10 (and other materials) and Cu etching of the hole's rims (prevents discharges)
- Very robust, mechanically self-supporting



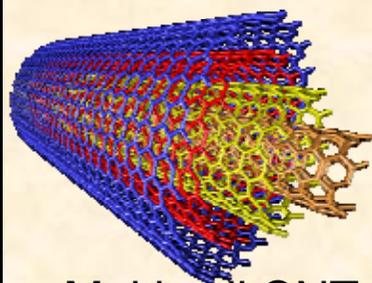
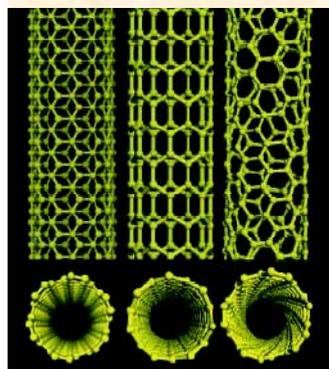
S-RETGEM made of resistive kapton using screen printing technology sizes up to 50x50 cm² and resistivity adapted to experiment's needs (V. Peskov, this conference)

IBF <10%
time resolution of 8 ns RMS

Thick GEM and spark-protected S-RETGEM are robust and cost effective solution for large area RICH applications (COMPASS and ALICE RICH upgrades)

Future prospects for novel photon detectors

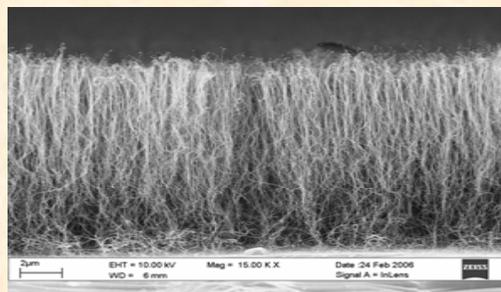
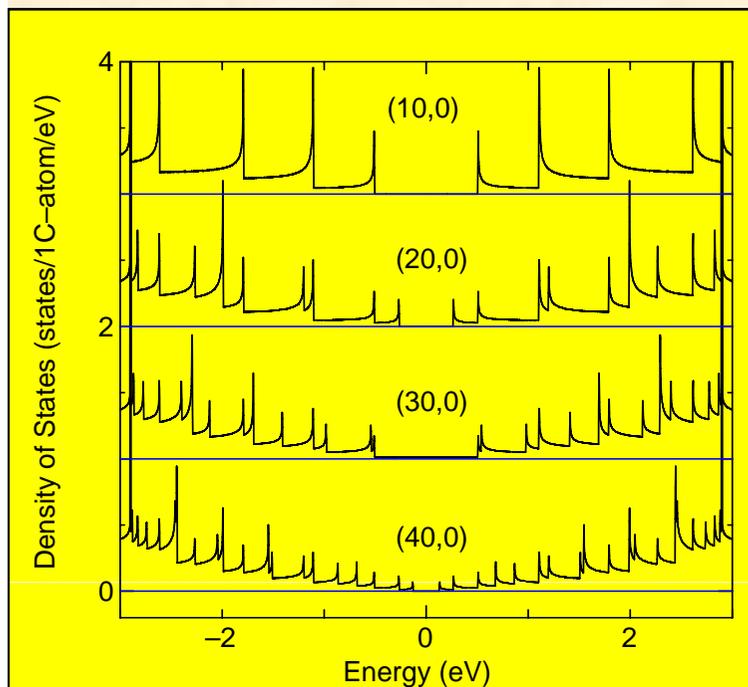
Carbon nanotube (CNT):
graphene sheet rolled up



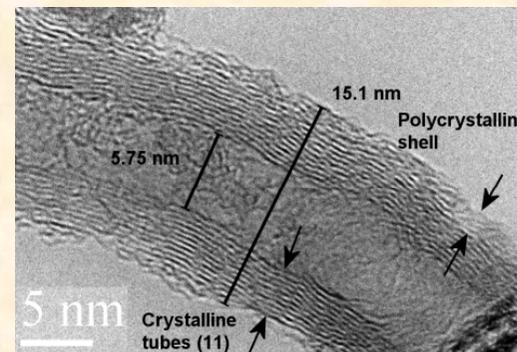
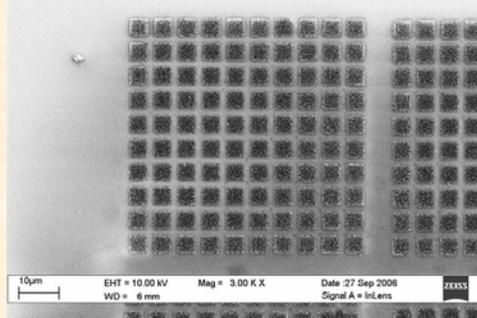
Multiwall CNT

A layer of Multiwall Carbon Nanotubes features a variety of nanotube diameters and chiralities making -> sensitivity to a large band of radiation wavelengths

MWCNTs made by
Chemical Vapour Deposition
(GINT Collaboration, M. Ambrosio NDIP08 Workshop)



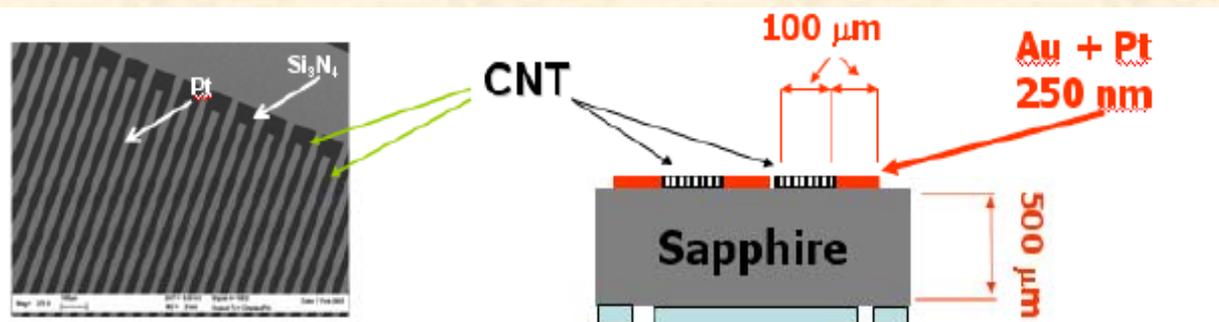
pixelization by nanolithography



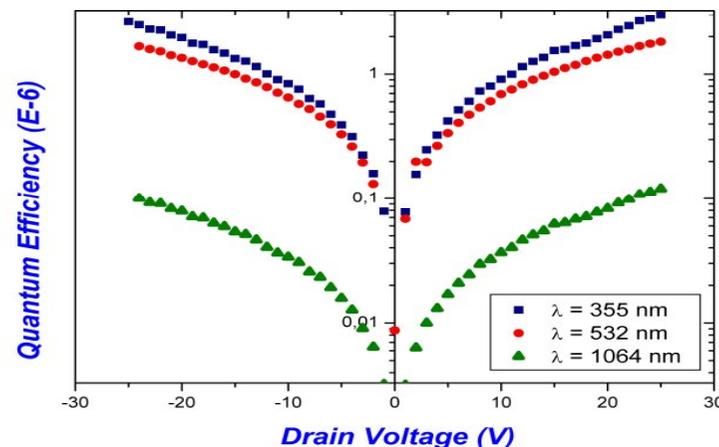
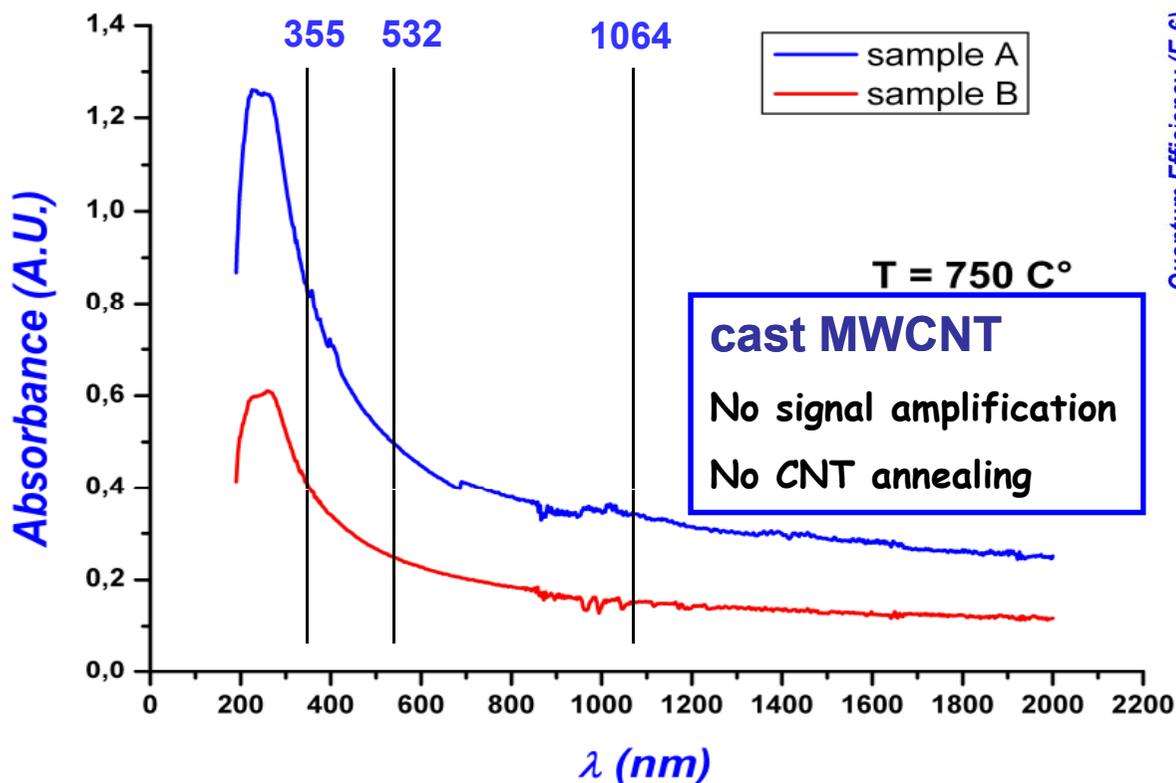
$\approx 10^8 - 10^{10}$ MWCNT/ mm²

very high CNT density:
huge number of nanotubes
sensitive to the radiation

First results on MWCNT photosensitivity



A. Ambrosio et al:
"A new radiation detector made of
multi-walled carbon nanotubes",
NIM A 589 (2008) 398-403



E_{th} for field emission= 1-3 V/μm
(for Mo tips, it is 100 V/μm)
A. Di Bartolomeo et al,
CARBON, Vol. 45, Issue 15, December 2007

Concluding Remarks

- **MCP-PMT**: excellent timing features, compatibility with magnetic fields. Low PDE, concern on rate stability and lifetime.

- **G-APD**: after a 10 year-development still no real improvement on noise performance, radiation tolerance and cost.

For Cherenkov Imaging applications, mandatory to
increase fill factor -> large cells ($100 \mu\text{m}^2$)
produce large arrays of $1 \times 1 \text{ mm}^2$ pads
improve the optical isolation between the cells

- **THGEM and S-RETGEM** : made possible through use of technologies developed for microelectronics (photolithography and chemical etching) allowing easy manufacturing and low cost. Too slow for TOP/focusing DIRC applications.
- **MWCNT**: very challenging and speculative development. If successful, it will be the future direction in Cherenkov Imaging applications and not only!

SPARE SLIDE 1

Growth of Carbon Nanotubes by CVD

