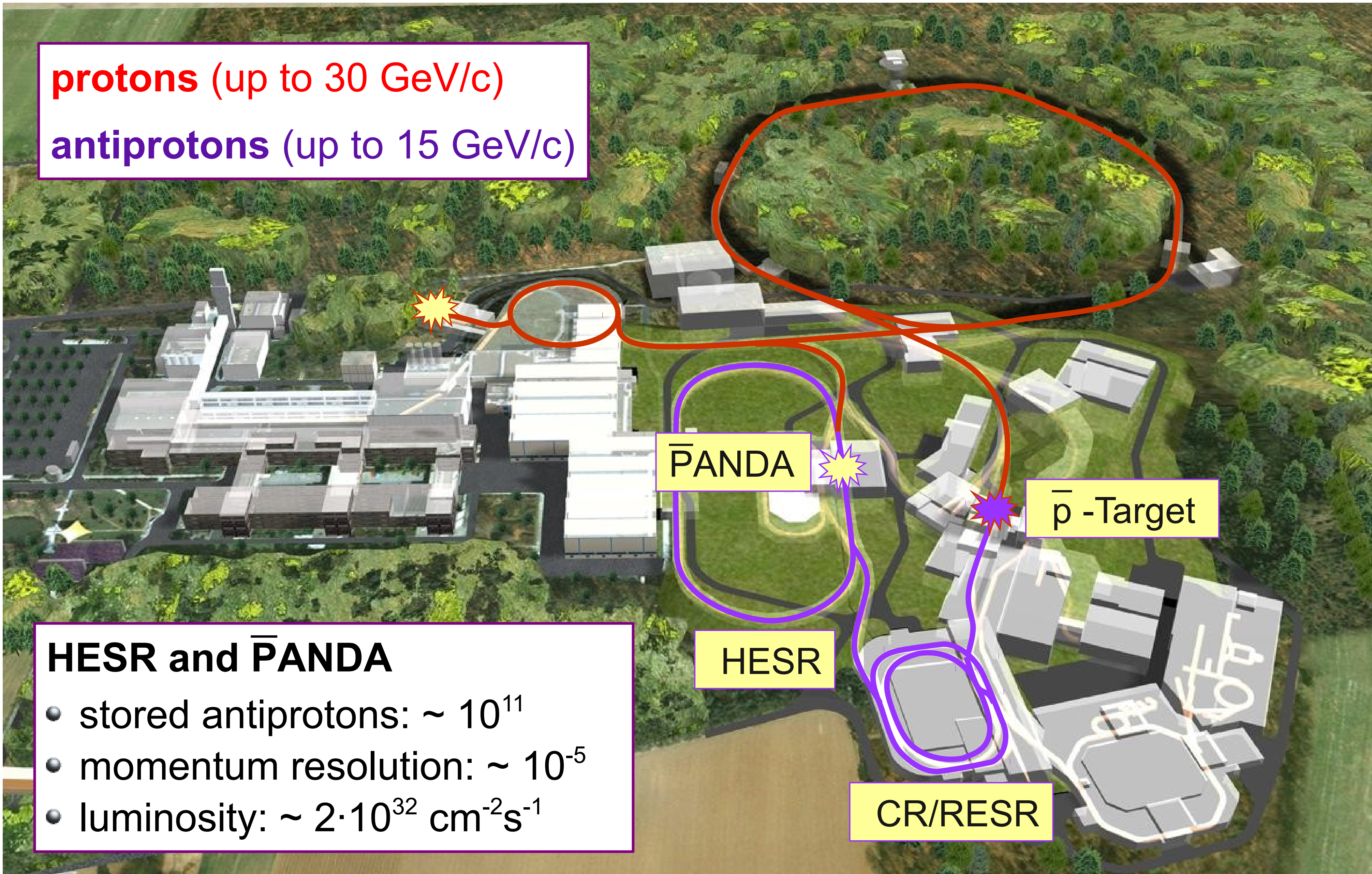
# Significantly Improved Lifetime of MCP-PMTs

**Albert Lehmann** (Universität Erlangen-Nürnberg)
on behalf of the PANDA Cherenkov group

- Motivation
- Pros and cons of MCP-PMTs
- Approaches to increase lifetime
- Results of aging tests
- Summary and outlook

# Antiproton Facility HESR at FAIR



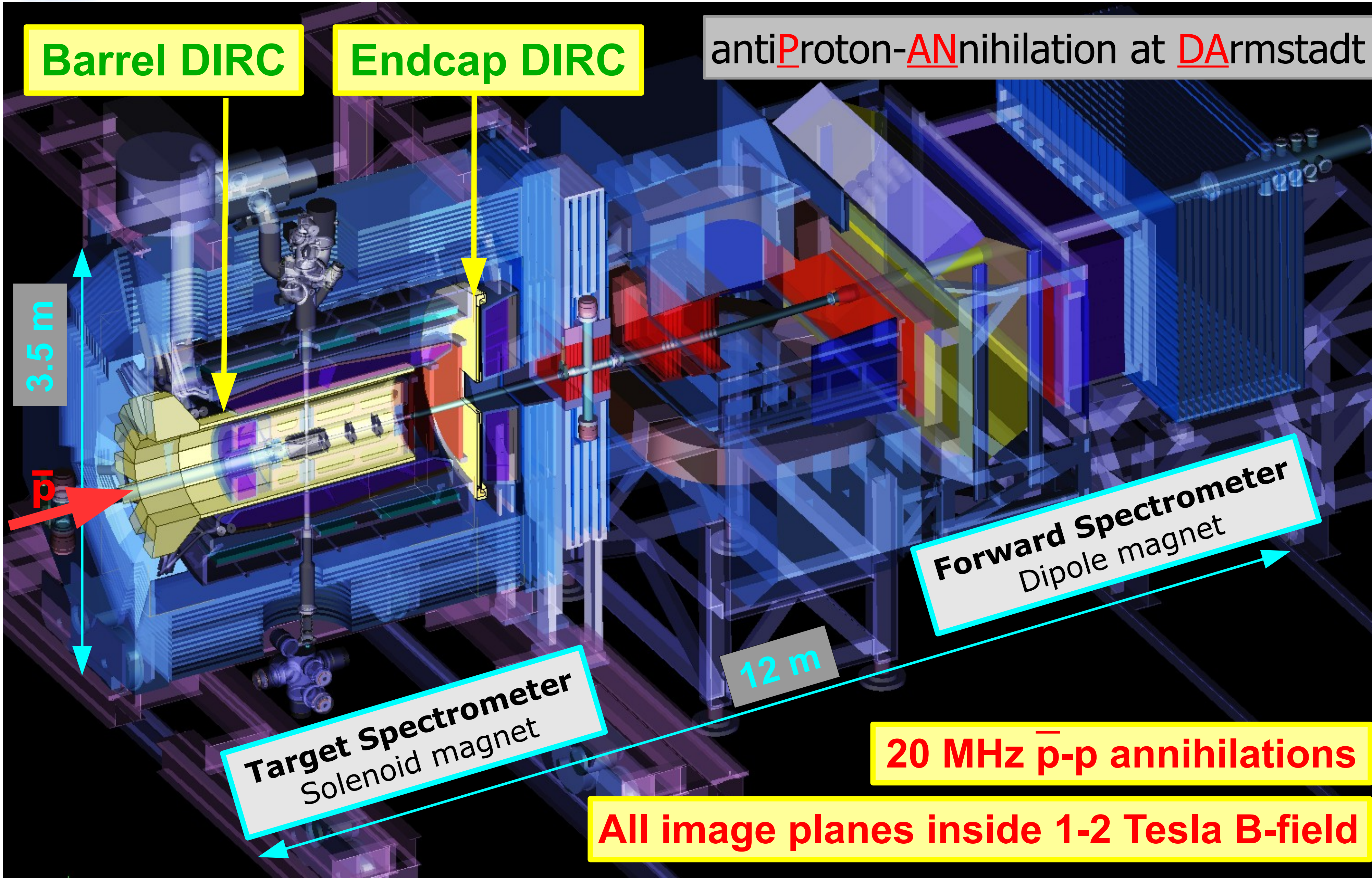

**protons** (up to 30 GeV/c)

**antiprotons** (up to 15 GeV/c)

**HESR and $\overline{\text{P}}$ANDA**

- stored antiprotons: ~ $10^{11}$
- momentum resolution: ~ $10^{-5}$
- luminosity: ~ $2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$

# $\overline{\text{P}}$ANDA Detector at FAIR



# Challenges to Photon Sensors

- Good geometrical resolution over a large surface
  - multi-pixel sensors with ~5x5 $mm^2$ anodes
- Single photon detection inside B-field
  - high gain (> $5*10^5$) in up to 2 Tesla
- Time resolution for ToP and/or dispersion correction
  - very good time resolution of < 100 ps for single photons
- Few photons per track
  - high detection efficiency $\eta$ = QE * CE * GE
    [QE = quantum efficiency; CE = collection efficiency; GE = geometrical efficiency]
  - low dark count rate
- Photon rates in the MHz regime
  - **high rate capability** with rates of several $MHz/cm^2$
  - **long lifetime** with integrated anode charge of 1-5 $C/cm^2/y$)

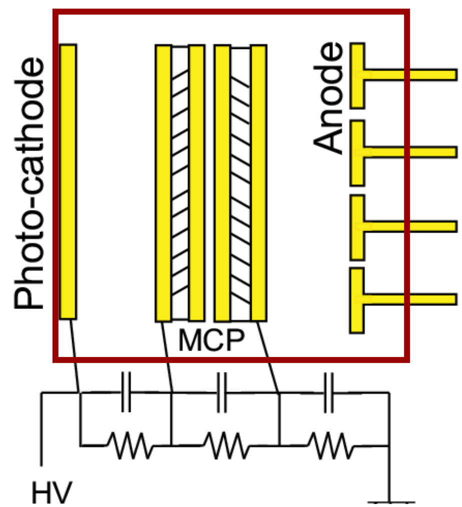
# Sensor Candidates

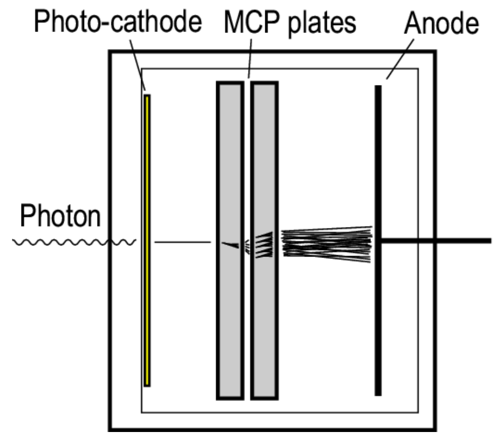
- multi-anode photomultipliers (MaPMTs)
  - (more or less) ruled out by magnetic field
- Geiger-mode avalanche photo diodes (SiPMs)
  - huge noise is very problematic
- **micro-channel plate photomultipliers** (MCP-PMTs)
  - preferred choice for PANDA DIRC
  - but problems with rate capability and **aging** (mainly QE)

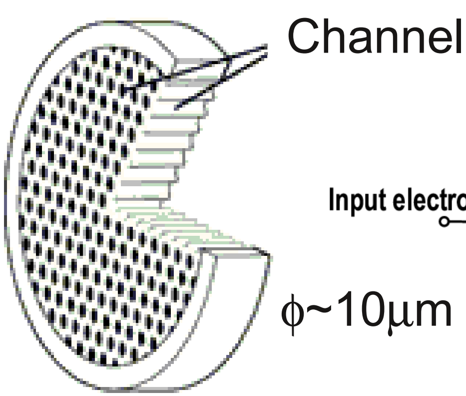
There was no ideal sensor for the PANDA DIRCs !

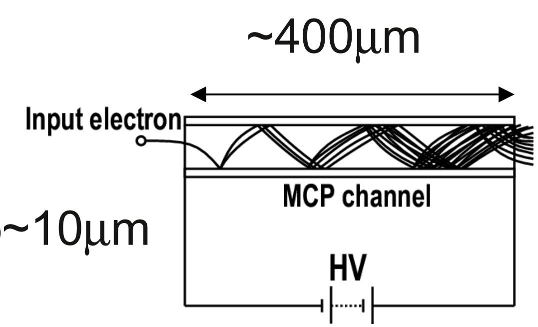
# Microchannel-Plate PMT

electron multiplication in glass capillaries ($\varnothing \approx$ 10-25 $\mu$m)



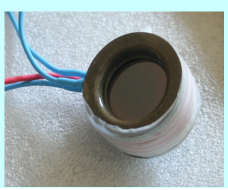
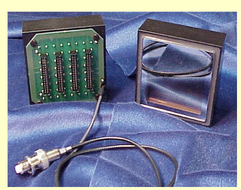




- usable in high magnetic fields
- high gain:
  - $>10^6$ with 2 MCP stages
  - single photon sensitivity
- very fast time response:
  - signal rise time = 0.3 – 1.0 ns
  - TTS < 50 ps
- low dark count rate
- quantum efficiency comparable to that of standard vacuum PMTs
- multi-anode PMTs available
- caveats:
  - lifetime (QE drops)
  - price

# Investigated MCP-PMTs

| | BINP | PHOTONIS | | | | Hamamatsu | |
|---|---|---|---|---|---|---|---|
| | | XP85011 | XP85013 | XP85012 | XP85112 | R10754-00-L4 | R10754X-01-M16 |
| pore size (μm) | 7 | 25 | 25 | 25 | 10 | 10 | 10 |
| number of pixels | 1 | 8x8 | 8x8 | 8x8 | 8x8 | 4x1 | 4x4 |
| active area (mm²) | $9^2\ \pi$ | 51x51 | 53x53 | 53x53 | 53x53 | 22x22 | 22x22 |
| total area (mm²) | $15.5^2\ \pi$ | 71x71 | 59x59 | 59x59 | 59x59 | 27.5x27.5 | 27.5x27.5 |
| geom. efficiency (%) | 36 | 52 | 81 | 81 | 81 | 61 | 61 |
| photo cathode | Multi-alkali | Bi-alkali | | | | Multi-alkali | |
| peak Q.E. | 22% @ 480 nm | -- | -- | 20% @ 380 nm | 22% @ 380 nm | 20% @ 300 nm | 21% @ 375 nm |
| comments | **better vacuum, new cathode** | -- | larger active area ratio | better vacuum, polished surfaces | **better vacuum, ALD surfaces** | -- | **protection layer between MCPs** |

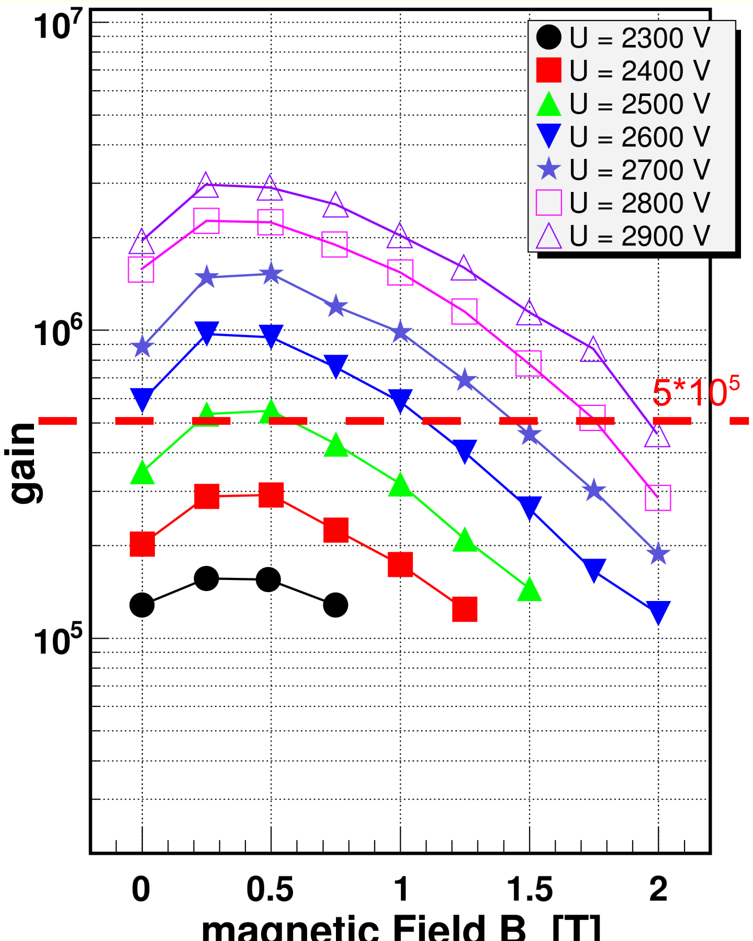



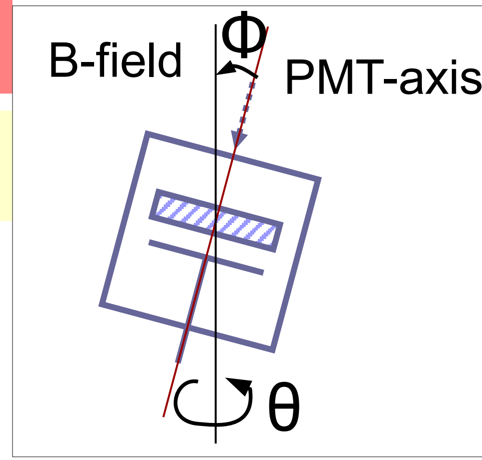
- usually comparison of several identical models of MCP-PMTs
- here: focus on new PHOTONIS XP85112 ; Hamamatsu R10754X-M16 and new BINP

# Gain inside B-Field

**10 μm pores sufficient at 2 T**

**PHOTONIS XP85112 (10 μm)**



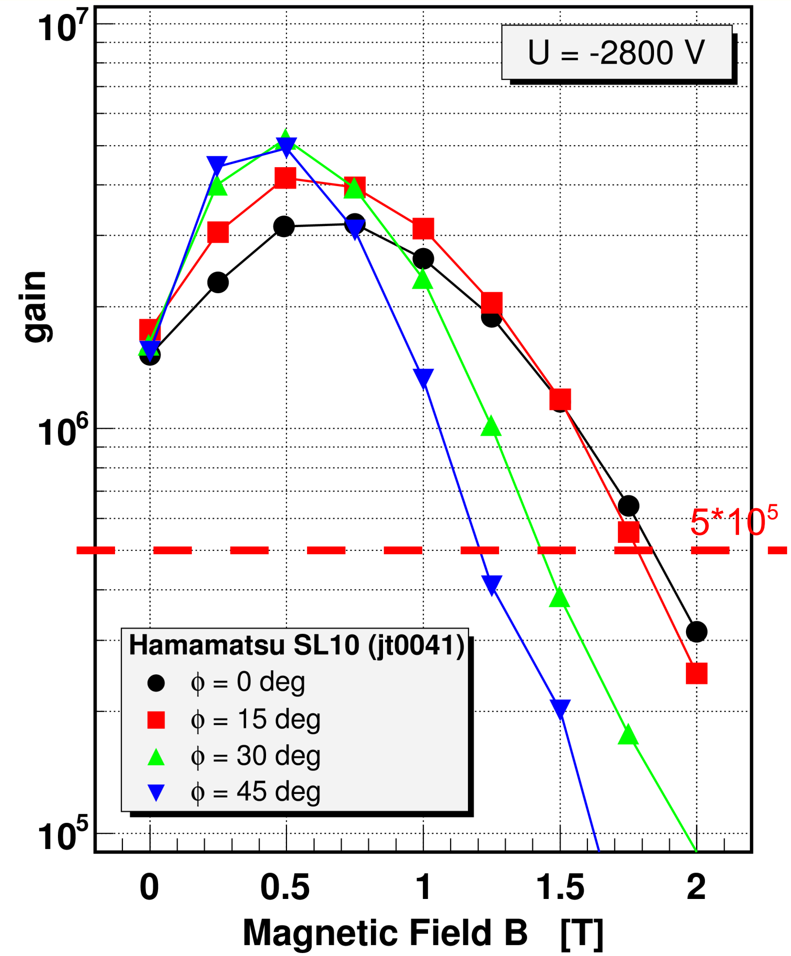

$\Phi$ = tilt angle between B-field direction and PMT-axis

$\theta$ = rotation angle of PMT around B-field direction

**Gain loss at high B-fields and large Φ-angles**

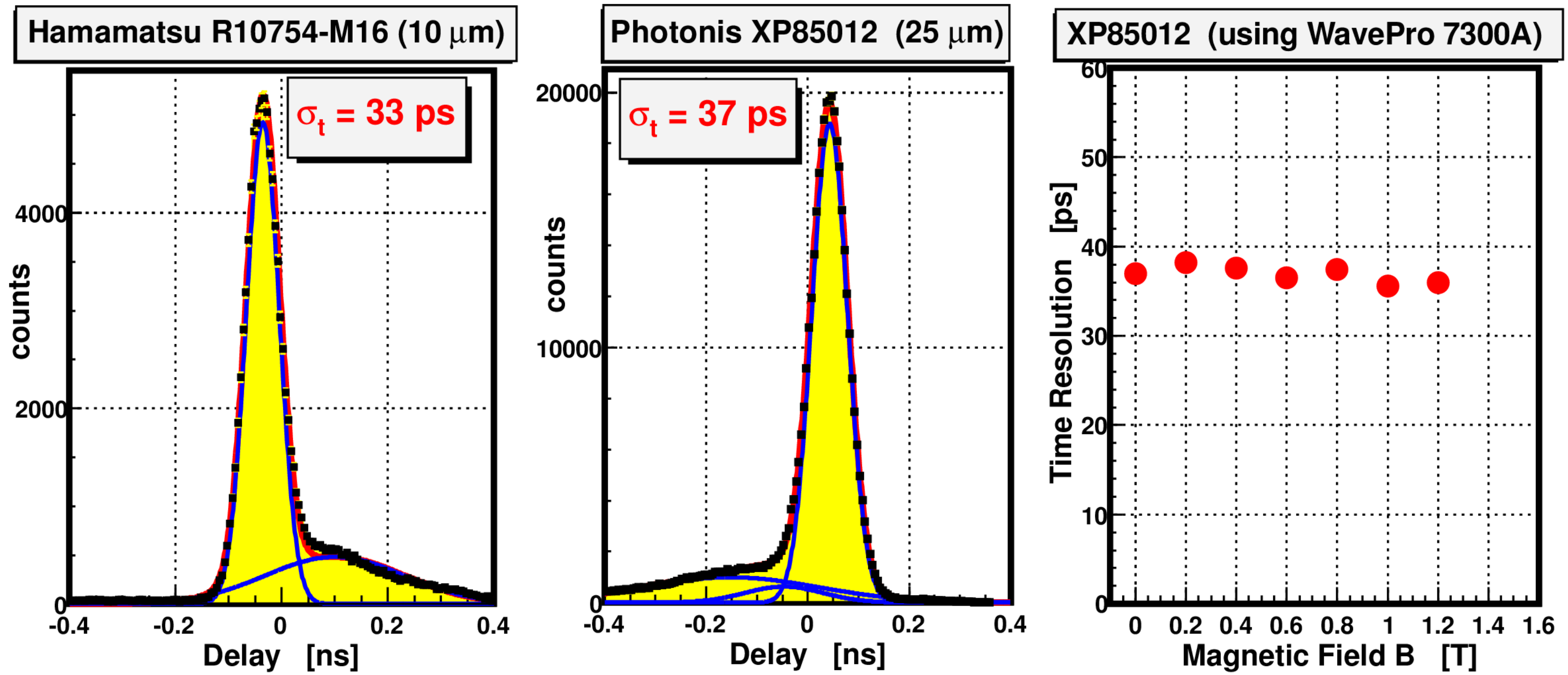
**gain versus tilt angle Φ**

**Hamamatsu R10754 (10 μm)**



# Single Photon Time Resolution

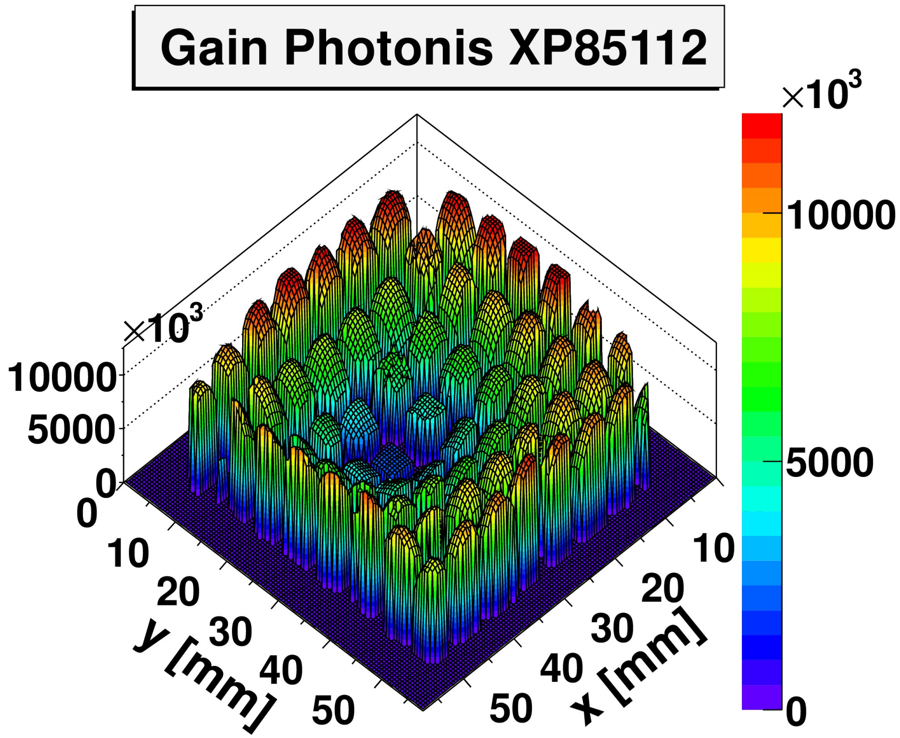
Amplifier Ortec FTA820 (x200; 350 MHz) --- Discriminator Philips Scientific 705

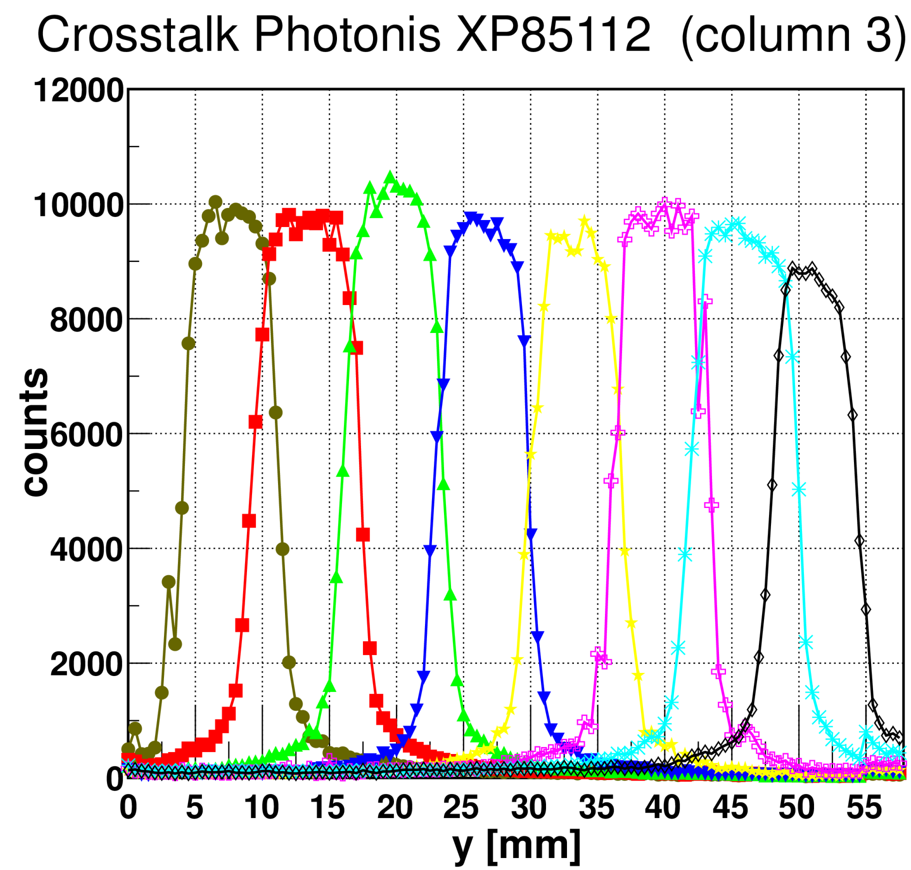



| BINP | PHOTONIS | | | | Hamamatsu | | |
|---|---|---|---|---|---|---|---|
| #73 | XP85011 | XP85012 | XP85013 | XP85112 | R10754 | R10754X-L4 | R10754X-M16 |
| 6 μm | 25 μm | 25 μm | 25 μm | 10 μm | 10 μm | 10 μm | 10 μm |
| **27 ps** | **49 ps** | **37 ps** | **51 ps** | **36 ps** | **32 ps** | **31 ps** | **33 ps** |

- time resolution of all MCP-PMTs 50 ps and better
- no dependence on the B-field

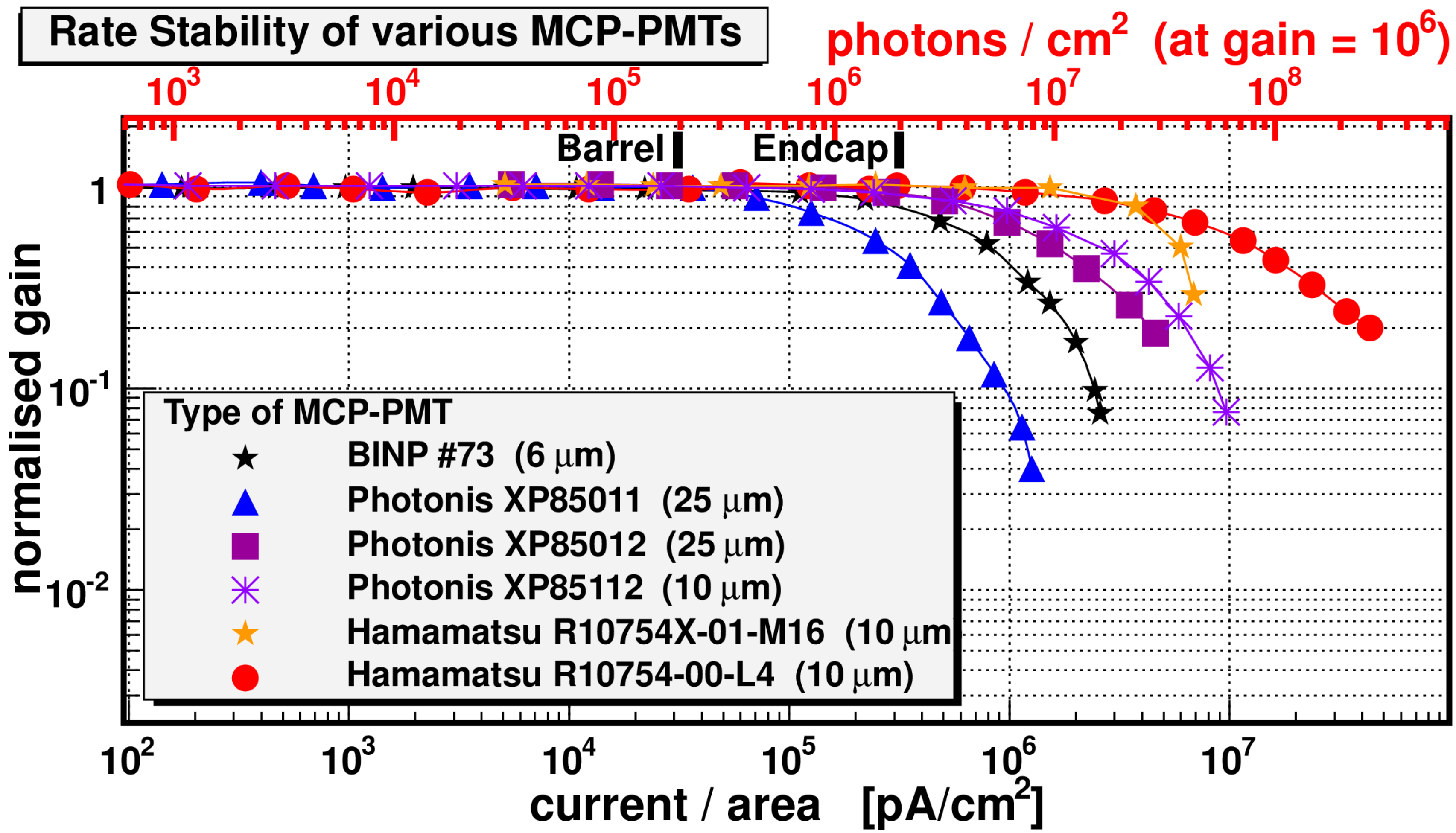
# Gain and Crosstalk of XP85112




- **substantial gain variations between pixels** (in center!)
- 50% crosstalk level extends ~1 mm into adjacent pixel
- but no long crosstalk tails

# Rate Capability

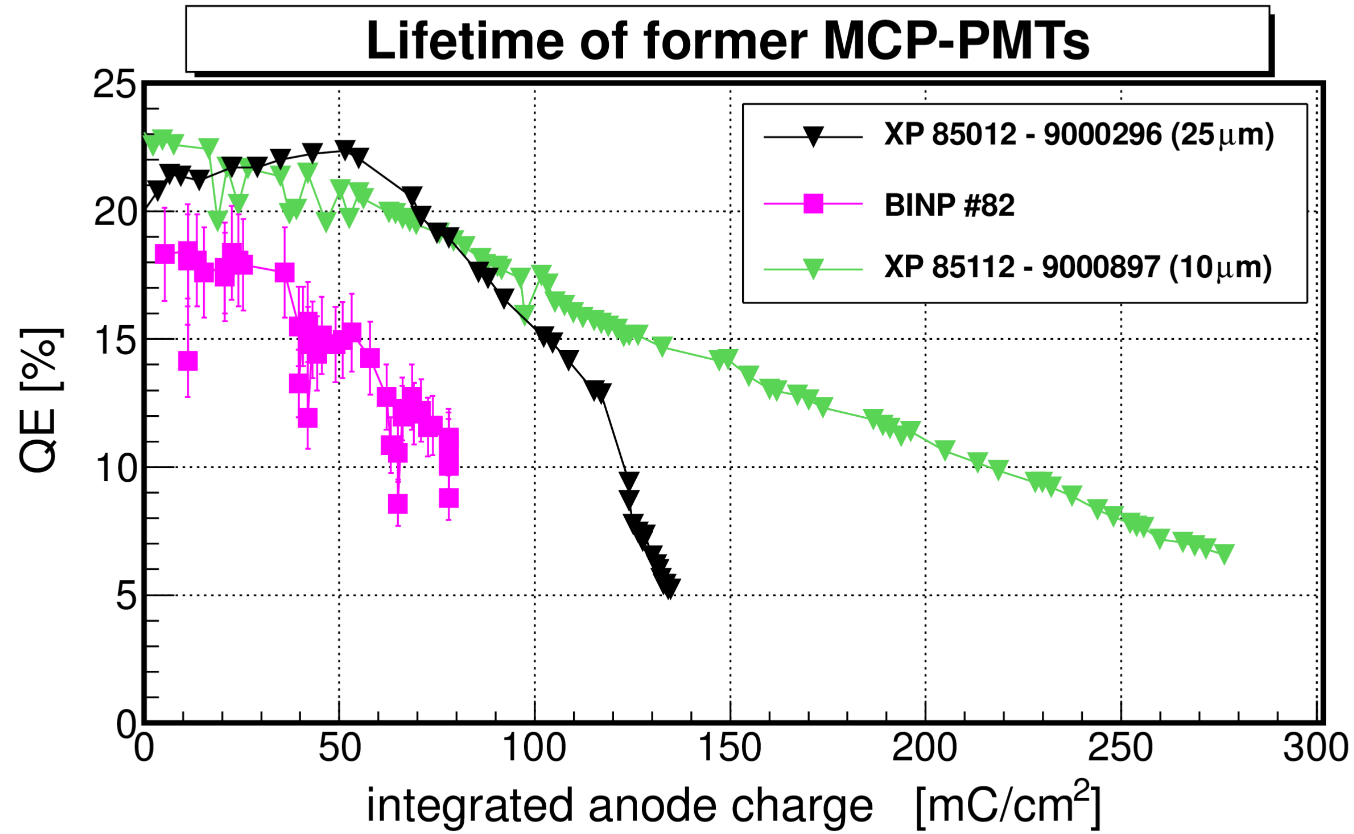



- most MCP-PMTs show stable operation to ~200-300 kHz/cm$^2$ single photons (at gain $10^6$)
- R10754X and XP85112 are suitable for both PANDA DIRCs

# Lifetime of former MCP-PMTs

**Status ~1 year ago**

- BINP with $Al_2O_3$ film at MCP entrance to stop feedback ions
- PHOTONIS with improved vacuum and electron scrubbing of surfaces




- Quantum efficiency reduced by 50% or more at <200 $mC/cm^2$
- By far not sufficient for PANDA

# Rate Estimates for PANDA

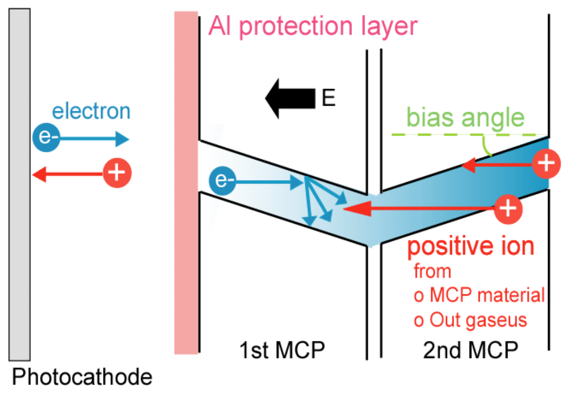
- **rate capability and lifetime are the most critical issues** for the application of MCP-PMTs in any high-rate particle physics experiment
- expected rates and anode charges of the PANDA DIRCs:

| | total rate | anode rate (after Q.E.) | integrated anode charge |
|---|---|---|---|
| | [MHz/cm$^2$] | [MHz/cm$^2$] | [C/cm$^2$/year] at $10^6$ gain |
| | | | |
| **Barrel DIRC** | | | |
| *at end of radiator* | *60* | *5.6* | *28* |
| at readout plane | 1.7 | **0.16** | **0.8** |
| | | | |
| **Endcap DIRC** | | | |
| TOP | 19 | **1.9** | **9.6** |
| focussing | 7.5 | **0.76** | **3.8** |

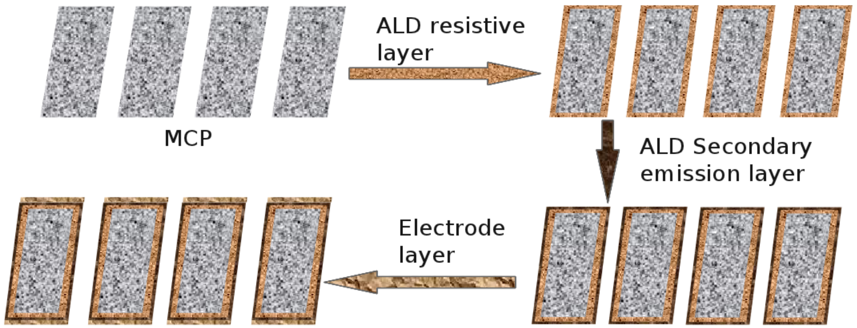
- Endcap DIRC with 5-10x higher photon rate than Barrel DIRC → very challenging

# Approaches to Increase Lifetime

- Protection layer
  - In front of first MCP layer (older BINP and Hamamatsu)
    - disadvantage: reduction of collection efficiency
  - Between MCP layers (new Hamamatsu)
    - anode region is hermetically sealed from photo cathode region [NIM A629 (2011) 111]




- Improved vacuum + treatment of MCP surfaces [NIM A639 (2011) 148]
  - Electron scrubbing (older PHOTONIS and new BINP)
  - Atomic layer deposition (new PHOTONIS



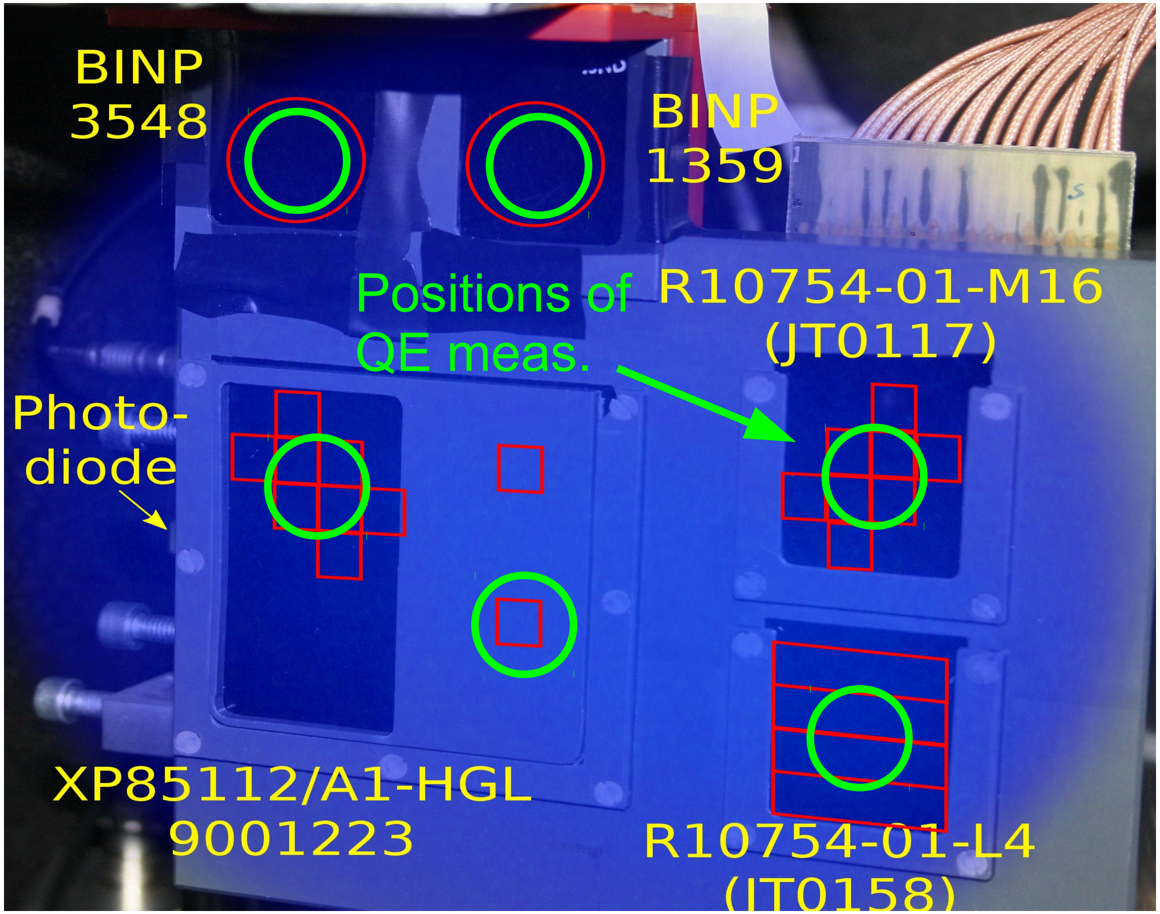

- New photo cathode [JINST 6 C12026 (2011)]
  - $Na_2KSb(Cs)$ + $Cs_3Sb$ (new BINP)
    - disadvantage: significantly higher dark count rate

# Aging of Several MCP-PMTs

- **Problem:** The few aging tests existing were done in very different environments → results are rather difficult to compare
- **Goal:** measure aging behavior for all currently available lifetime-enhanced MCP-PMTs in same environment
- **Simultaneous illumination** with common light source → same rate
- MCP-PMTs included in aging tests:
  - 2x BINP
    - improved vacuum and scrubbed surfaces
    - new photo cathode
  - 2x Hamamatsu R10754X (L4 and M16)
    - protection layer between 1$^{st}$ and 2$^{nd}$ MCP
  - 1x PHOTONIS XP85112
    - ALD surfaces
    - surface half covered during illumination

# Measurement of MCP Lifetime

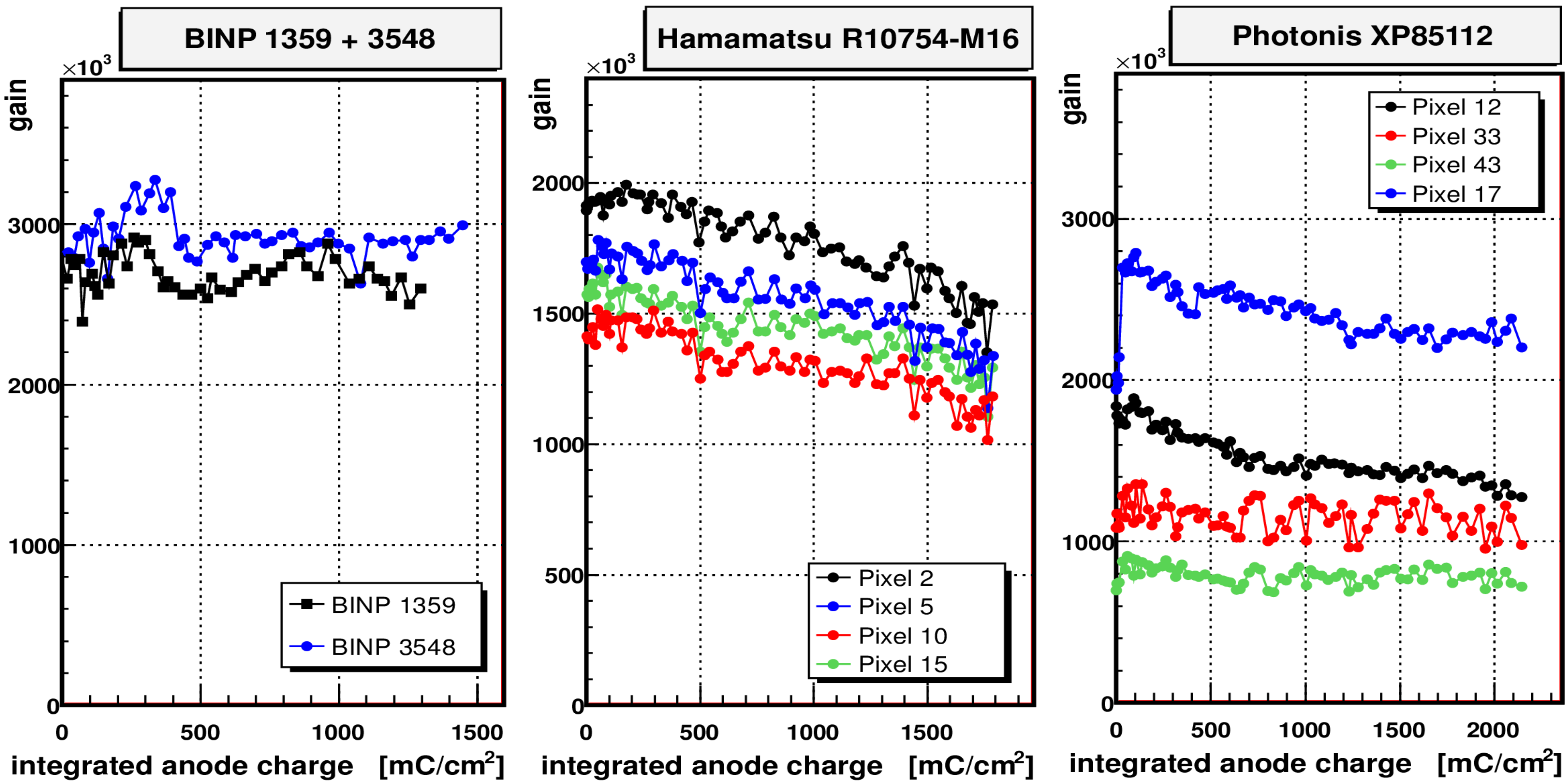
- Continuous illumination
  - 460 nm LED at 0.25 to 1 MHz rate attenuated to single photon level $\rightarrow$ 3 to 14 mC/cm$^2$/day
- Permanent monitoring
  - MCP pulse heights and LED light intensity
- Q.E. measurements
  - 300–800 nm wavelength band with monochromator $\Delta\lambda$ = 1 nm
  - every few days: wavelength scan
  - every few weeks: complete surface scan



# Illumination Overview

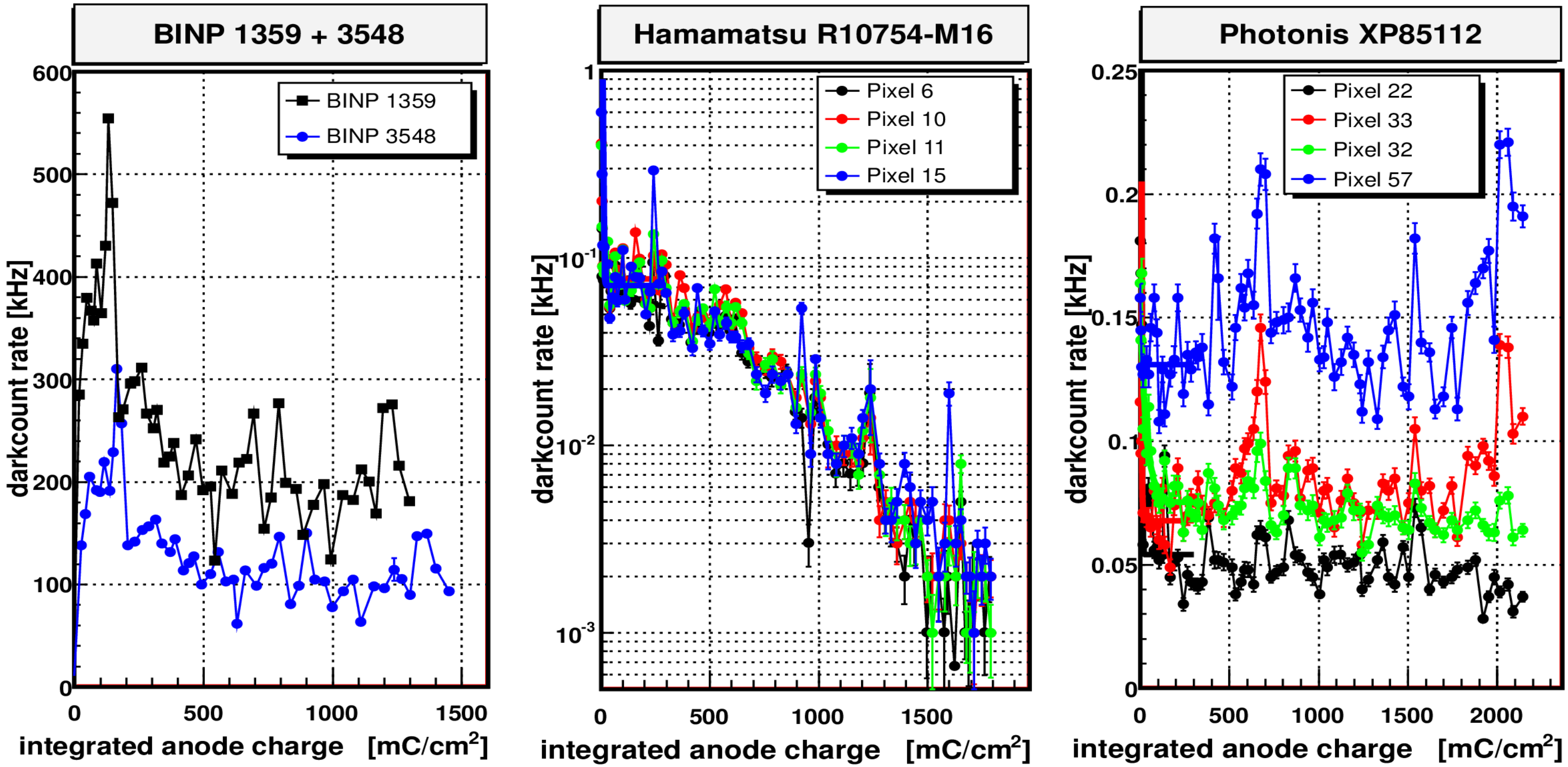
| | Hamamatsu R10754X-01-M16 | PHOTONIS XP85112/A1-HGL | BINP 1359 | BINP 3548 |
|---|---|---|---|---|
| Integrated Anode Charge (May 16th) [mC/cm²] | **1789** | **2143** | **1303** | **1451** |
| Max applied current per anode [nA] | 45.3 | 56 | 315 | 346 |
| Specified max. DC anode cur. [nA] | 100 | 47 (64 Chans.)<br>94 (32 Chans.) | 1000 | 1000 |
| Max Differential Charge [mC/cm²/d] | **14.1** | **13.4** | **10.6** | **11.7** |
| Anode area per pixel (cm²) | 0.32 | 0.36 | 2.54 | 2.54 |
| Number of measurements | 73 | 73 | 50 | 50 |
| Measured Channels | 8 | 8 + 2 (unexposed) + MCP-Out | 1 | 1 |
| QE-Scans | 7 | 7 | 6 | 5 |
| Illuminated area | 100% | **50%** | 100% | 100% |
| Applied voltage using voltage divider (V) | 3300 | 2050 | 3100 (+100) | 3000 (+100) |

# Gain vs. Integrated Anode Charge



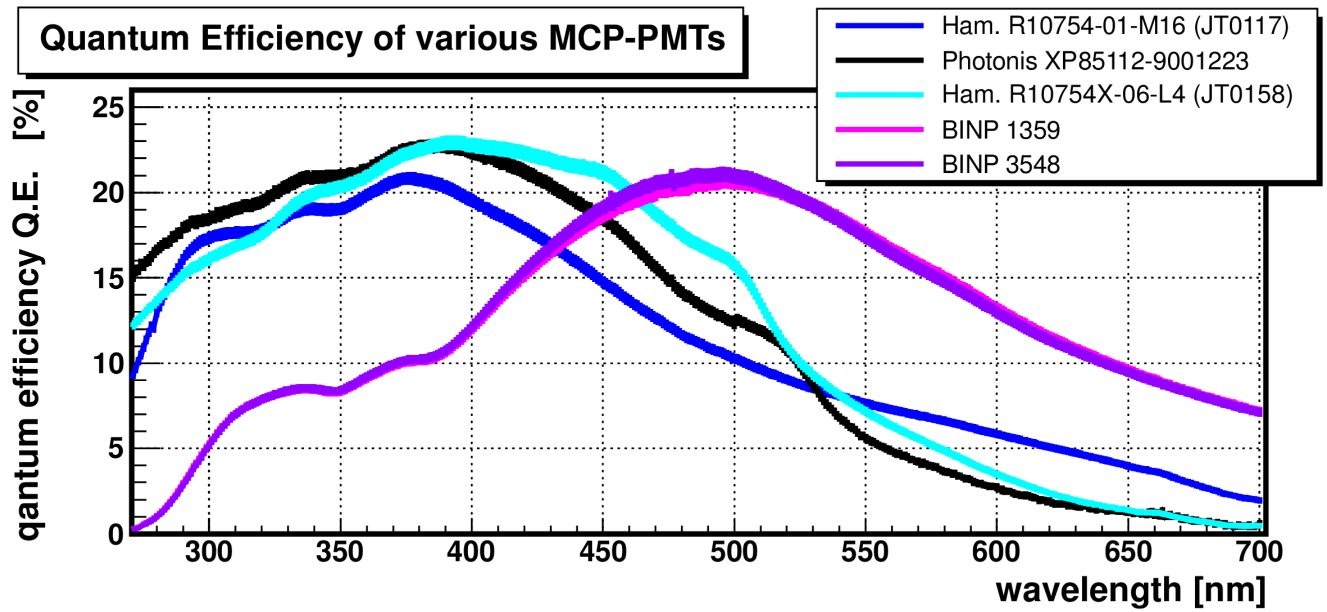

- Only moderate gain changes
- **This was different in the former MCP-PMTs !**

# Darkcount vs. Anode Charge




- Only few changes of darkcount rate for BINP and PHOTONIS
- **Big reduction in Hamamatsu R10754X**

# Quantum efficiency



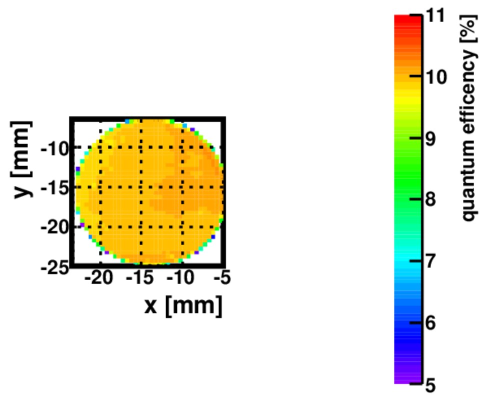

| MCP-PMT | Peak Q.E. (nm) | Photo cathode |
|---|---|---|
| **XP85112/A1⁻HGL (1223)** | 390 | bi-alkali |
| **R10754X-01-M16** | 375 | multi-alkali |
| **R10754X-06-L4** | 390 | bi-alkali |
| **BINP 1359** | 495 | $Na_2KSb(Cs)+Cs_3Sb$ |
| **BINP 3548** | 495 | $Na_2KSb(Cs)+Cs_3Sb$ |

# Q.E. Scans

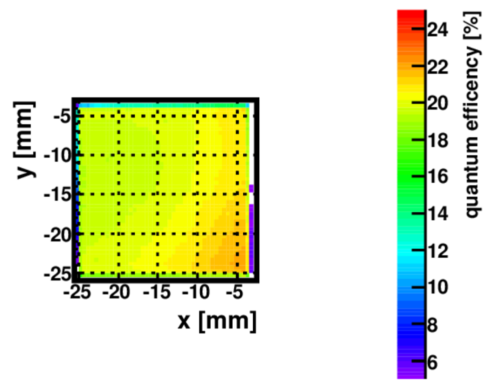
**Q.E. measured at 372 nm**

| BINP 3548 | Ham. R10754X-M16 | PHOTONIS XP85112 |
|---|---|---|

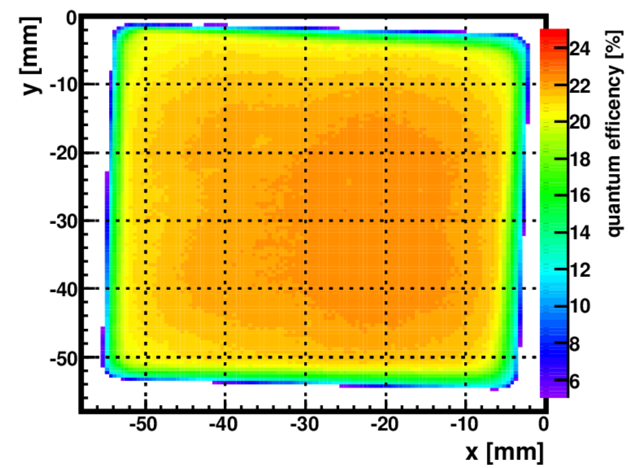
186 mC/cm$^2$



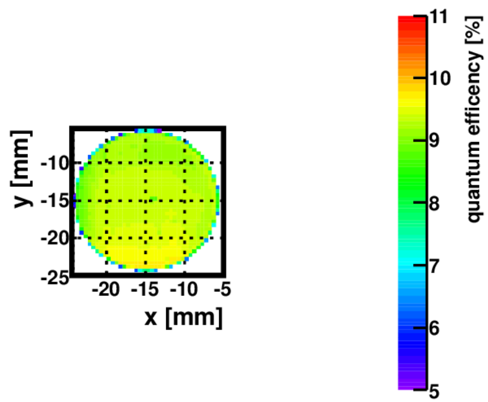

100 mC/cm$^2$



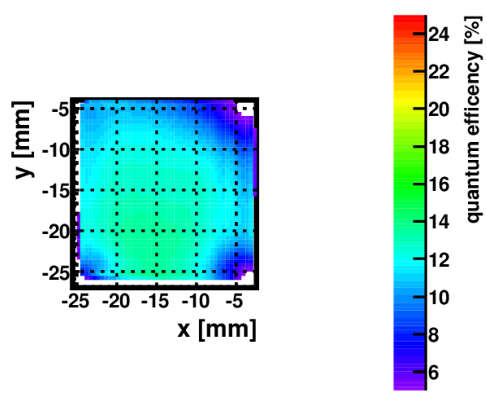

125 mC/cm$^2$



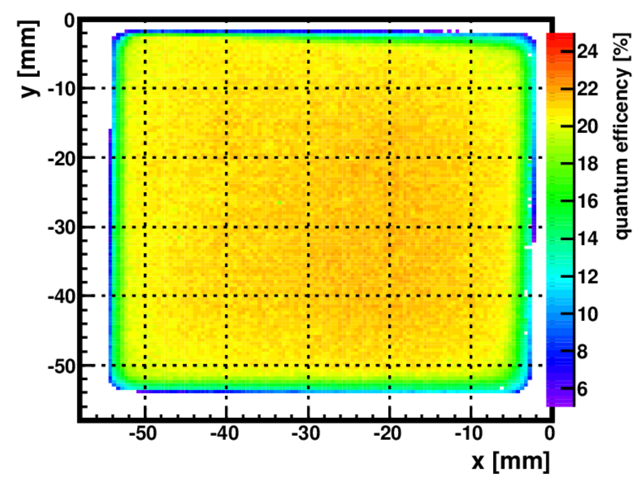

1401 mC/cm$^2$



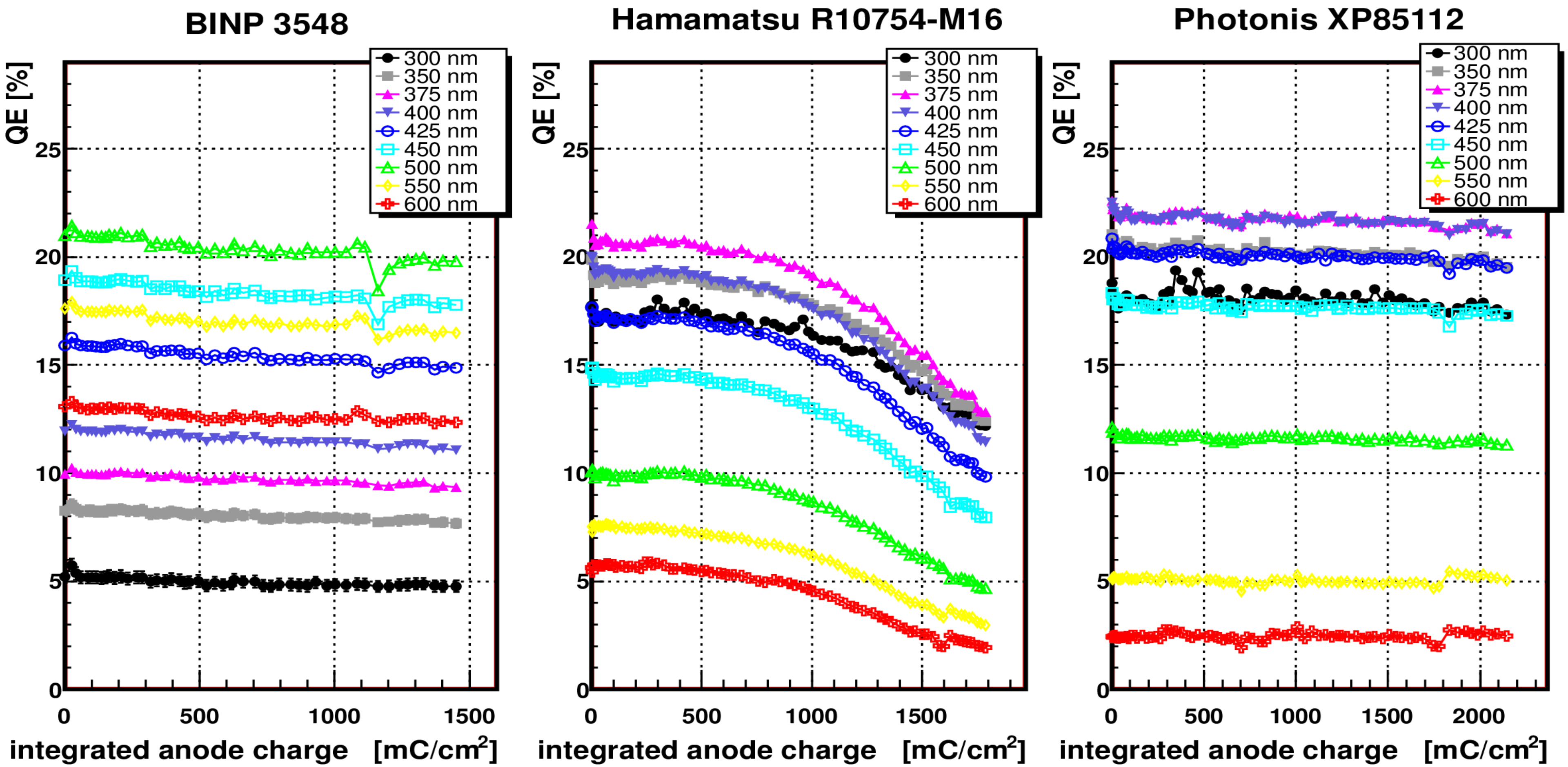

1765 mC/cm$^2$




2090 mC/cm$^2$

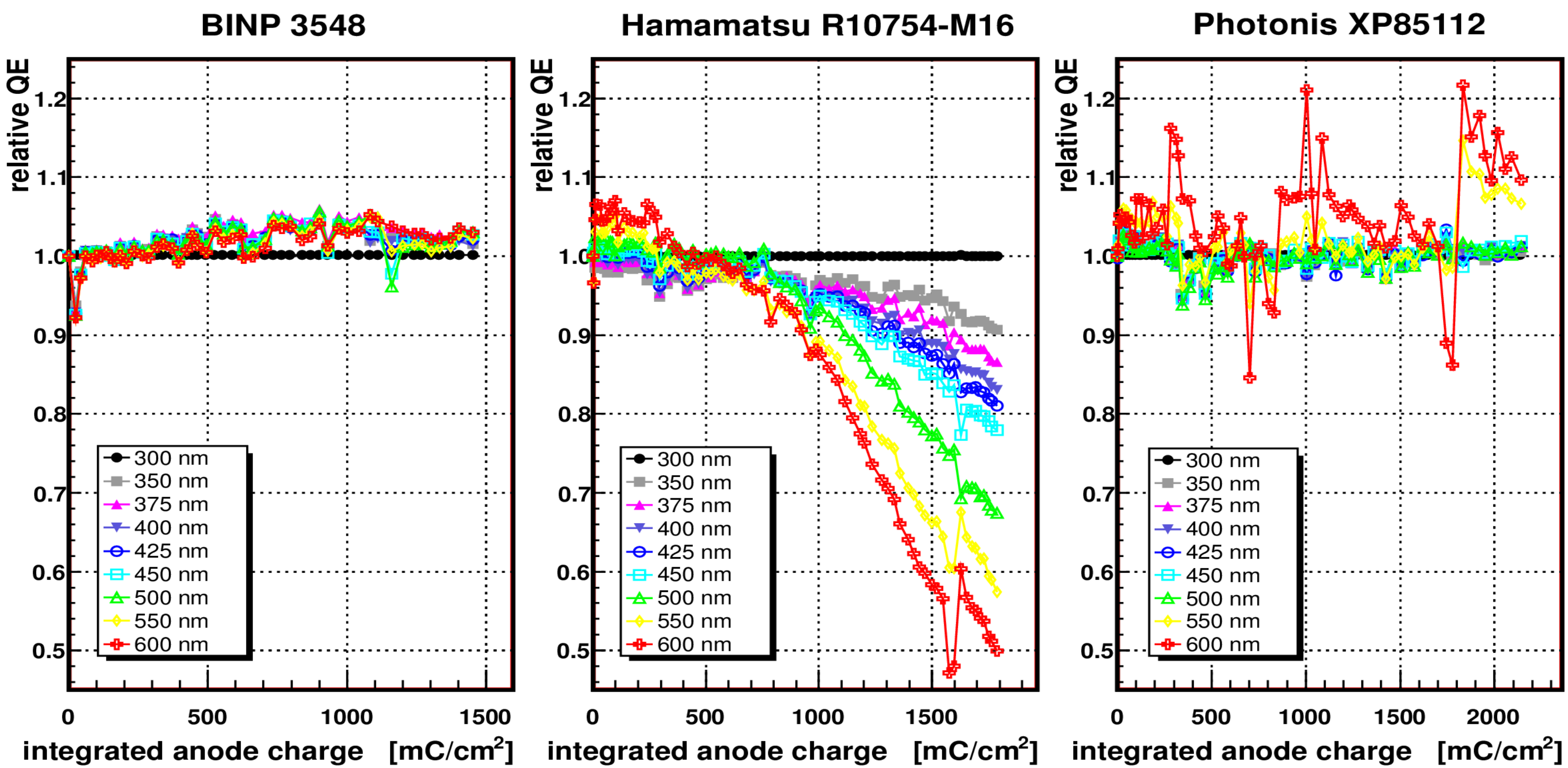


# Q.E.(λ) vs. Integral Anode Charge




- Hamamatsu: Q.E. drops significantly above ~1 C/cm2
- **BINP and PHOTONIS: few or no Q.E. drop, resp.**

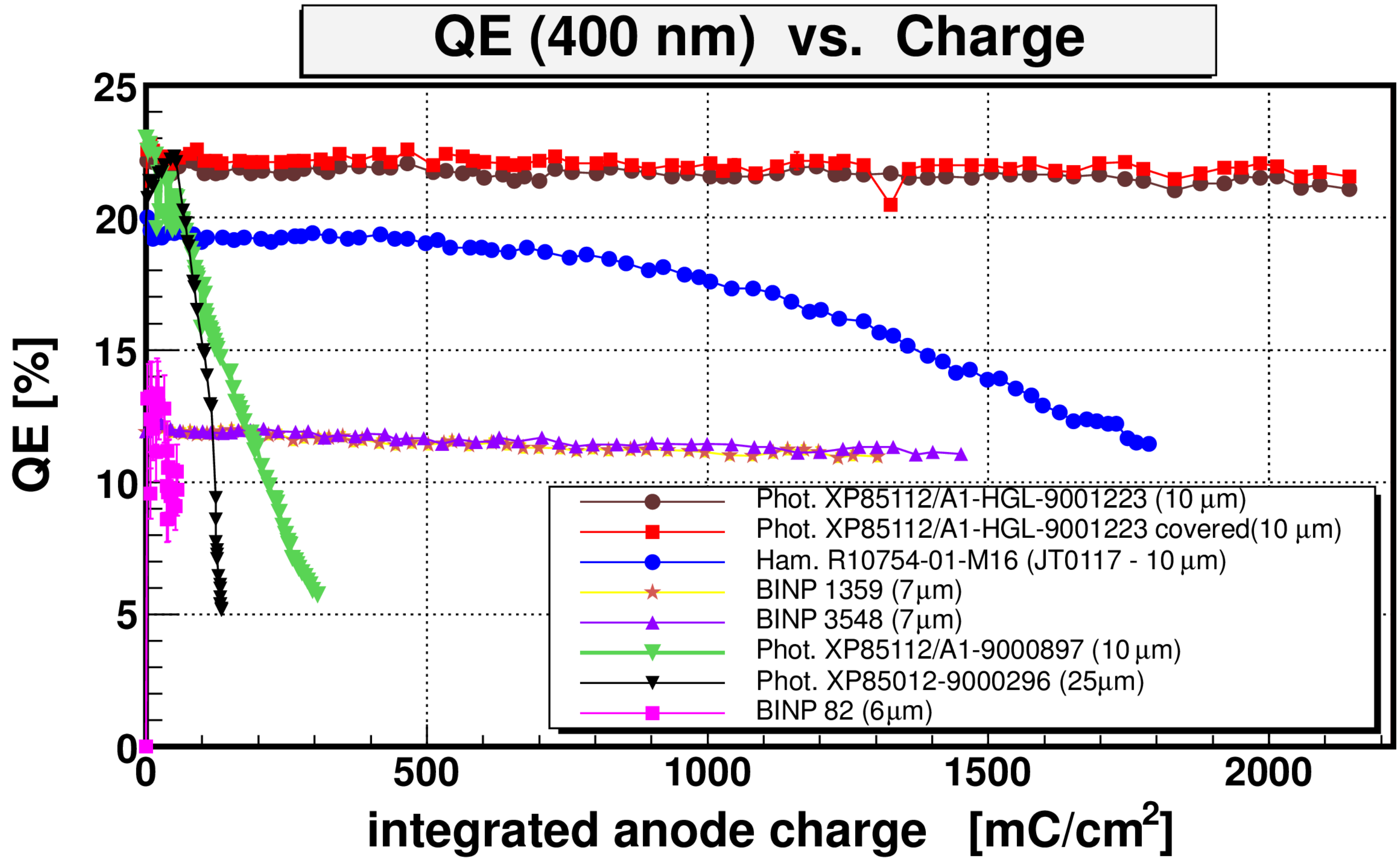
# Relative Q.E.(λ) vs. Anode Charge




<u>Ham. R10754X-M16:</u> longer wavelengths drop faster than short ones

<u>BINP 3548 and PHOTONIS XP85112:</u> **no relative Q.E. degradation**

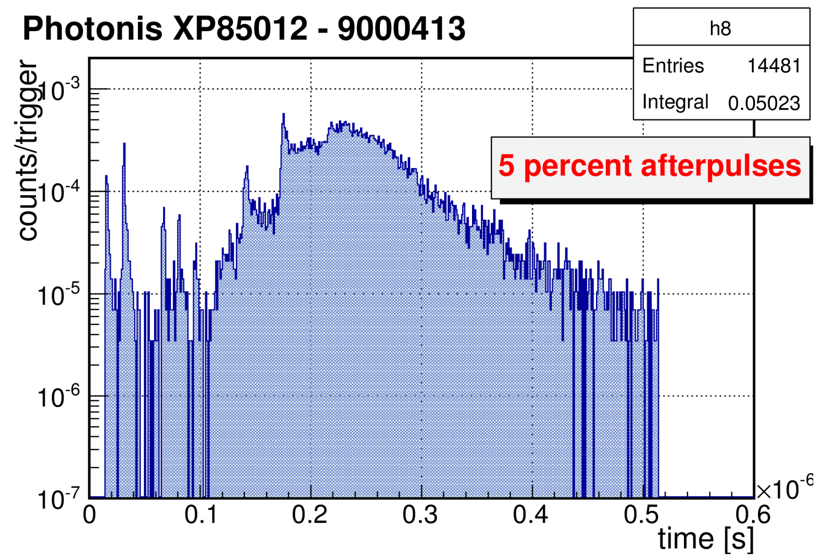
# Lifetime of Different MCP-PMTs

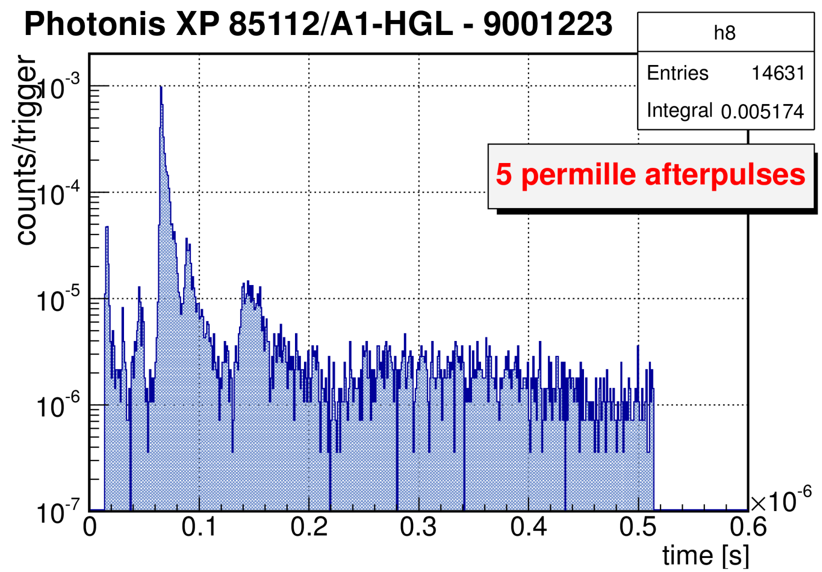



- older BINP and PHOTONIS MCP-PMTs: rapid Q.E. degradation
- new PHOTONIS XP85112: **still no Q.E. drop at >2 C/cm$^2$**

# Afterpulsing

- How to guess MCP-lifetime before (and during) aging?
- Measure fraction of pulses (p.e.) followed by an afterpulse (ion)
  - The higher the fraction of afterpulses the higher the amount of restgas inside tube
  - Time delay spectrum may allow to guess the type of ions
- New MCP-PMT with ALD surfaces shows lowest afterpulsing.
- More studies necessary!



# Summary and Outlook

- Latest MCP-PMT models fulfill most requirements of PANDA DIRC.
- **Significant increase of lifetime of MCP-PMTs** due to the recent improvements in design
  - **huge step forward !**
  - equipping the PANDA DIRCs with MCP-PMTs is in reach
- **ALD technique appears very promising**
- Further improvements could possibly come with
  - modified photo cathodes (see BINP)
  - MCP materials with less outgassing
    (e.g., borsilicate glass instead of lead glass)