Bremsstrahlung and Fluorescence in PMTs causing fast afterpulses
+
Development of an Optical Module for the LENA Project

Marc Tippmann

Technische Universität München
Lehrstuhl für Experimentelle Astroteilchenphysik

Max Knötig, German Beischler, Max Knötig, Randolph Möllenberg, Dominikus Hellgartner,

Jean-Côme Lanfranchi, Lothar Oberauer

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LENA (Low Energy Neutrino Astronomy)

Physics goals

- Neutrino properties:
  Mass hierarchy, CP violating phase, sterile neutrino flavours, …
- Proton decay
- Astroparticle physics:
  Galactic supernova neutrinos, diffuse supernova neutrinos, …
- Geophysics: Geoneutrinos

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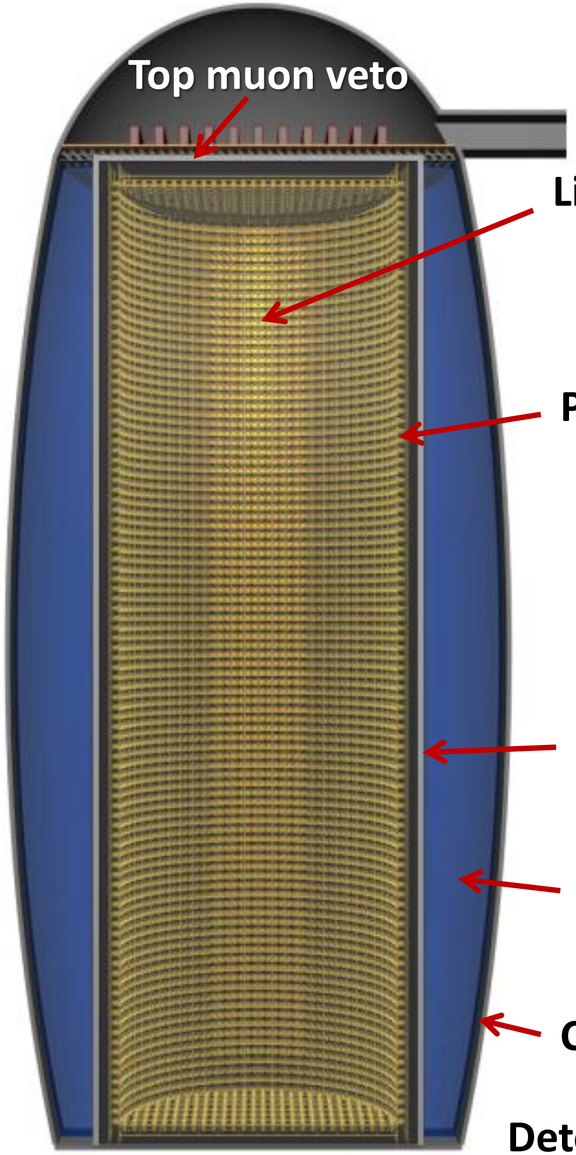

Detector layout

Liquid scintillator
LAB + 3g/l PPO + 20mg/l bis-MSB
Active volume: 50.8kt

PMT support structure
30,000 Optical Modules:
12“-PMT, light concentrator, buffer liquid

30% optical coverage

Concrete tank
r = 16m, h = 100m

Water Cherenkov muon veto
2000 12“-PMTs (encaps.)

Cavern: 4000 mwe rock overburden

Detector lifetime foreseen: > 30 years

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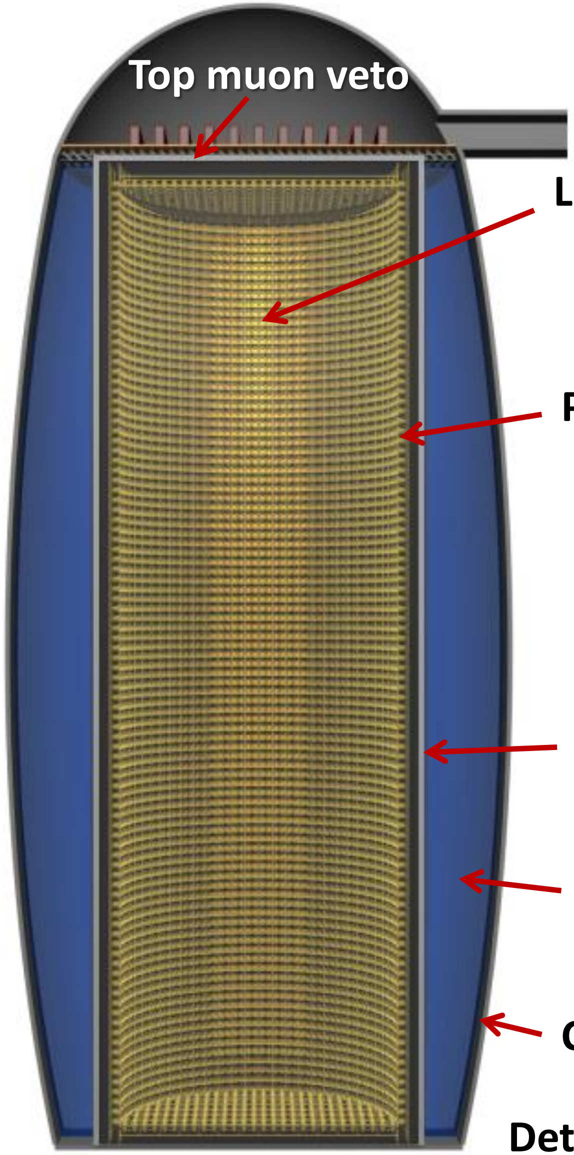

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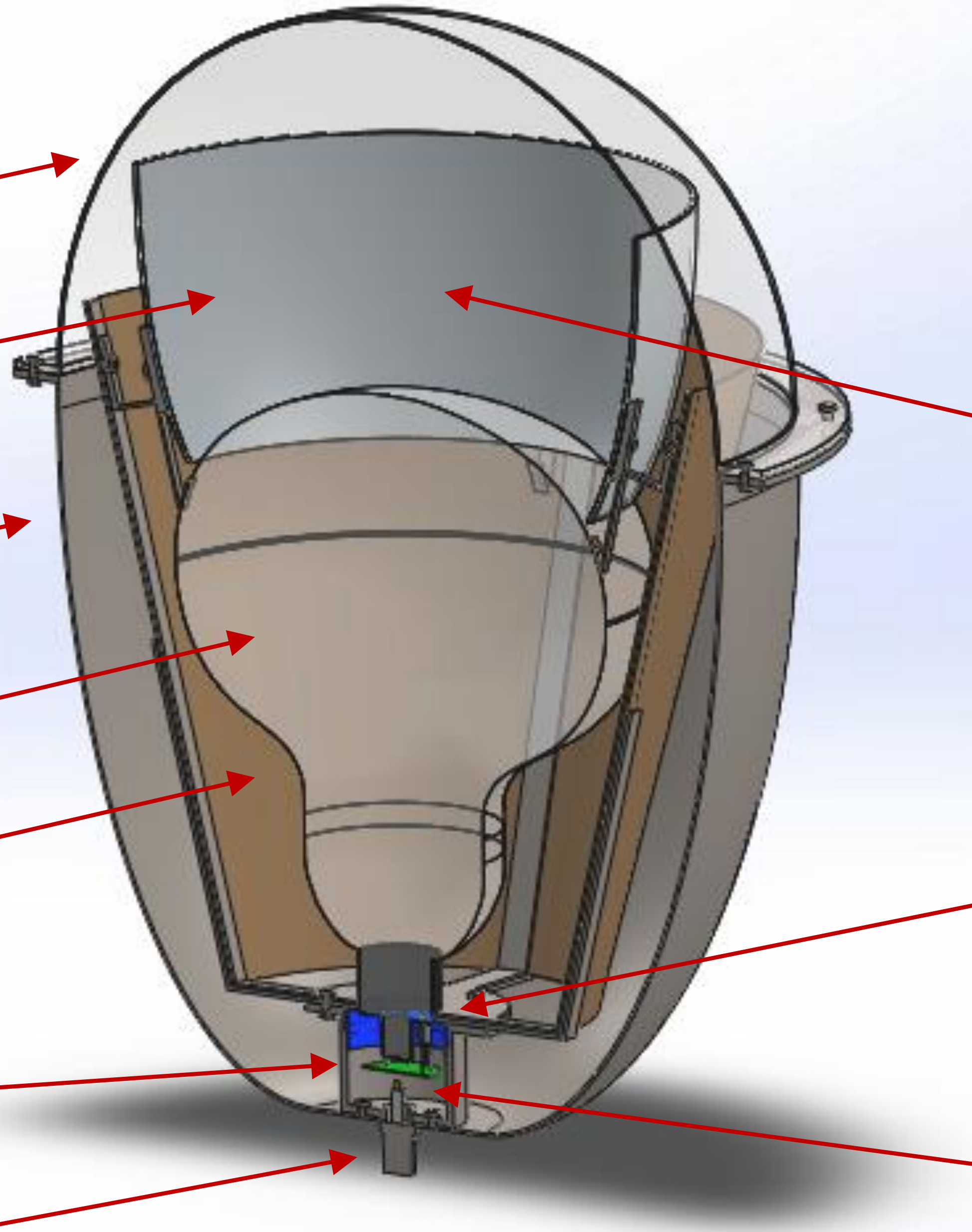
Optical Module



Acrylic glass window

Light concentrator

Stainless steel housing

Photomultiplier (PMT)

Mu-metal

Voltage divider

Connector

Buffer:
Mineral oil (LAB)

Silicone

Polyurethane

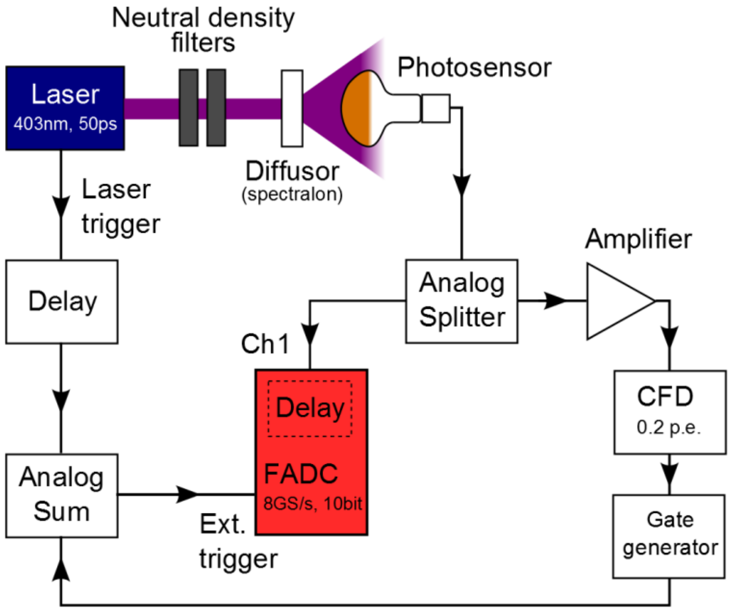
Photomultipliers (PMTs)

- Establish requirements on properties from experience (Borexino, KamLAND, DoubleChooz) + Monte Carlo simulations

  → Other photo sensor types than PMTs ruled out

- Measure properties of candidate PMT series

  → Constructed photo sensor test facility:
    - Dark box
    - Faraday cage
    - 50ps 405nm diode laser
    - FADC 10bit 8GS
    - Coincidence electronics
  - Measurements ongoing…
  - Favored series: Hamamatsu R11780 + ETEL D784

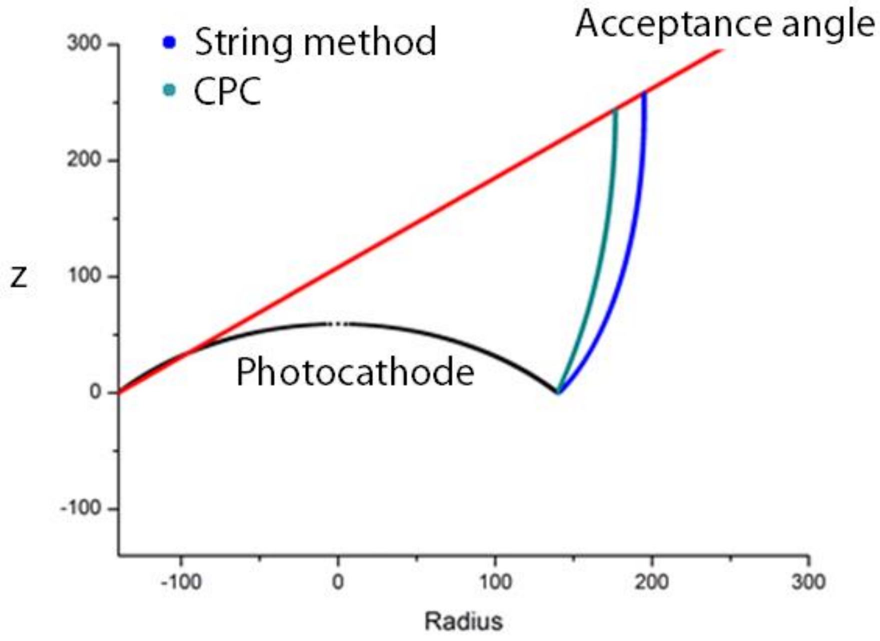


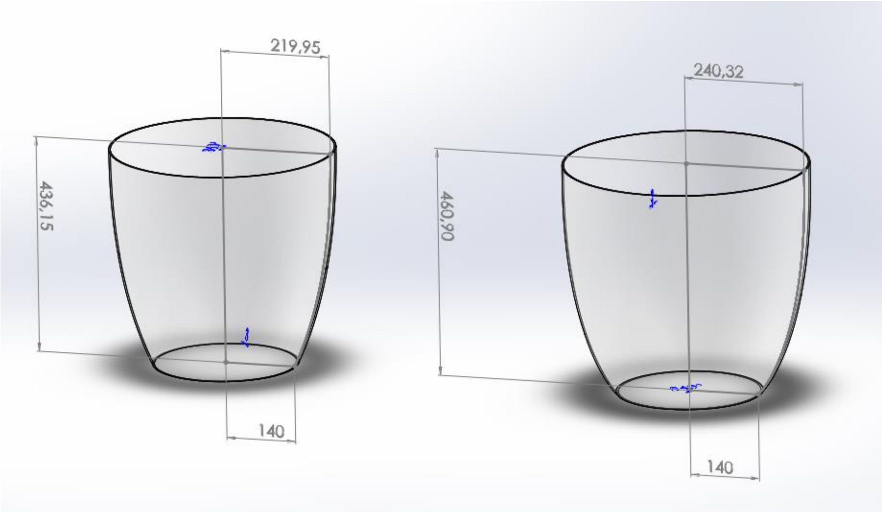
Light concentrators - Shape

- Why use light concentrators?
  - Less PMTs → less background from radioactive impurities in PMT glass + reduced costs
  - Improved detector homogeneity

- Concentrator types studied:
  - Compound parabolic concentrator (“Winston Cone“)
  - Compound elliptic concentrator
  - Construct using string-method for flat and spherical photocathode
  - Varied acceptance angle for all types

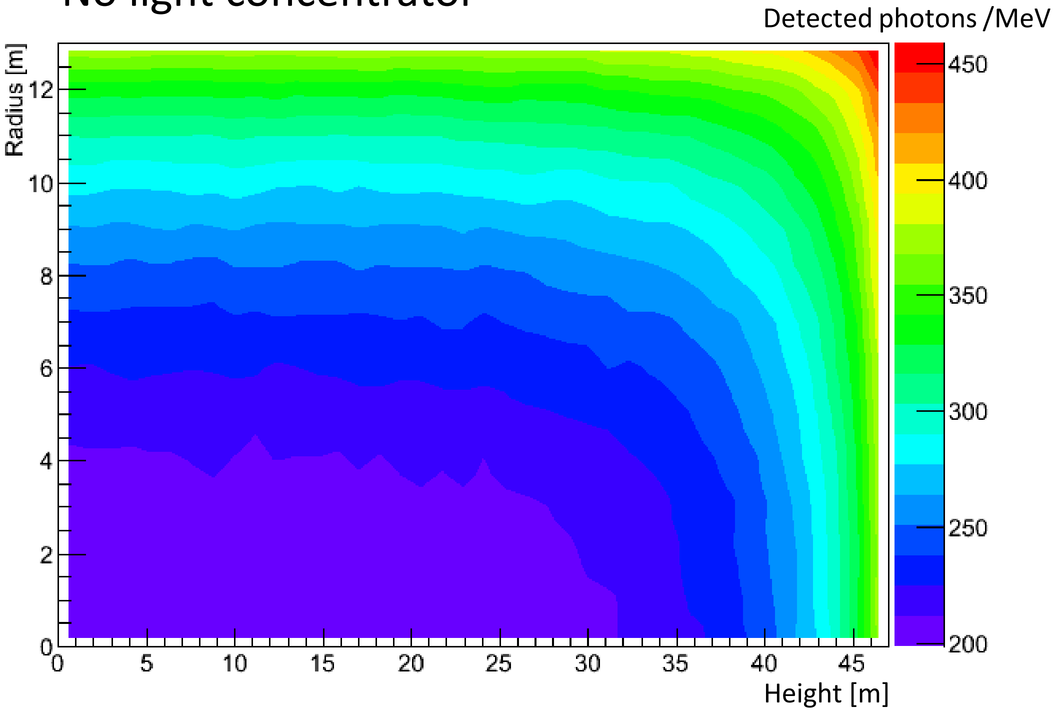
- Geant4 MC detector simulations using full optical model to determine optimum shape



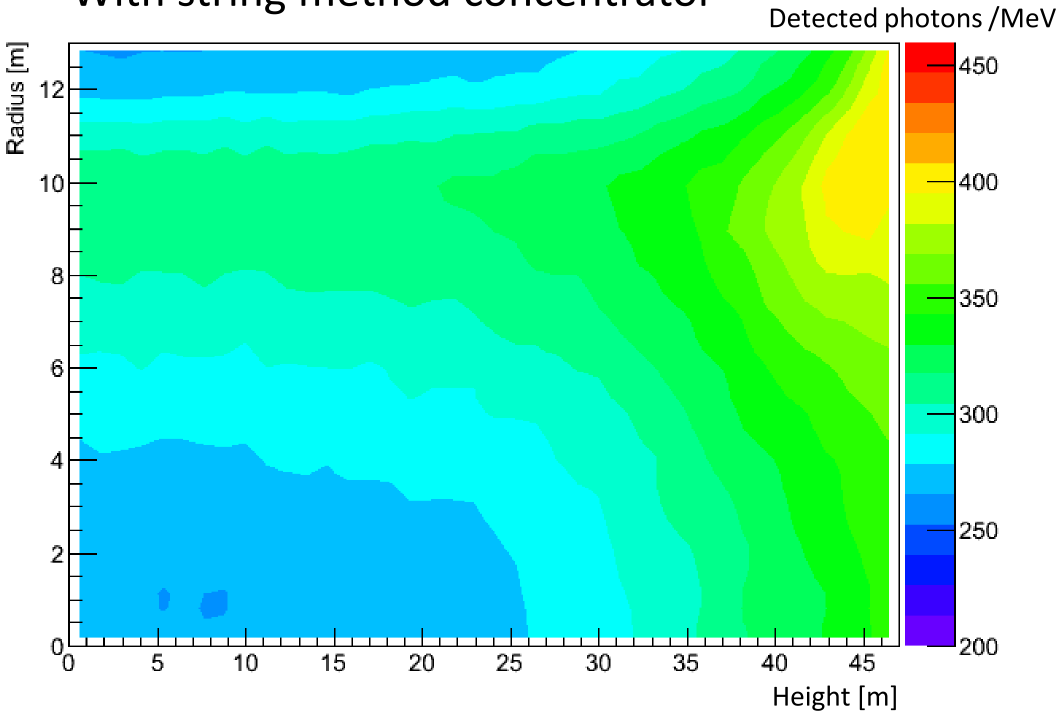


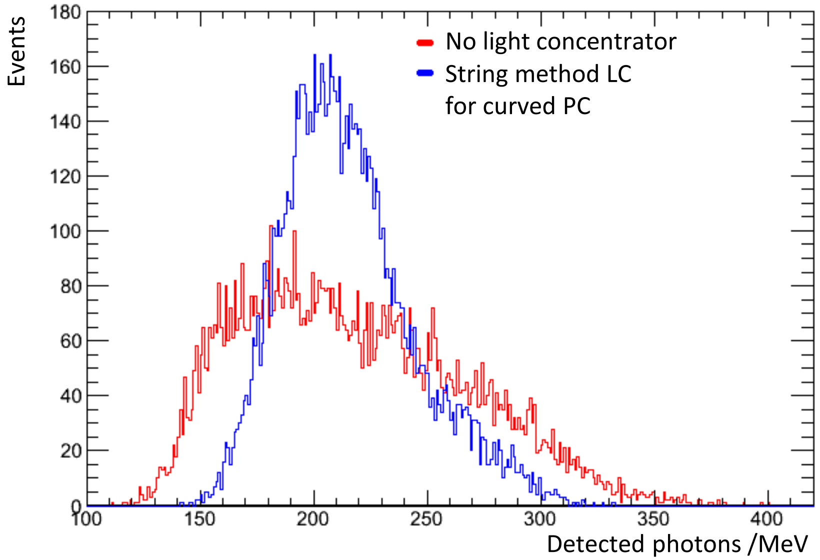
Light yield:

No light concentrator



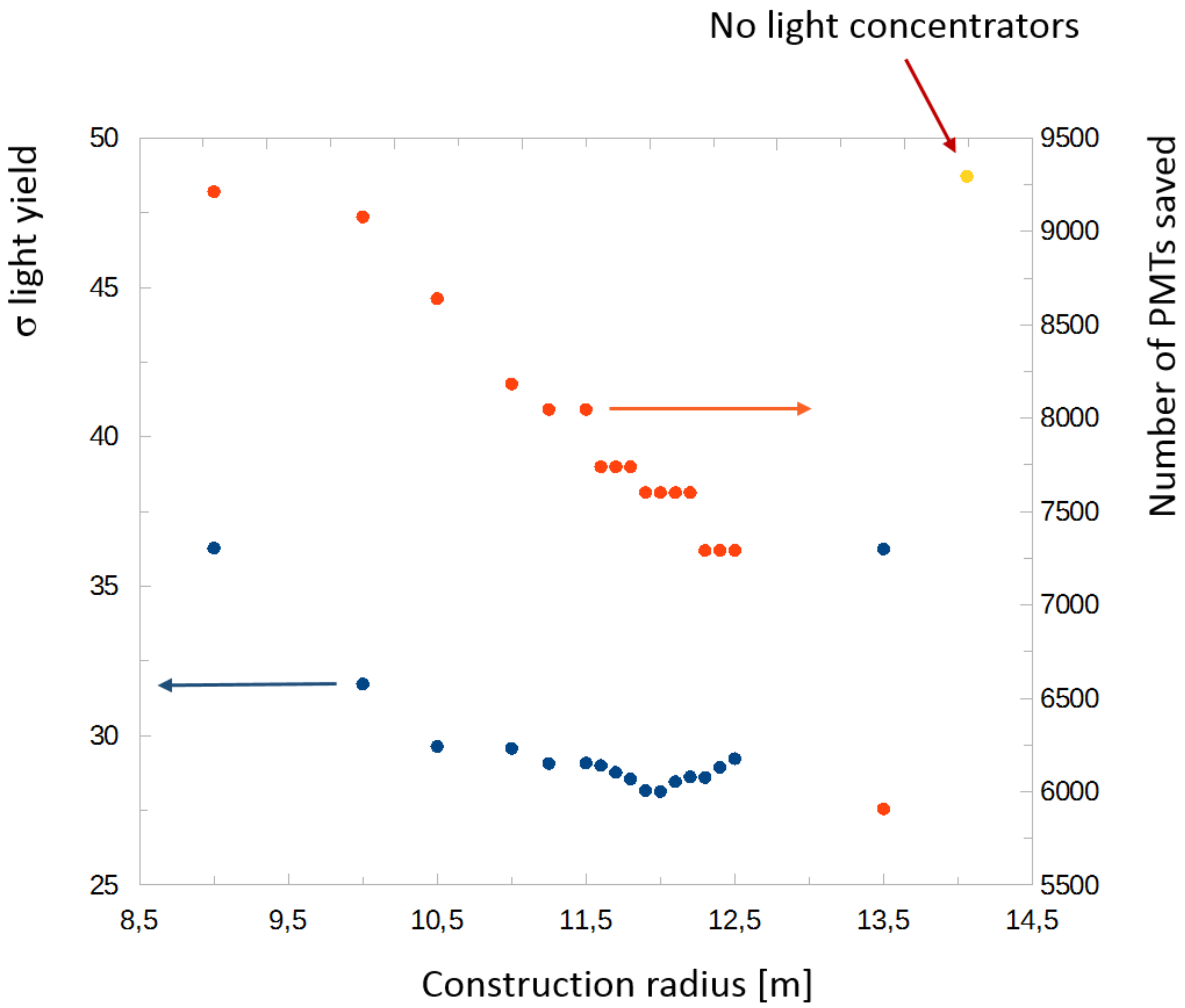
With string method concentrator





Light concentrators - Shape

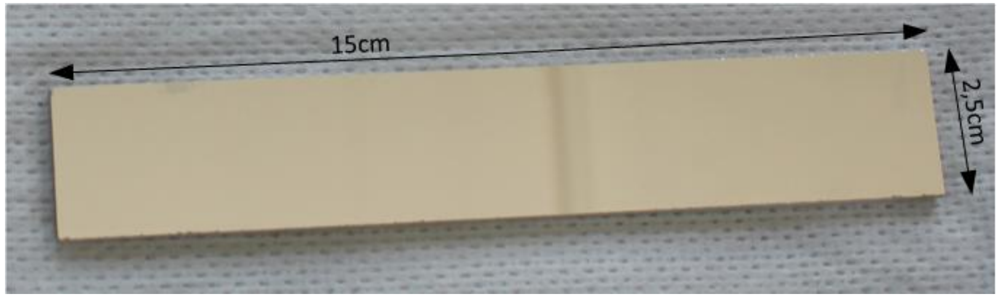
- String method concentrator for spherical photocathode for a construction radius of 12m (=57.6° acceptance angle) shows best homogeneity as well as large effective magnification



Light concentrator - Material

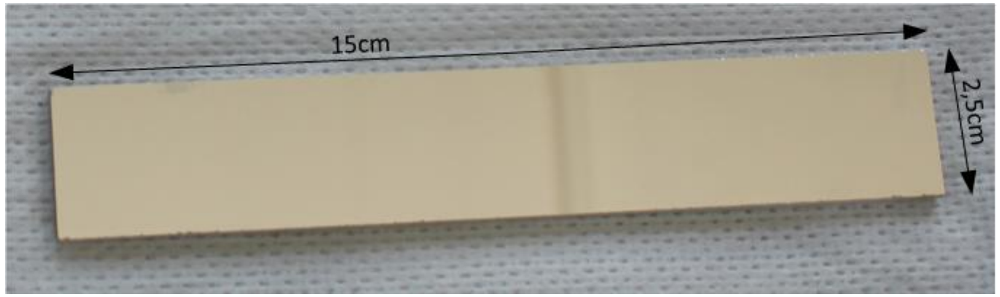
- Requirements:
  - High reflectivity from ≈400-500nm

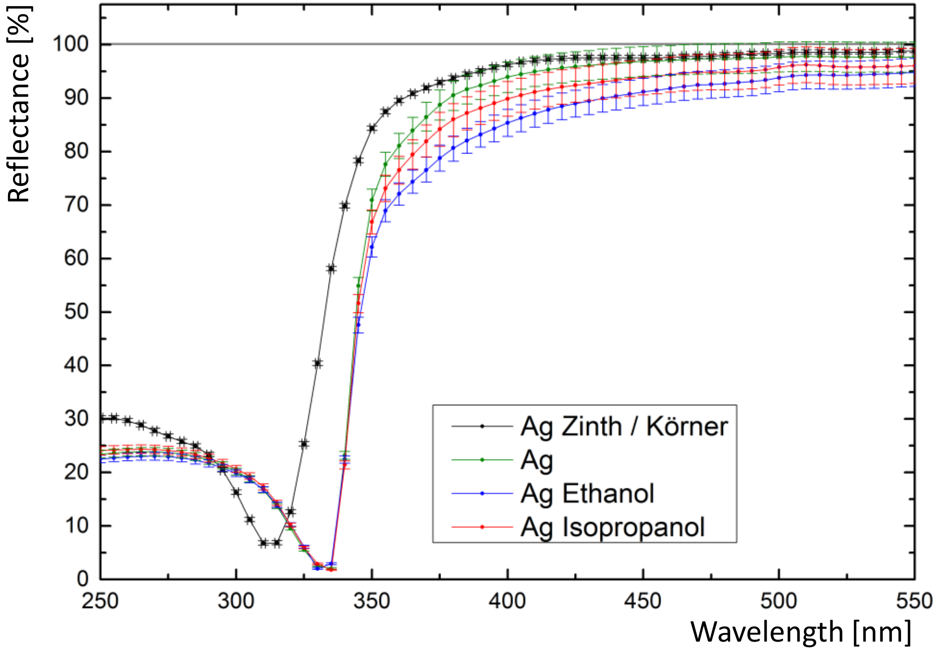
    → Al or Ag → acrylic glass coated with thin Al/Ag layer
  - Low background → screen materials with Ge detector
  - Low costs for material + production
  - Compatibility with buffer liquid (LAB)
    - Place samples in LAB + artificial aging via increased T
    - Measure transmission
    - Surface dissvolves → transmission decreases

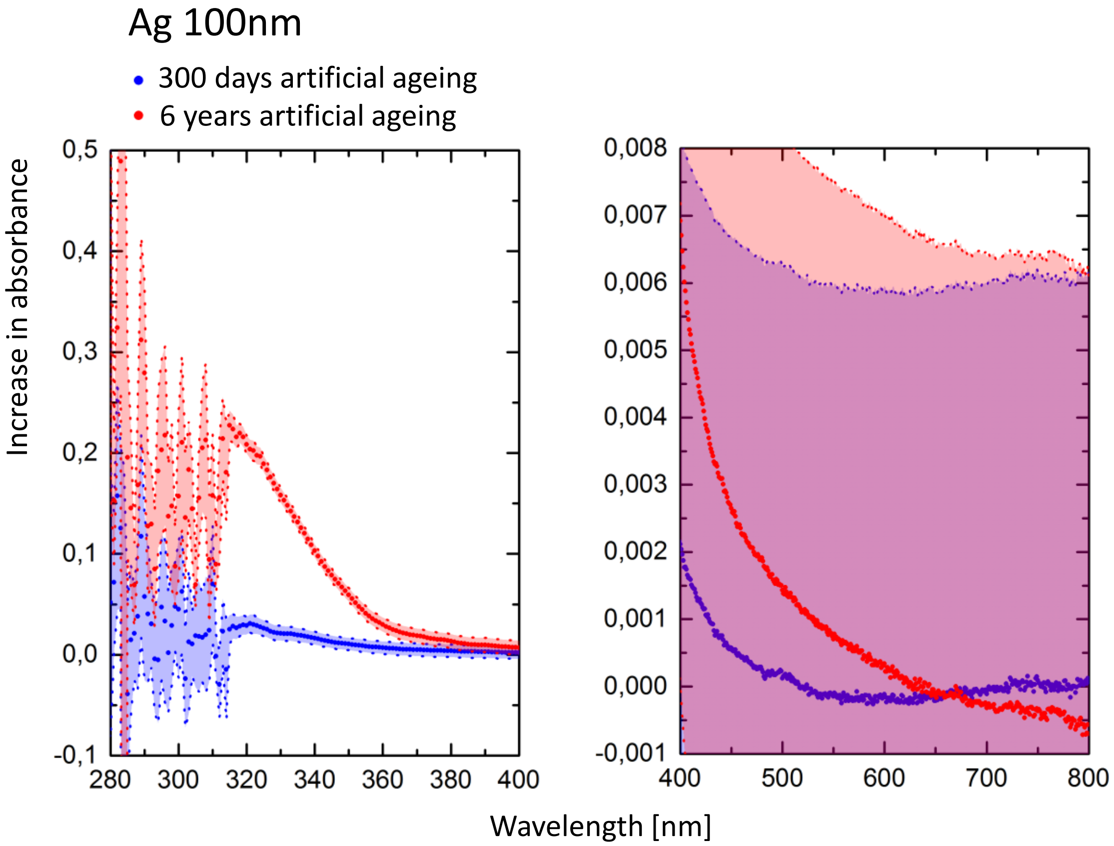


Light concentrator - Material

- Artificial ageing of samples of acrylic glass with various coatings + protective layers in LAB via increased temperature
- Measured absorbance of LAB before + after
  - Increases betweeen 400-450nm mostly compatible to 0
  - Below 400nm increase for all samples → probably acrylic glass
- Measured reflectance before + after
  - Best reflectance before + after for Ag 100nm coating, 400-450nm: 95.7% → 92.2%



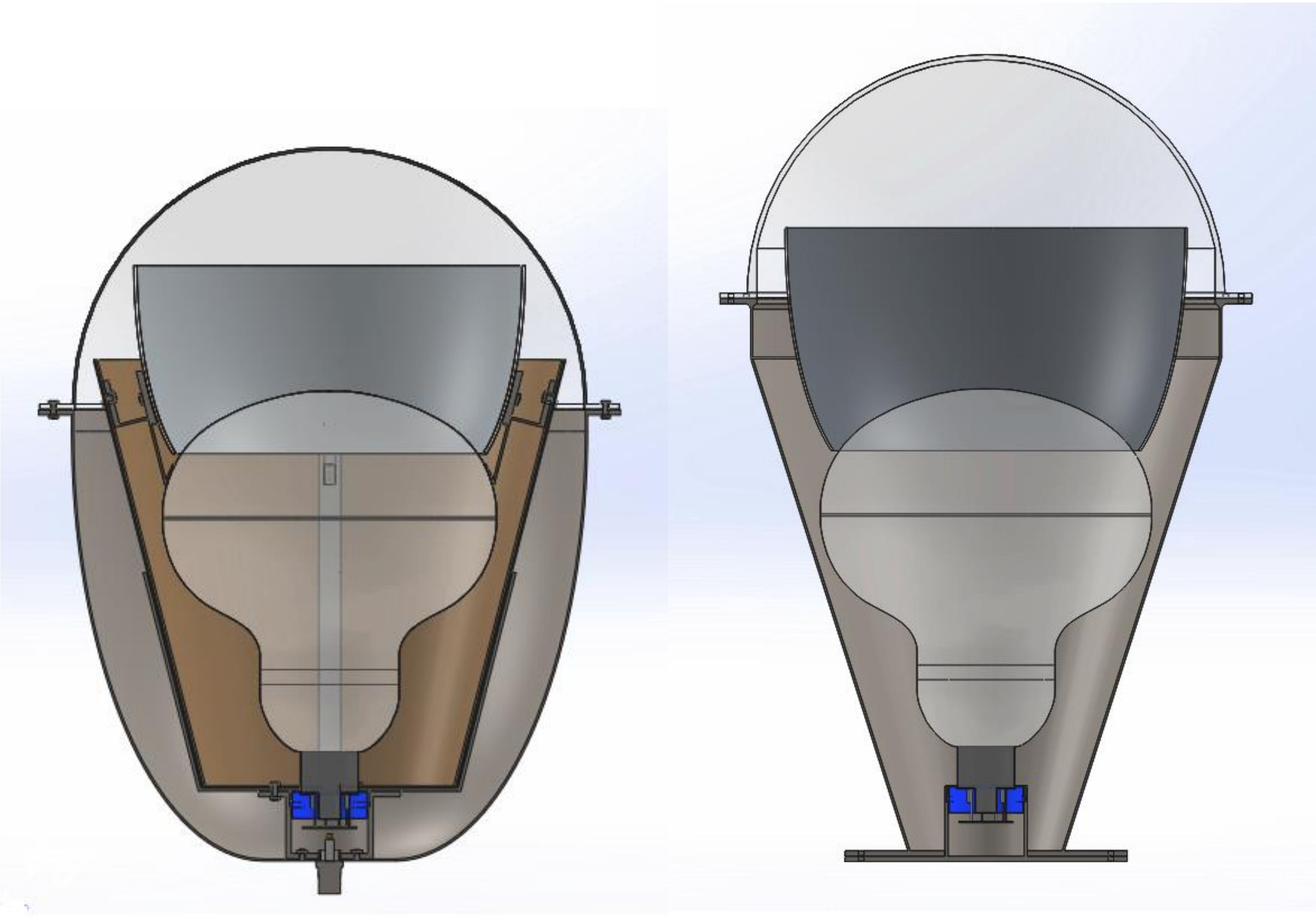



Ag 100nm

- 300 days artificial ageing
- 6 years artificial ageing

Pressure encapsulations

- Liquid head of 100m + liquid handling system, atmospheric pressure + overpressure in mine,
  → in worst case up to 12.0 bar
  → need pressure housing for PMTs
- Detector precleaned with water → protects voltage divider
- Need inactive buffer liquid in front of PMTs to shield detector from intrinsic radioactivity
  → incorporate in encapsulation
  - Minimize weight → less background
- FEM simulations with SolidWorks
  → Two designs in final selection: conical + elliptical encapsulations
  - Conical favoured due to ease of construction + low weight



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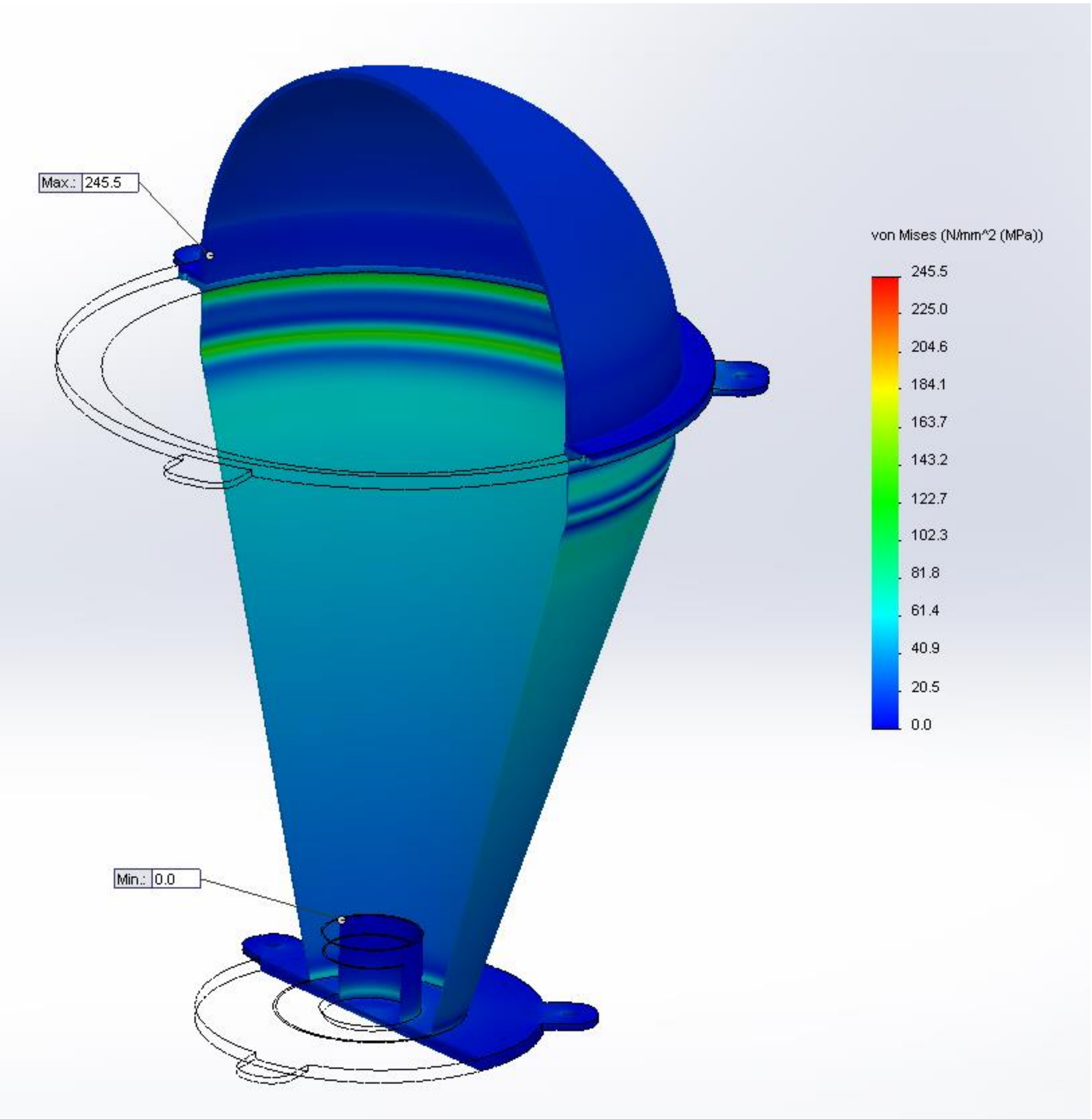
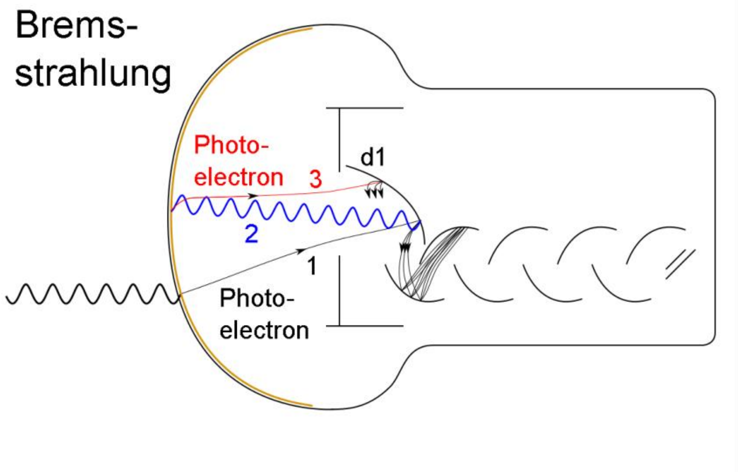


Light emission from PMTs

Why are we studying this?

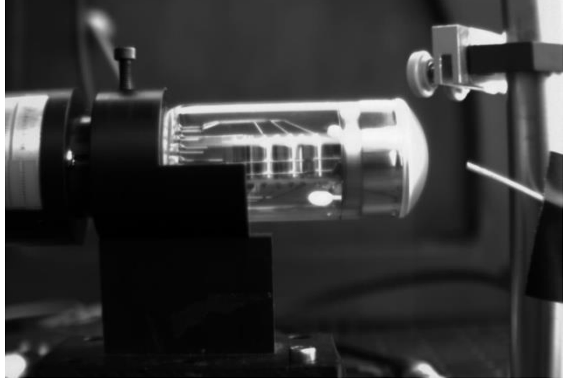
- Physics goals + detector layout of large experiments
  ⟶ various requirements on PMTs, amongst others:
  low fake detection (e.g. dark noise, afterpulses)
- Electron avalanche in PMT can cause light emission
  ⟶ can produce fake events



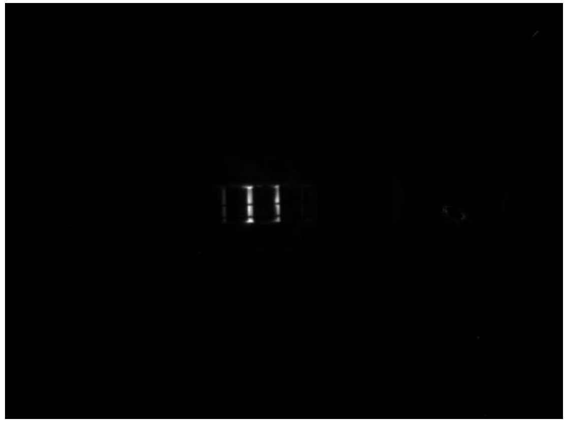
Collaboration with Max Knötig + Razmik Mirzoyan from MAGIC/CTA group at MPI Physik to study these effects

Measurement of light emission: CTA-PMT: R11920-100 (1,5“)

- CCD-camera looking at dynode chain of PMT
- Sensible in vis-NIR (370-1000nm)
- Light emission from dynodes 3+5 visible!



Dark box open, HV off



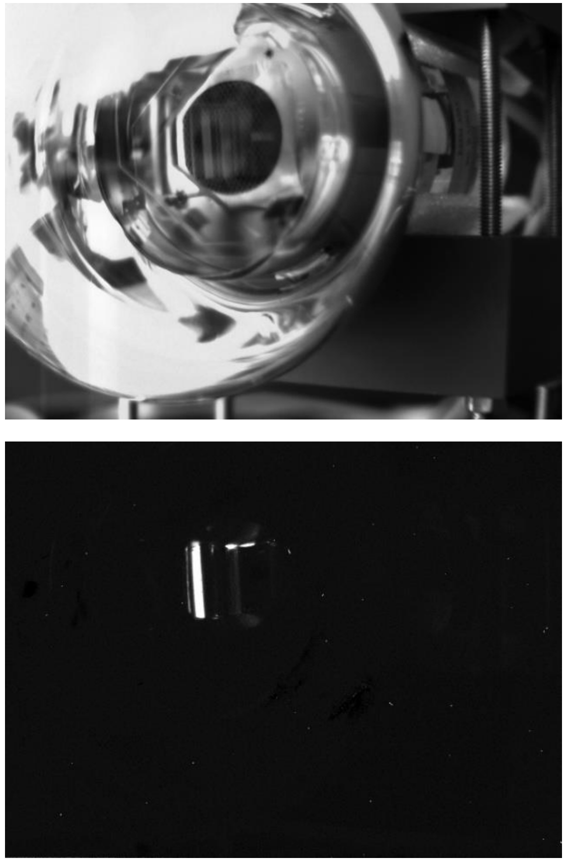
Dark box closed, laser on, HV on, 600nm filter

pictures from Max Knötig

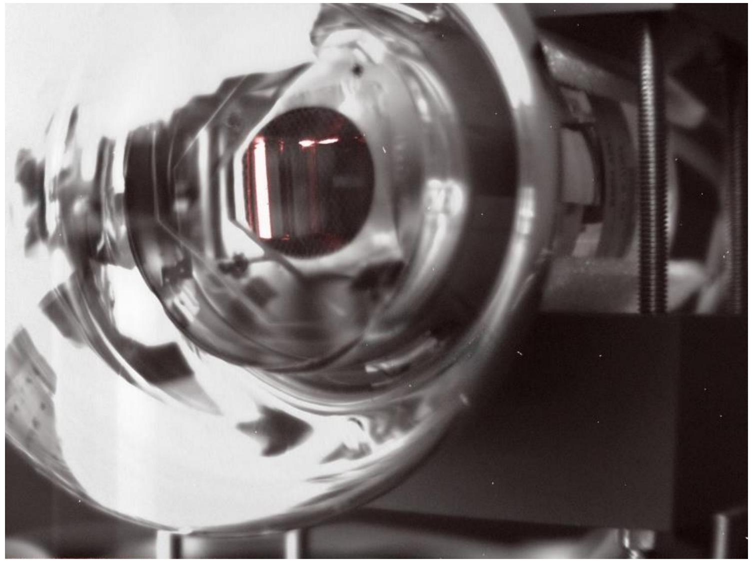
+1200V, laser 405nm, 20MHz rep.rate ⟶ several 10k phdet/tr, 1s integration time

Measurement of light emission: LENA-candidates: R6594 (5“)

- CCD-camera looking at first dynode at an angle from front
  - Dynode chain encapsulated → look on front
  - Light emission from later dynodes being reflected onto cathode!



Max Knötig

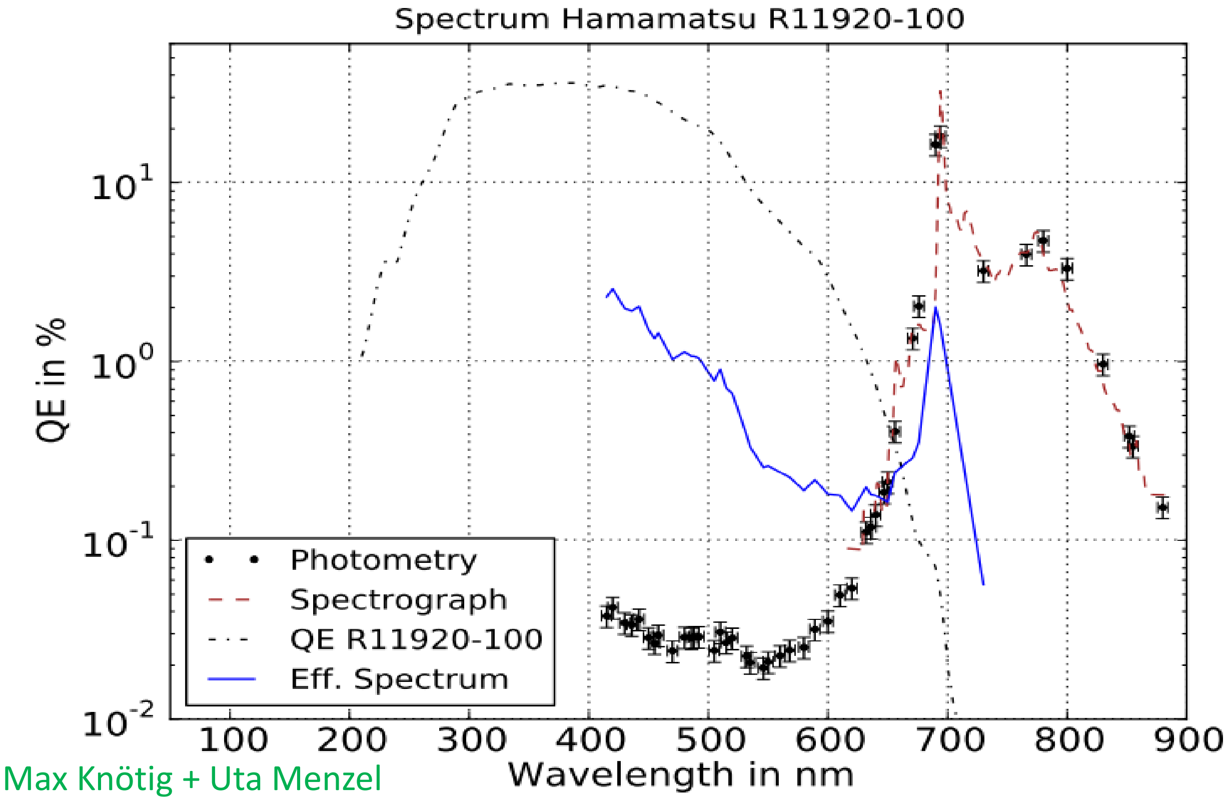


Laser 405nm, repetition rate 100kHz, ≈100 photons detected per trigger, 3600s integration time

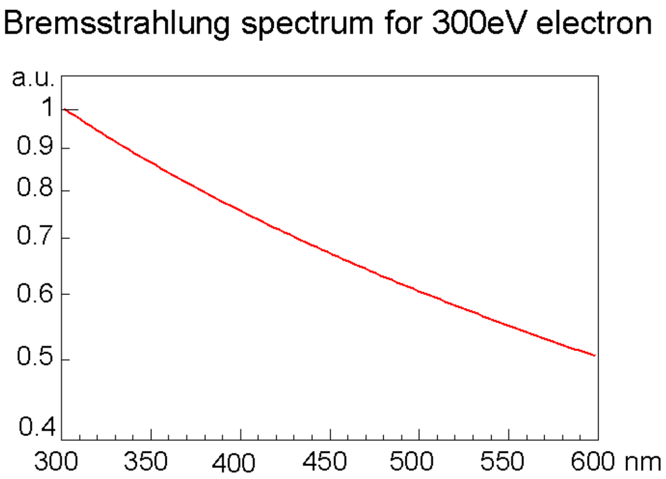
Measurement of light emission: CTA-PMT: R11920-100 (1,5“)

- Spectrum of emitted light
  a) Bandpass wavelength filters in front of CCD-camera → count hits
  b) Spectrograph

- 400-550nm: Bremsstrahlung of electrons in dynodes



Max Knötig + Uta Menzel



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- Spectrum of emitted light
  - a) Bandpass wavelength filters in front of CCD-camera → count hits
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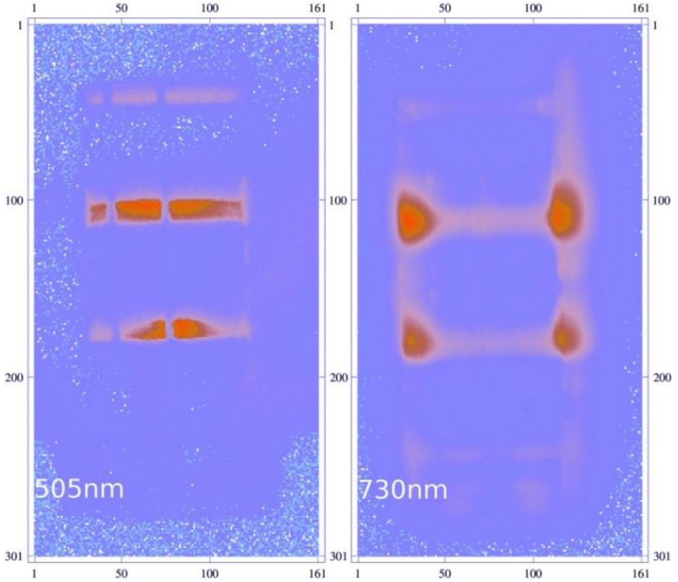
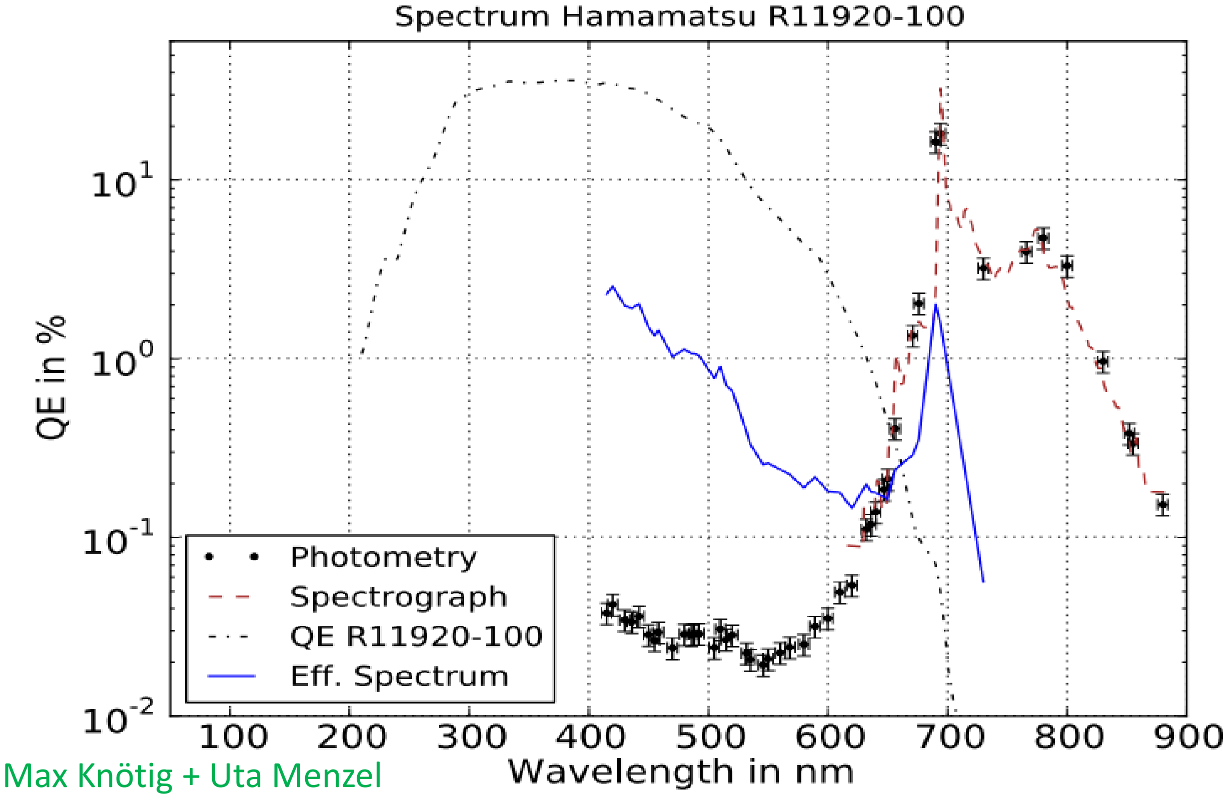
- 400-550nm: Bremsstrahlung of electrons in dynodes
- Peak at 700nm: Dynode mount = ruby → fluorescence with 694.3nm emission line, 3ms lifetime → contribution to dark count



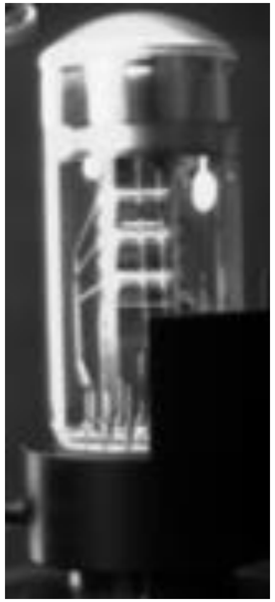


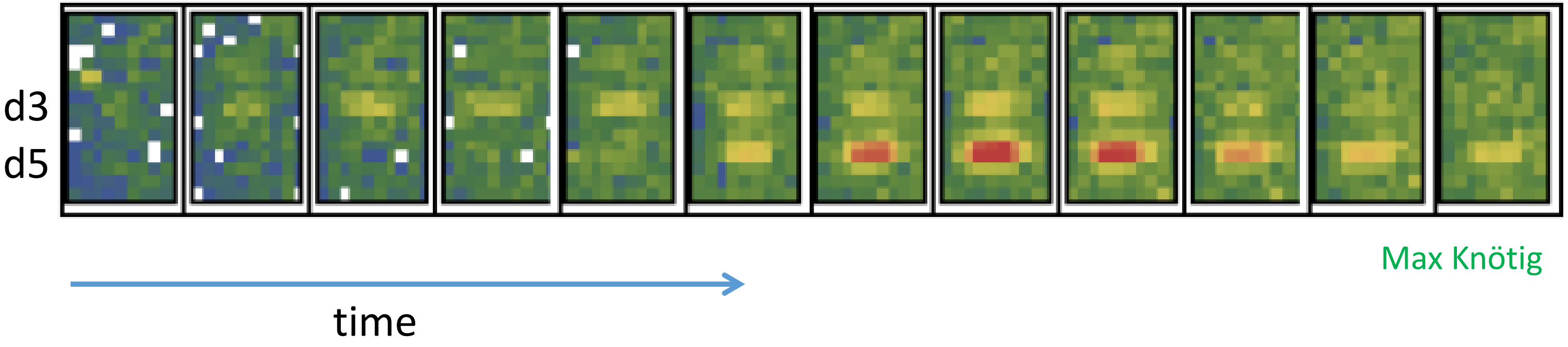
Max Knötig + Uta Menzel

Measurement of light emission: CTA-PMT: R11920-100 (1,5“)

- Gated micro-channel plate in front of CCD-camera looking at dynode chain → video of light emission
- MCP has photocathode → peak sensitivity around 400nm
- Gate width 3ns, 1.5ns rise+fall time, 1.5ns between each picture
- 3rd+ 5th dynode clearly visible!
    - More electrons → more bremsstrahlung → later dynodes emit more light

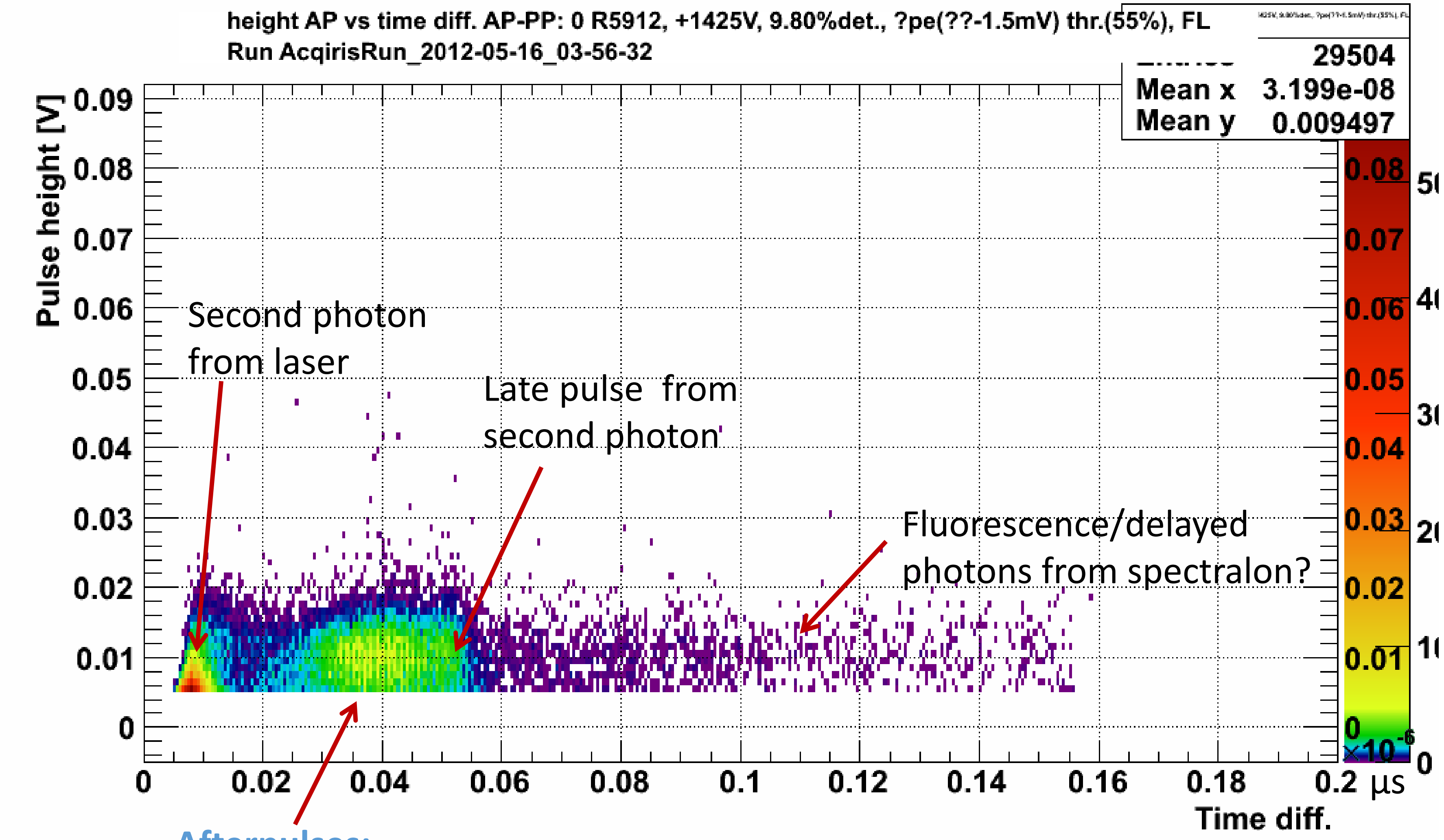
Front





Max Knötig

LENA-candidates: R5912 (8“): Fast afterpulses: pulseheight vs. delay



Second photon from laser

Late pulse from second photon

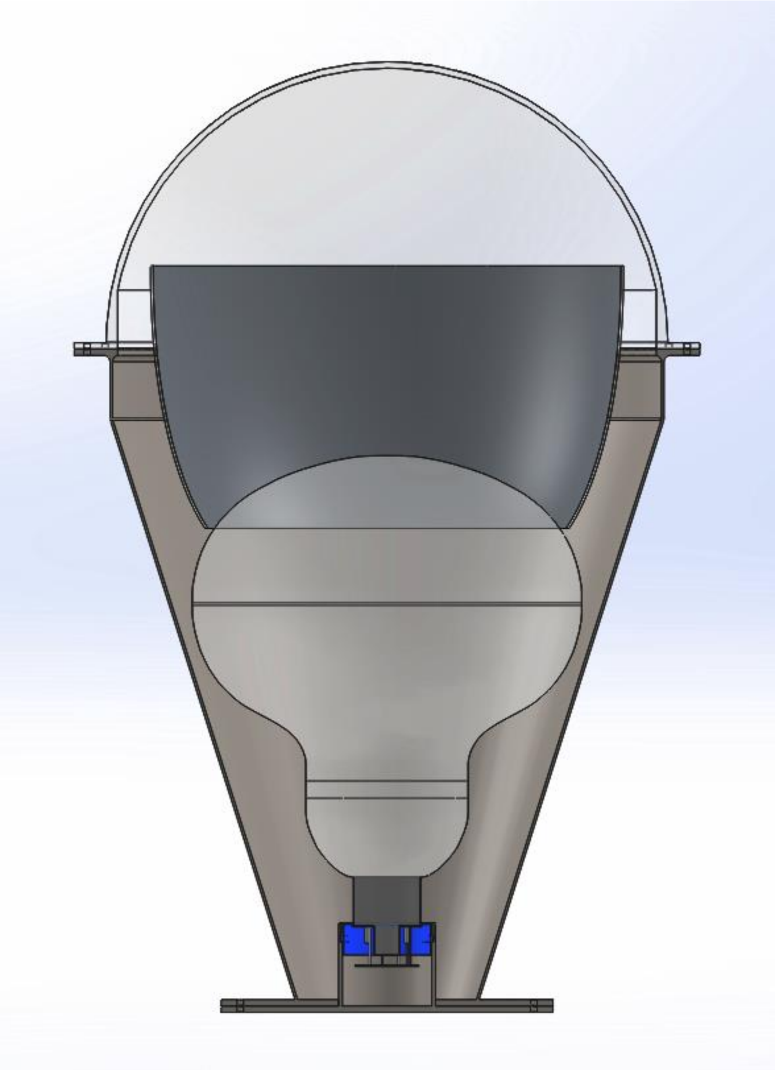
Fluorescence/delayed photons from spectralon?

Afterpulses:

- height distribution centered around 10mV → as normal pulses
- peak around 35-45ns delay → bremsstrahlung from later dynodes, light reflected inside dynode chain

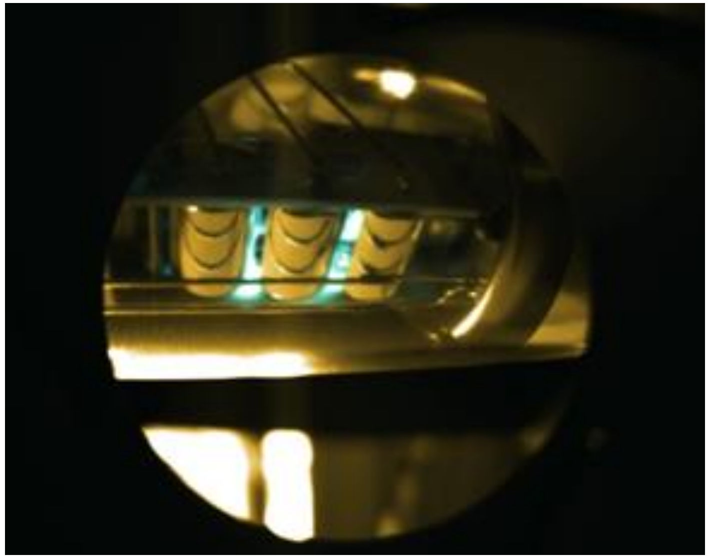
Conclusions

Conclusions



- LENA is a 50kt next-generation liquid scintillator detector with a broad range of (astro)particle physics goals
- ≈30k Optical Modules
  - PMT: R11780 or D784
  - Light concentrator:
    - MC simulations → String method concentrator for curved photocathode for a viewing window of 12m radius
    - Material: Acrylic coated with 100nm Ag → compatible with buffer liquid + highest reflectivity
  - Mu-metal shielding
  - Buffer liquid (LAB) in front of PMT
  - Pressure encapsulation housing all of it
    - FEM simulations → conical design most promising

Conclusions



- Observed light emission from dynode chain
  - Bremsstrahlung:
    - Dominant below 550nm
    - Causes fast afterpulses with normal pulse height distribution
  - Fluorescence:
    - Dynode mount → ruby emission line around 694nm, τ=3ms → contribution to dark count
    - Possibly fluorescence on short time-scale
- Main cause of fast afterpulses probably is bremsstrahlung
- Remedies:
  - Possibly reduce emission at 694nm by Fe addition to dynode mount
  - Complete encapsulation of dynodes / optical shielding from cathode
  - Smaller aperture to first dynode

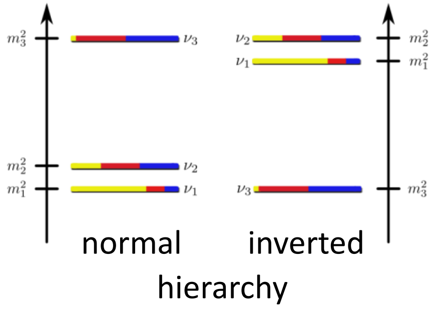
Backup slides

Physics goals:

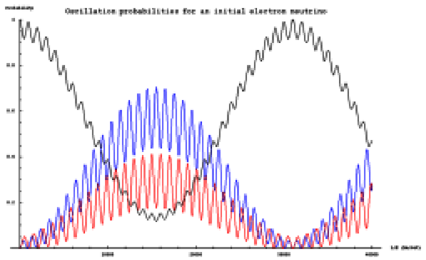
Particle physics

Neutrino properties

- Mass:
  - Mass differences
  - **Mass hierarchy**



- Neutrino oscillations:
  - **Oscillation parameters**
  - Search for **unknown neutrino types**



Proton decay

$p \longrightarrow K^+ \bar{\nu}$
$\tau > 4 \cdot 10^{34}$ years

better understand **particle physics**

Astroparticle physics

Neutrinos from:

A supernova in the Milky Way

All past supernovae in the whole universe

The sun

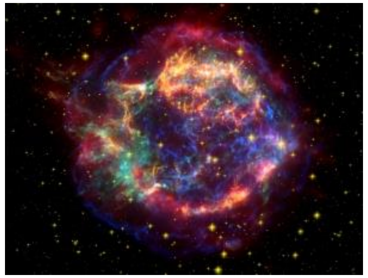
The atmosphere

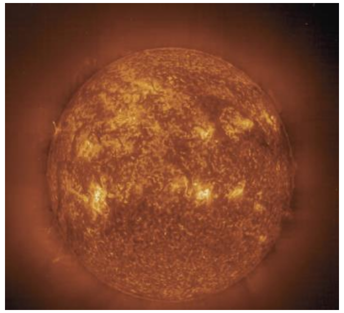
Dark Matter annihilation or decay

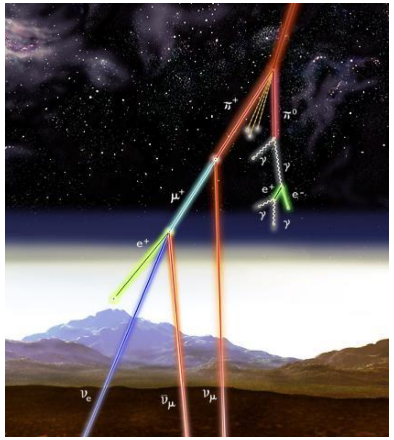
Geophysics

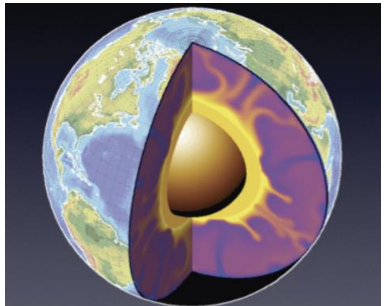
Neutrinos from the interior of the earth

better understand **particle sources**

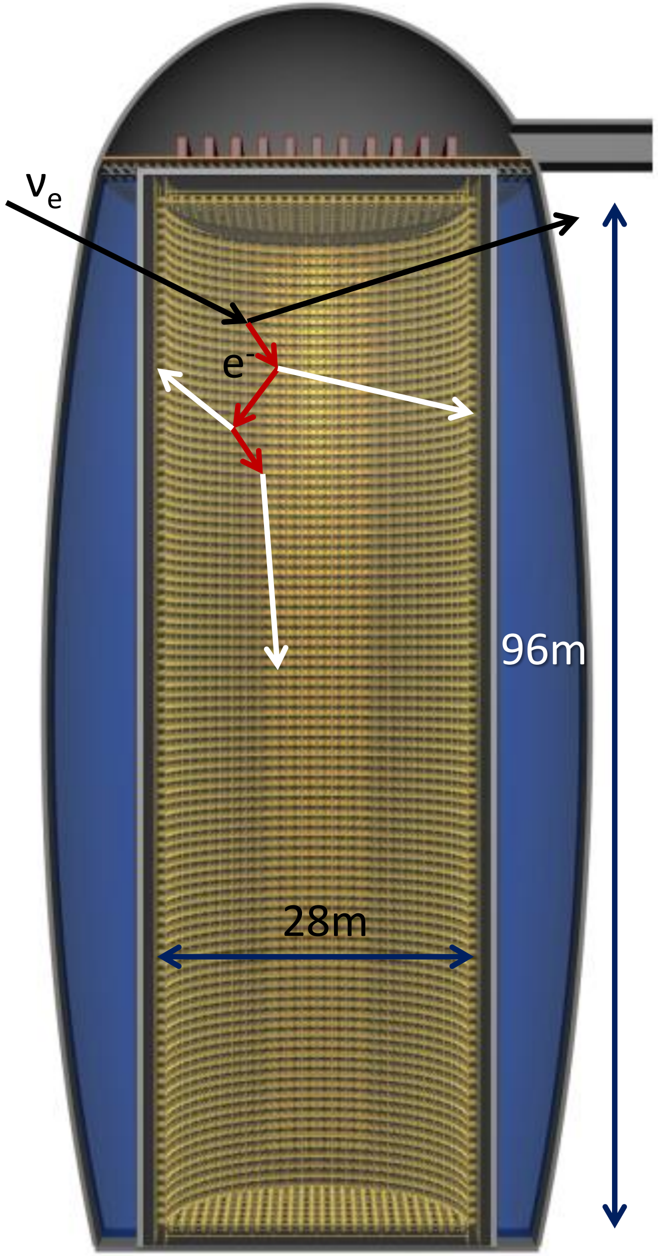








Which demands result from our physics agenda?



- Event detection in liquid scintillator detectors:
  Neutrino scatters off electron
  → Electron freed
    → Loses kinetic energy via excitation of scintillator molecules
      → Emit light at deexcitation
- Low interaction cross-section
  → Big active volume
    → Big surface (9700m²)
- Deposited energies: 200keV - ≈20GeV
  → 700 - $60 \cdot 10^6$ photons arriving at photosensor surface
- Low energies:
  Only energy of event available to distinguish neutrino sources
- High energies (e.g. neutrino beam):
  Also directionality
- Background (radioactivity inside + outside of detector, atmospheric muons, …); neutrino beam
  → Event reconstruction

Sensor requirements:

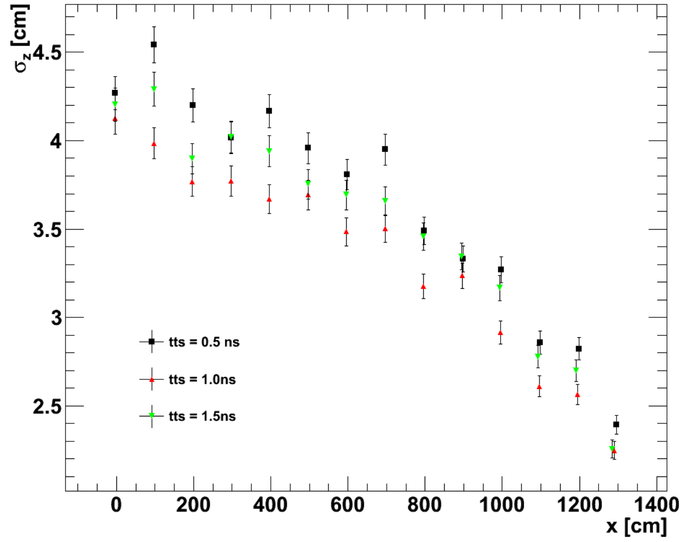
- sensitive around 420nm
- pressure-withstanding, long-term reliability
- low price/detector area
- single photon detection, high detection efficiency, large dynamic range
- good energy resolution
- low fake detections: dark count, afterpulsing good time resolution
- low radioactivity

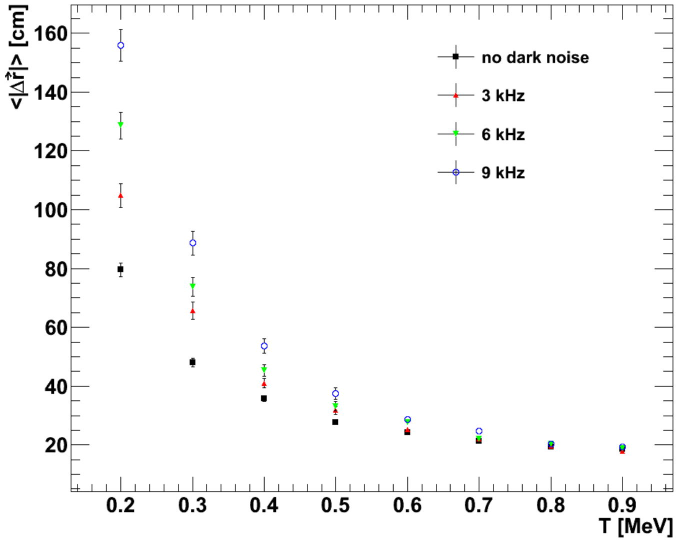
How can we obtain limits for the sensor requirements?

- First estimate through comparison with previous liquid scintillator experiments (Borexino, KamLAND, DoubleChooz)
- Improve values of limits via geant4 Monte Carlo simulations
  - Determine influence of sensor properties on overall detector behavior
  - If detector properties needed to achieve physics goals are known → can infer demands on sensor

- MC studies in progress, first results:
  - Position and energy resolution (Dominikus Hellgartner)
    - Timing uncertainty:
      - First simulations, still fighting some problems with small timing uncertainties
      - First impression: no big influence
    - Dark Noise:
      - No big influence for energies around 1MeV or bigger
      - For 200keV position + energy resolution ≈30% worse

  - α/β-discrimination (Randolph Möllenberg)
    - Dark Noise:
      - Strong influence on efficiency
    - Late Pulses + Fast Afterpulses
      - Negligible effect
    - Winston Cones (50° opening angle)
      - Improve separation by a factor of two





LENA photosensor requirements

Property	Current limit
Timing uncertainty (single photoelectrons(spe), FWHM)	<3.0ns
Early pulses	<1%
Late pulses	<4%
Quantum efficiency @420nm	>21%
Optical coverage, using 1.75x light concentrators	30%
Dynamic range	spe→0.3pe/cm²
Gain (PMTs)	$>3\cdot10^6$
Peak-to-valley ratio (spe)	>2
Dark count	< 15Hz/cm²
Slow afterpulses (0.2-200µs)	<5%
Fast afterpulses (0-200ns)	<5%
Pressure resistance	>13bar
^{238}U content	$< 3\cdot10^{-8}$g/g
^{232}Th content	$< 1\cdot10^{-8}$g/g
$^{\mathrm{nat}}$K content	$< 2\cdot10^{-5}$g/g
Lifetime	>30y

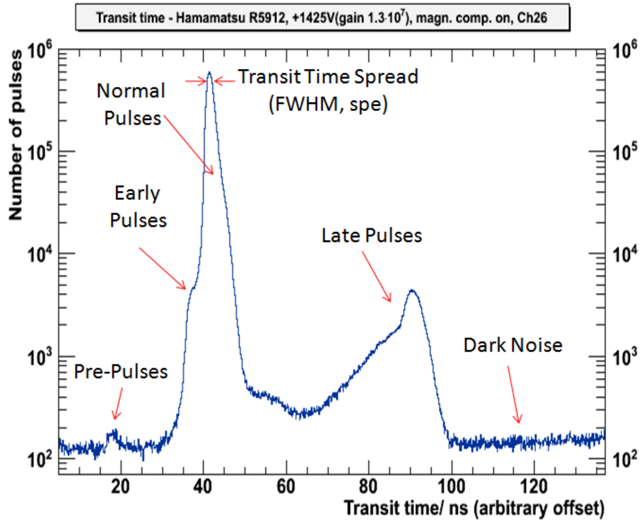
First MC results:

possibly higher value allowed

probably needs to be increased

order of magnitude correct for big sensors; currently simulating with different trigger layout to establish value for SiPMs

can be increased



Most probably PMTs will be the photosensor for LENA

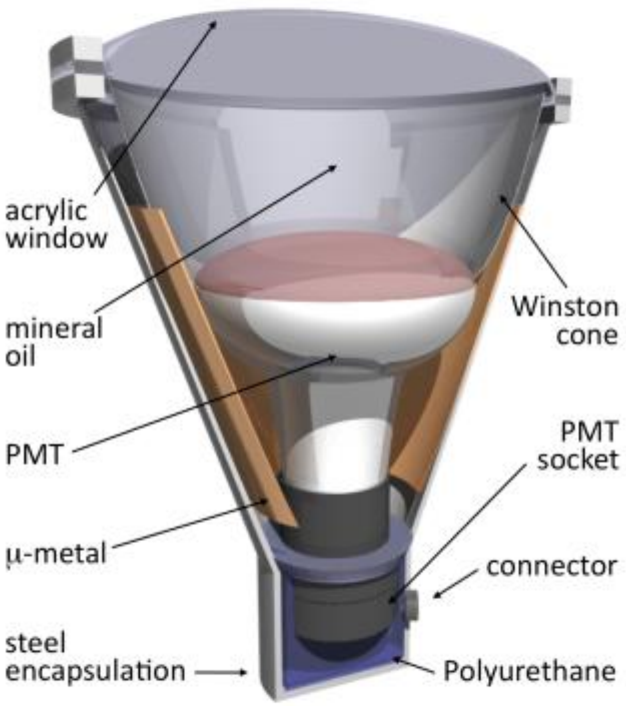
→ What components do we need for optimum performance?

Optical Module

- PMT
- Increase active area + limit field of view
  - → Light concentrator (Winston Cone)
- Shield PMT from earth magnetic field
  - → mu metal
- Power supply
  - → Voltage divider
- Electronics? (Amplifier, signal processing)
- Pressure
  - → Encapsulation, acrylics glass window + stainless steel housing
- During filling, tank is filled with water → conductive
  - → Cast voltage divider into insulator compatible with ultrapure water + liquid scintillator: polyurethane
- Need to shield scintillator from radioactive contamination contained in the PMT's glass → layer of inactive buffer liquid between scintillator and PMTs

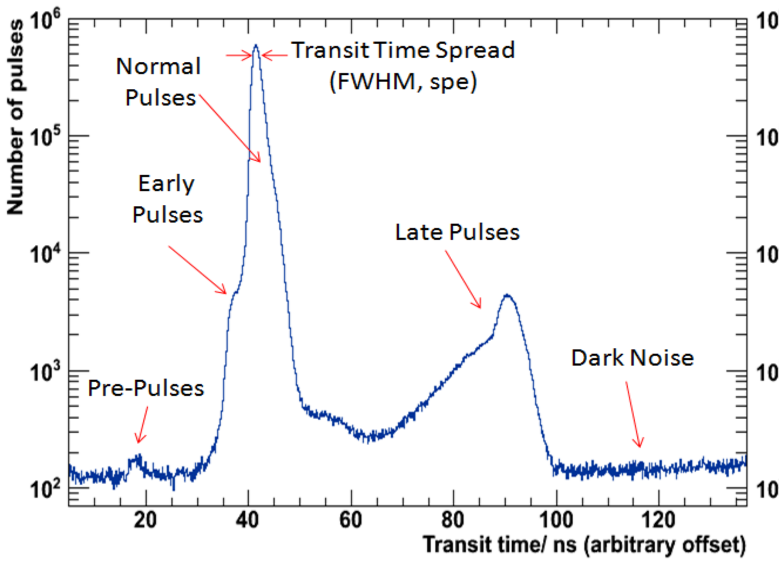
New design: include buffer liquid into pressure encapsulation

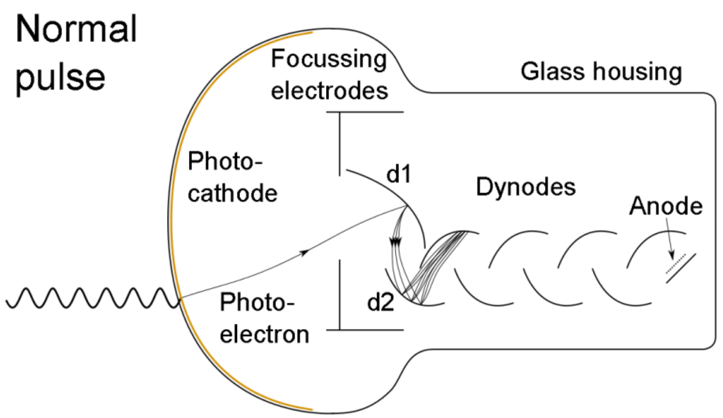
→ Bigger active volume!

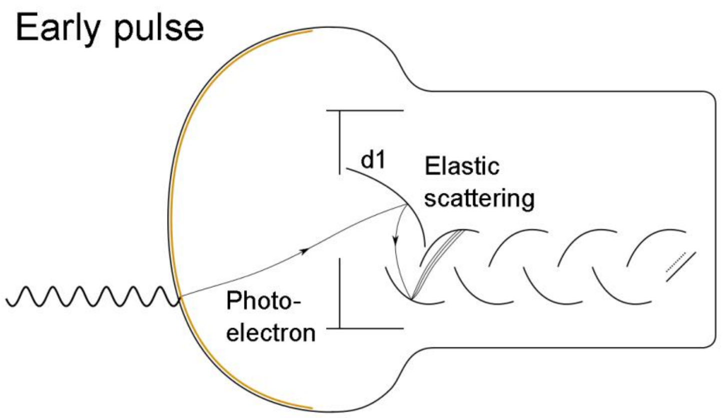


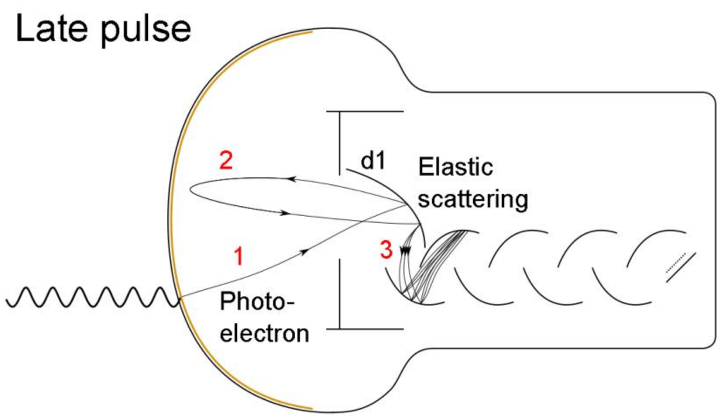
Disruptive effects on timing

- Elastic scattering on first dynode
  probability: ≈10%
  - Early pulse: scattered onto second dynode
    - Early by a few ns (8“ PMT: ≈5ns),
    - Pulse smaller by factor 3-4
  - Late pulse: scattered towards cathode
    - Late by ≈2·drift time from cathode to first dynode (8“ PMT: ≈50ns)
    - Normal height
  - Backscattering losses: Crashes into focussing elctrodes/glass ⟶ no pulse





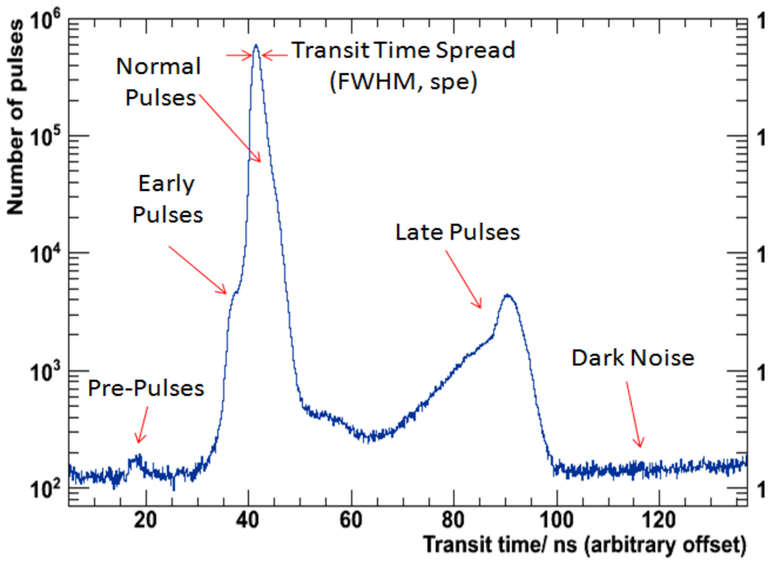




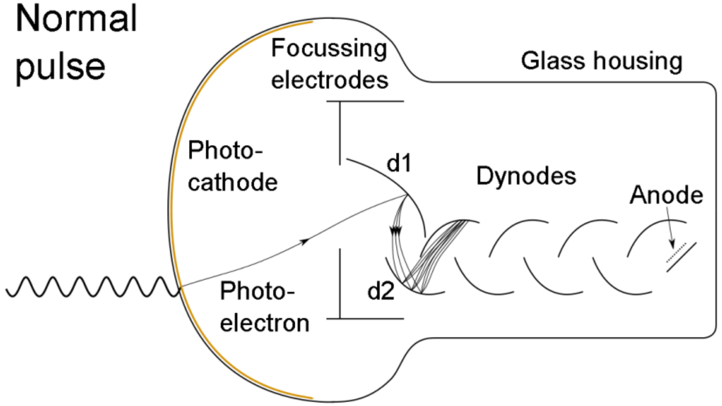
Disruptive effects on timing

- Inelastic scattering on first dynode → part of kinetic energy converted to phonon
  probability: several %
  - Inelastic early pulse: scattered onto second dynode

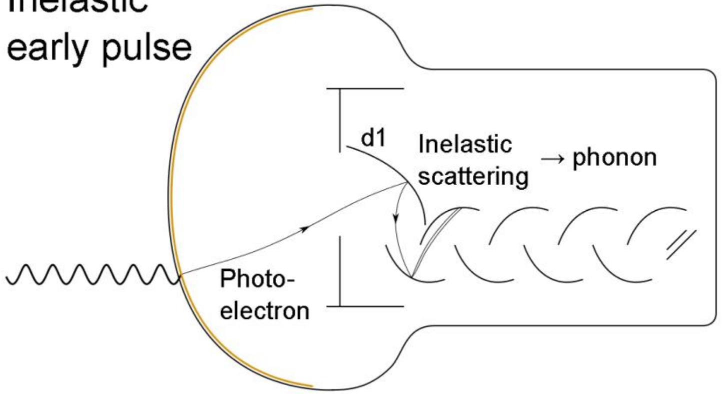
    HYPO-THETIC
    - Early by a few ns, but less than early pulse
    - Pulse smaller by factor >4
  - Inelastic late pulse: scattered towards cathode
    - Late by 0ns - 2·drift time from cathode to first dynode (8“: 0 - 50ns)
    - Pulse smaller



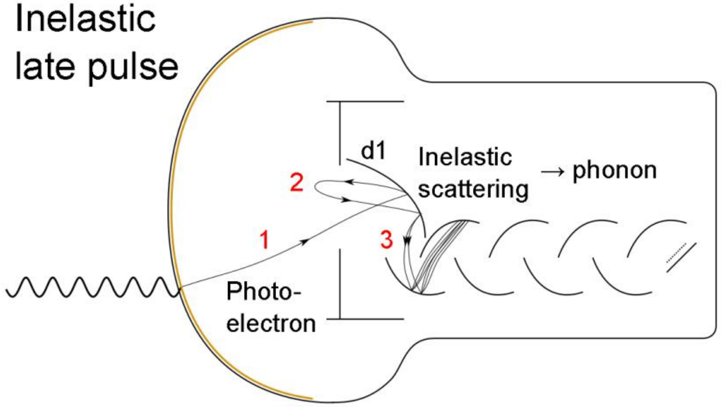
Normal pulse



Inelastic early pulse

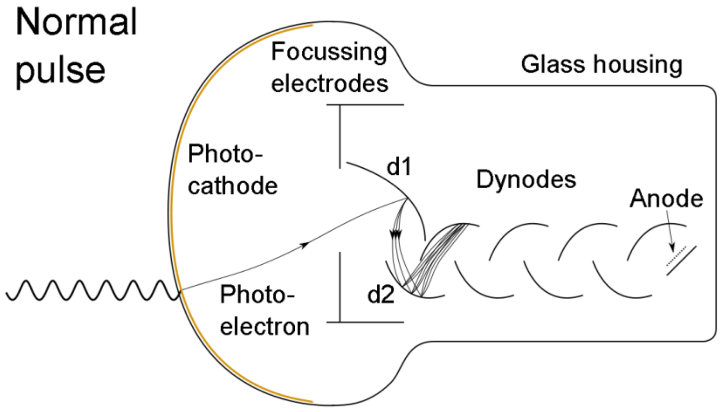


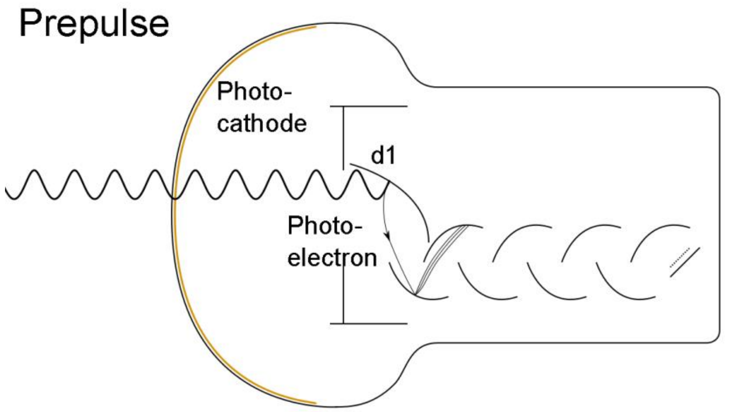
Inelastic late pulse

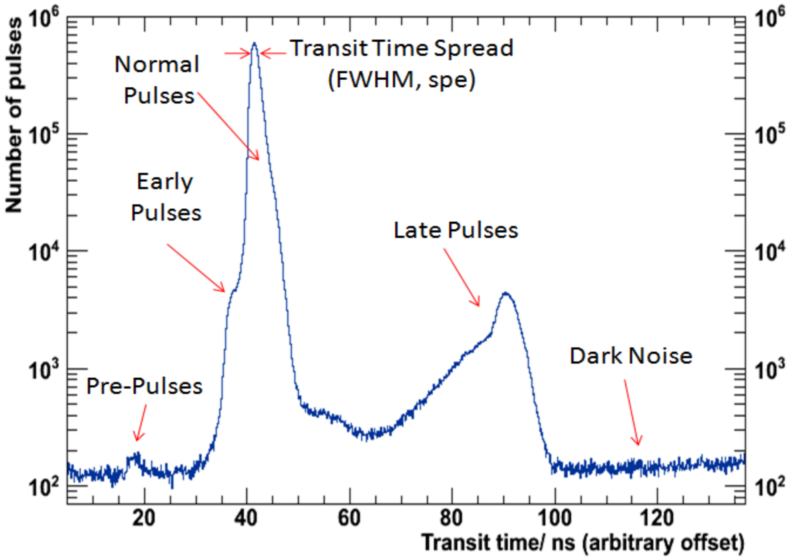


Disruptive effects on timing

- Prepulse: Photon hits first dynode → photoelectron
  probability: ≈ 0.1%
  - Early by drift time from cathode to first dynode (8“ PMT ≈25ns)
  - Pulse smaller by factor 6-10

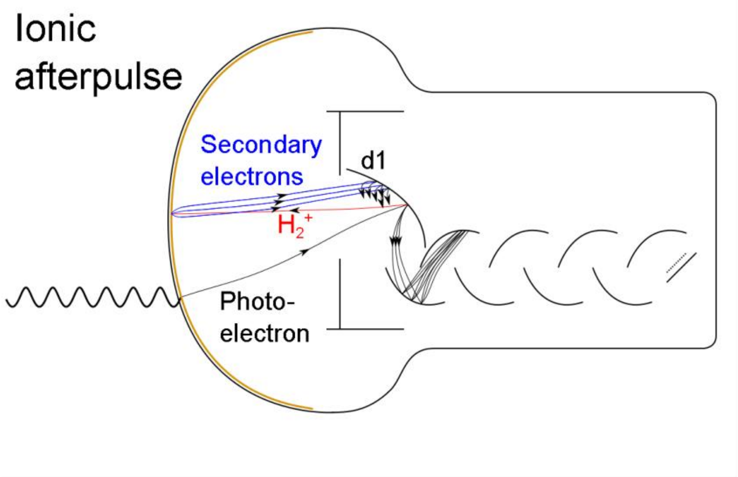






Effects causing afterpulses

- Ionic afterpulse: Electron ionizes + knocks out molecule adsorbed to dynodes → HV accelerates onto cathode or previous dynodes
  - Delay depends on mass + charge (8“: 200ns - 30µs)
  - Height ≈4·normal



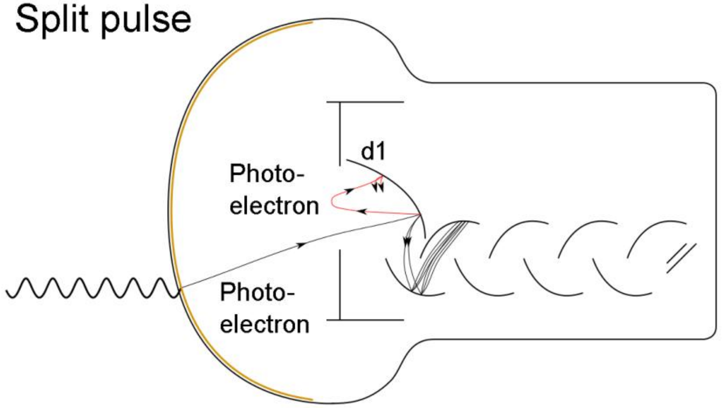
Effects causing afterpulses

- Fast afterpulse: Can occur with delays of several 10ns
  - Split pulses: Photoelectron scatters elastically on first dynode but first produces some secondary electrons → normal pulse with smaller height + late pulse with smaller height
    - Delay = 0ns - 2·drift time (cathode - first dynode)
    - Height ratio correlated to delay
  - Bremsstrahlung of electrons on nuclei in dynodes
  - Fluorescence of materials inside PMT when hit by electron

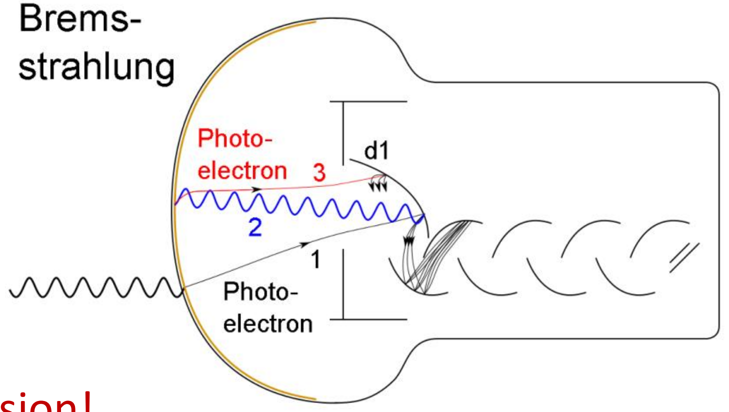
HYPO-THETIC

Light emission!

Split pulse



Brems-
strahlung

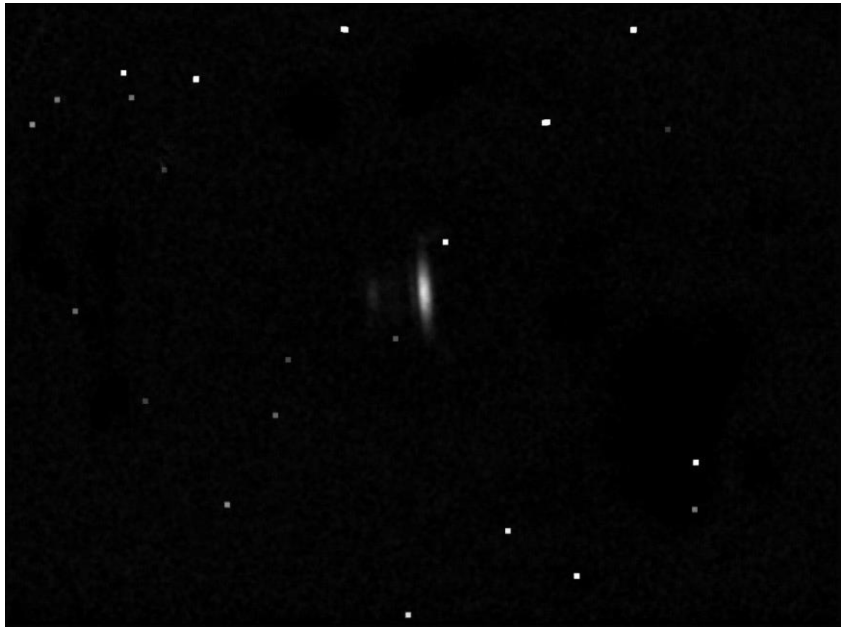


a) Photon hits cathode → afterpulse
   - Late by drift time from cathode to emitting dynode (8“: ≈25-50ns) + delay
   - Normal height

b) Photon hits first dynode → afterpulse
   - Late by drift time from first dynode to emitting dynode (8“: <25ns)
   - Smaller by factor 6-10

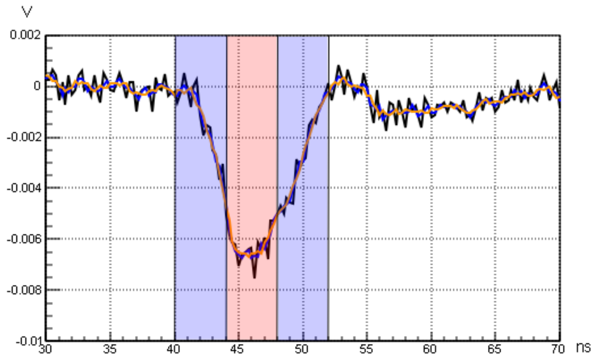
Measurement of light emission: LENA-candidates: R5912 (8“)

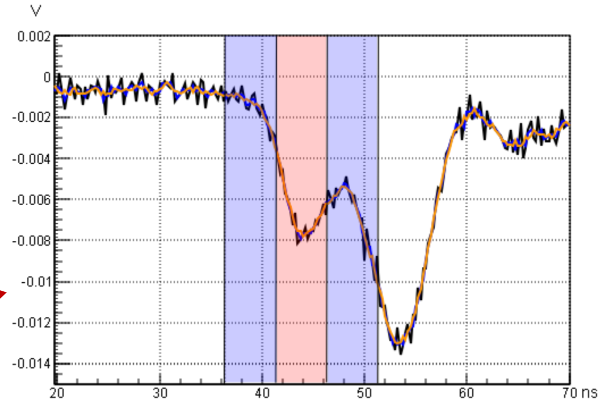
- CCD-camera looking at first dynode
  - Dynode chain encapsulated
    → look on front
  - Again light emission



Measurement of fast afterpulses: Evaluation

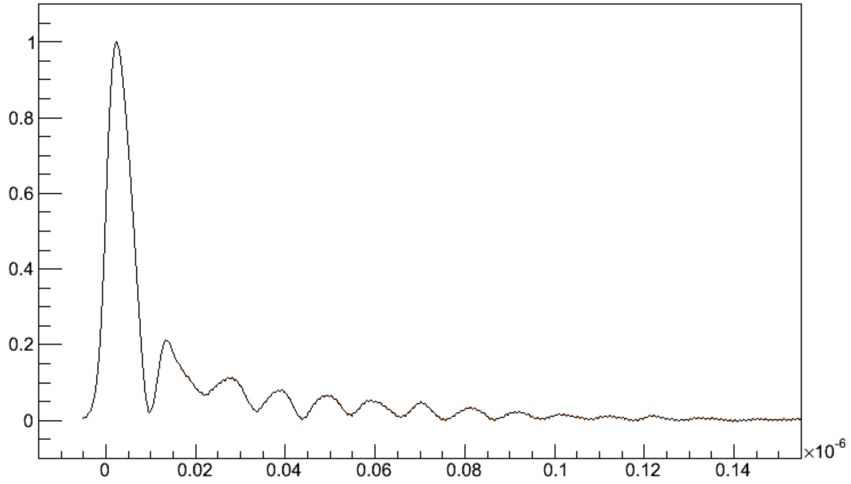
- First 10ns ⟶ determine std. deviation + mean value
- Throw away pulses with muons or noise
- Subtract baseline
- Find primary pulse:
    - Loop over pulse:
      voltage > threshold ⟶ search for maximum
    - Compare three adjacent areas, each containing x datapoints
    - max(central area) > max(other areas)
      ⟶ maximum found
    - Problems:
      Small x ⟶ finds first peak reliably, sometimes runs into fluctuations
      Large x ⟶ doesn‘t run into fluctuations, but sometimes detects pileup instead of first peak
    - Solution: If peak (small x) ≠ peak (big x)
      ⟶ Is valley in between > fluctuations?
      Yes ⟶ pileup, use value obtained with small x
      No ⟶ use value obtained with large x





Measurement of fast afterpulses: Evaluation

- Find afterpulse:
    - Subtract scaled average pulseshape to eliminate first pulse including ringing
    - Remaining maxima = afterpulses
    - Voltage > threshold → afterpulse found

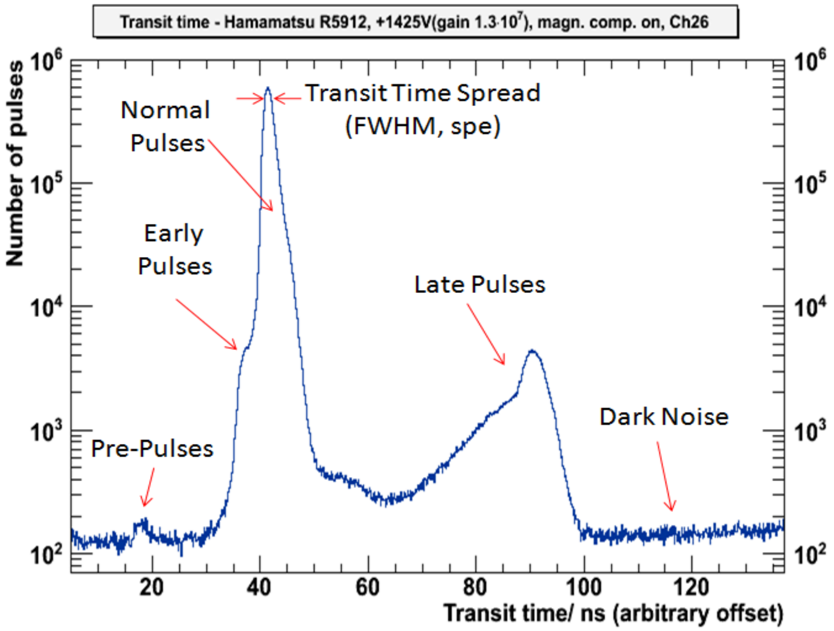


Average pulseform, R5912, +1425V

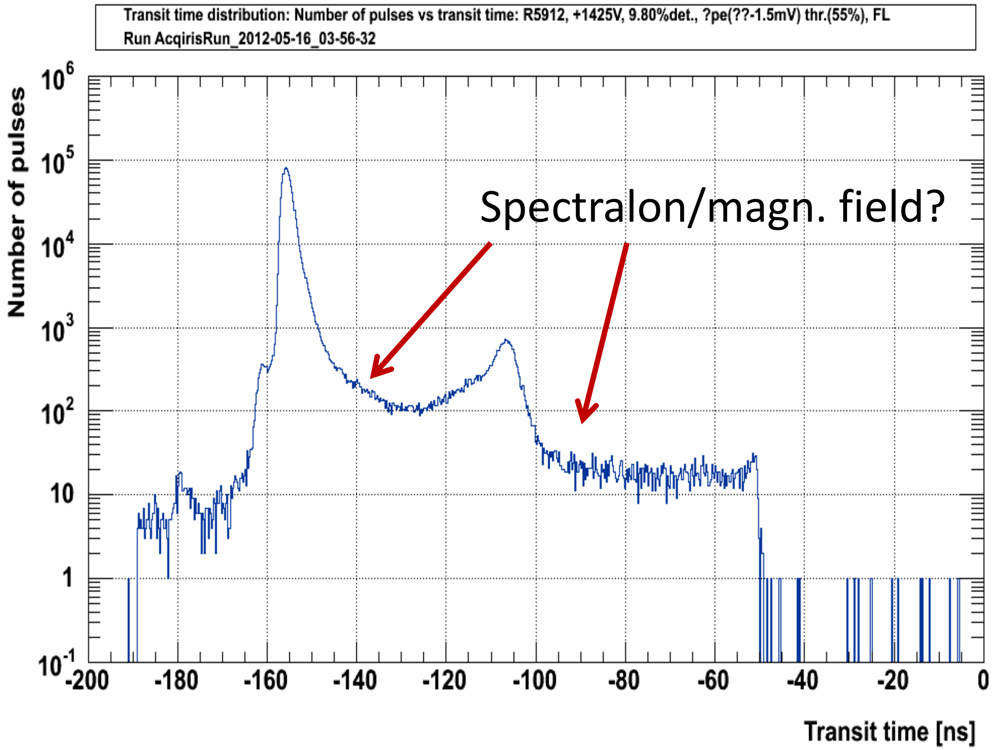
On the following slides:

- R5912 (8“), +1425V, gain 10^7
- 405nm laser, 16% photons detected / laser trigger
- Threshold 1.5mV (to avoid triggering on noise), for afterpulses 5mV

LENA-candidates: R5912 (8“): Transit time distribution



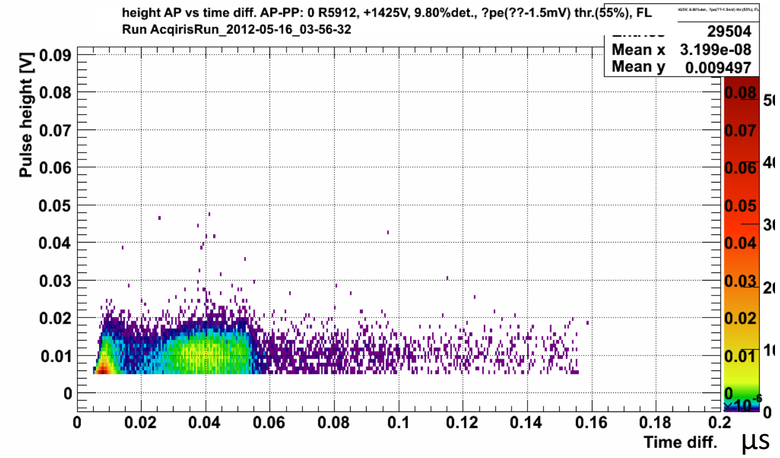
Measurement at LNGS, Italy

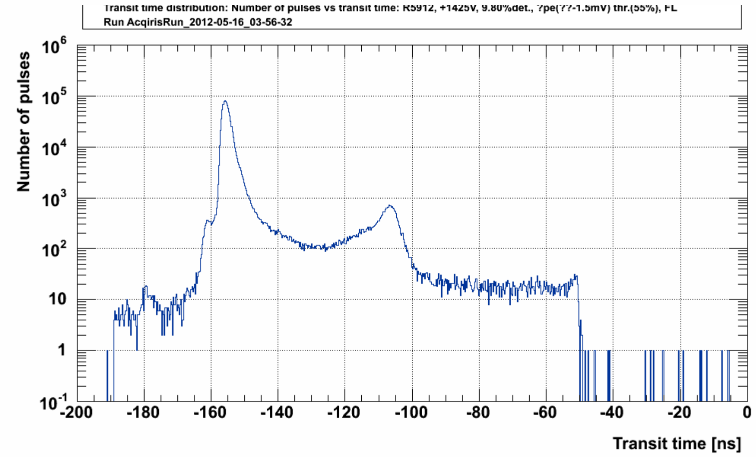


Measurement at MPI Physik

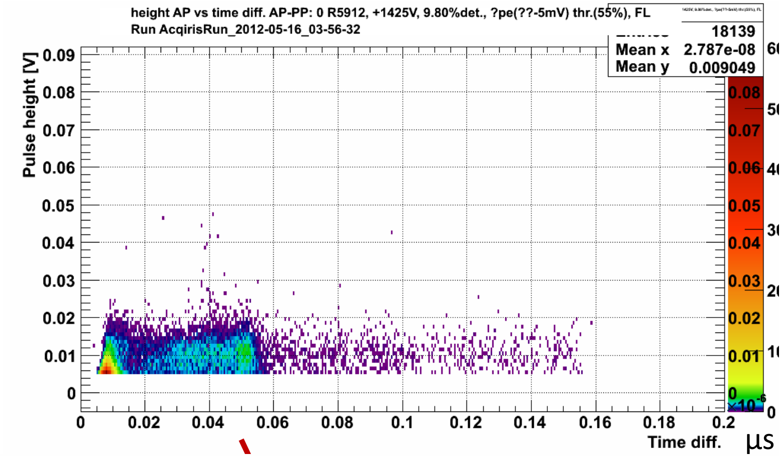
LENA-candidates: R5912 (8“): Fast afterpulses: pulseheight vs. delay

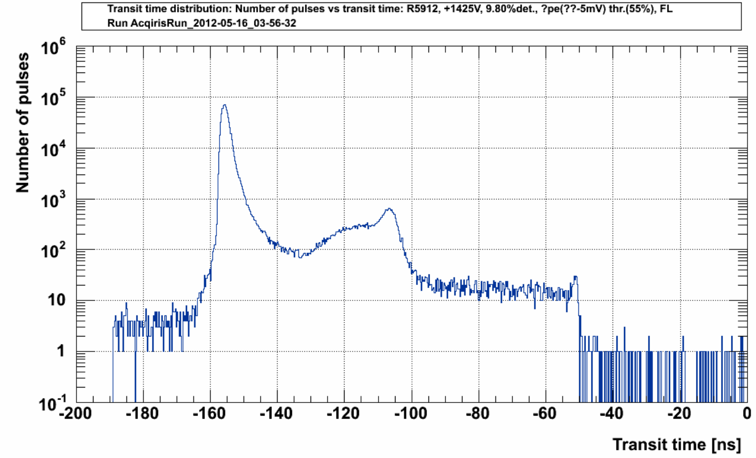
threshold for primary pulse 1.5mV



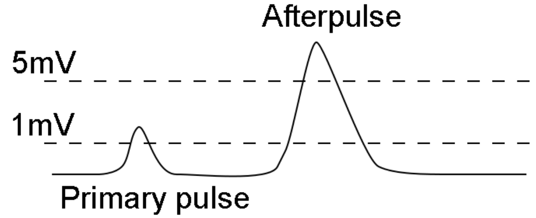


5mV



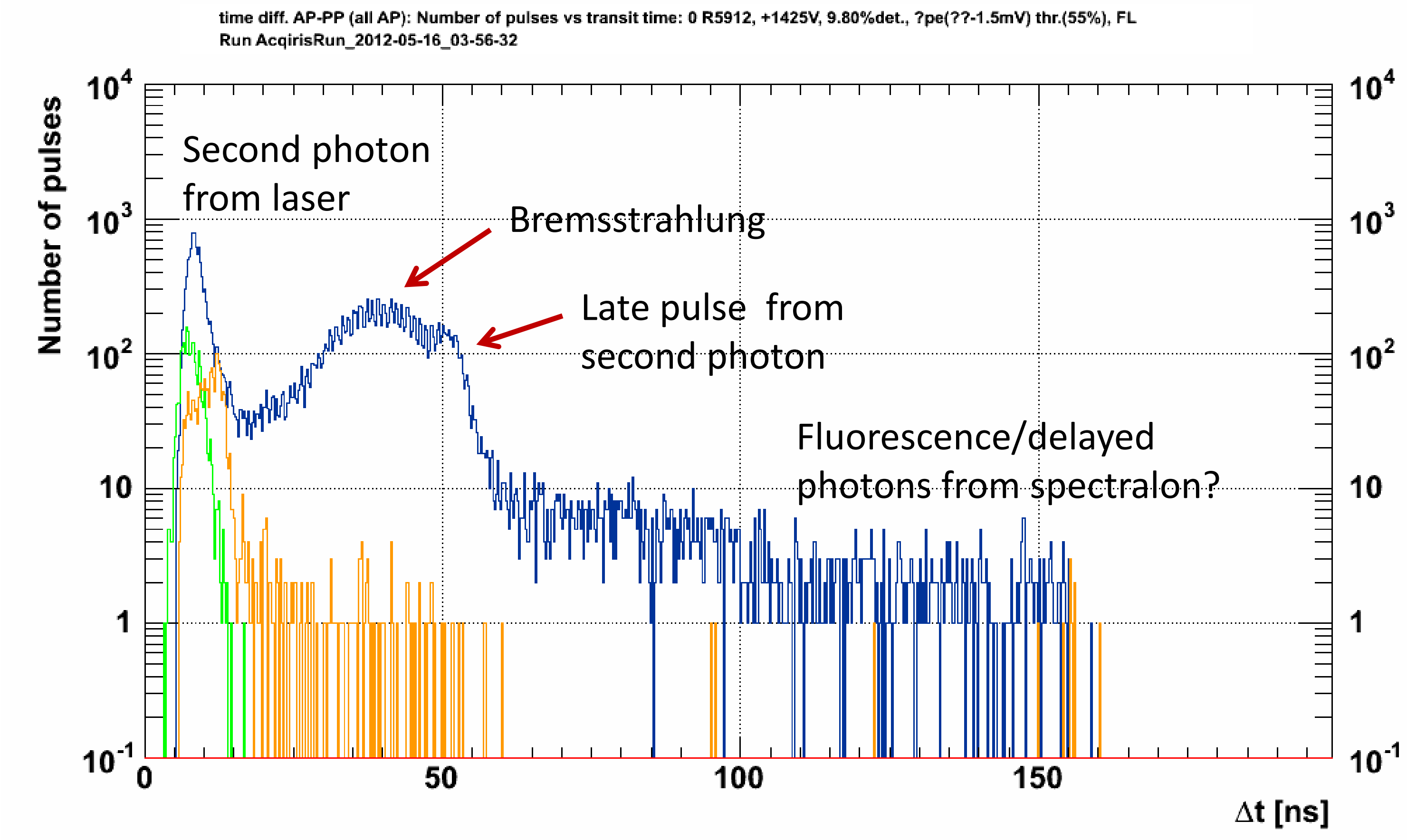


- Threshold for primary pulse higher
  → Small pulses not detected anymore → (big) afterpulse detected instead
  → Afterpulses disappear in afterpulse distribution, appear in transit time distribution



LENA-candidates: R5912 (8“): Time distribution of fast afterpulses

All primary pulses > 1.5mV (0.15pe)



Second photon from laser

Bremsstrahlung

Late pulse from second photon

Fluorescence/delayed photons from spectralon?

Green:	algorithm looking for maximum of primary pulse finds valley
Orange:	absolute maximum in pulseshape > height of primary pulse
Blue:	**subtract primary pulse, voltage > threshold → afterpulse**