Large-area photosensors for neutrino detection using wavelength shifters

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HAP Workshop: Advanced Technologies
KIT
January 24th 2013

Towards a low-energy ν detector

IceCube (build)

- 80 strings, 125m / 16m spacing
- E_{thresh} ~ 100 GeV

  ➔ astrophysical CR-sources

DeepCore (build)

- +6 strings, 72m / 7m spacing
- E_{thresh} ~ 10 GeV

  ➔ WIMPs, neutrino oscillations,...

PINGU (proposal stage)

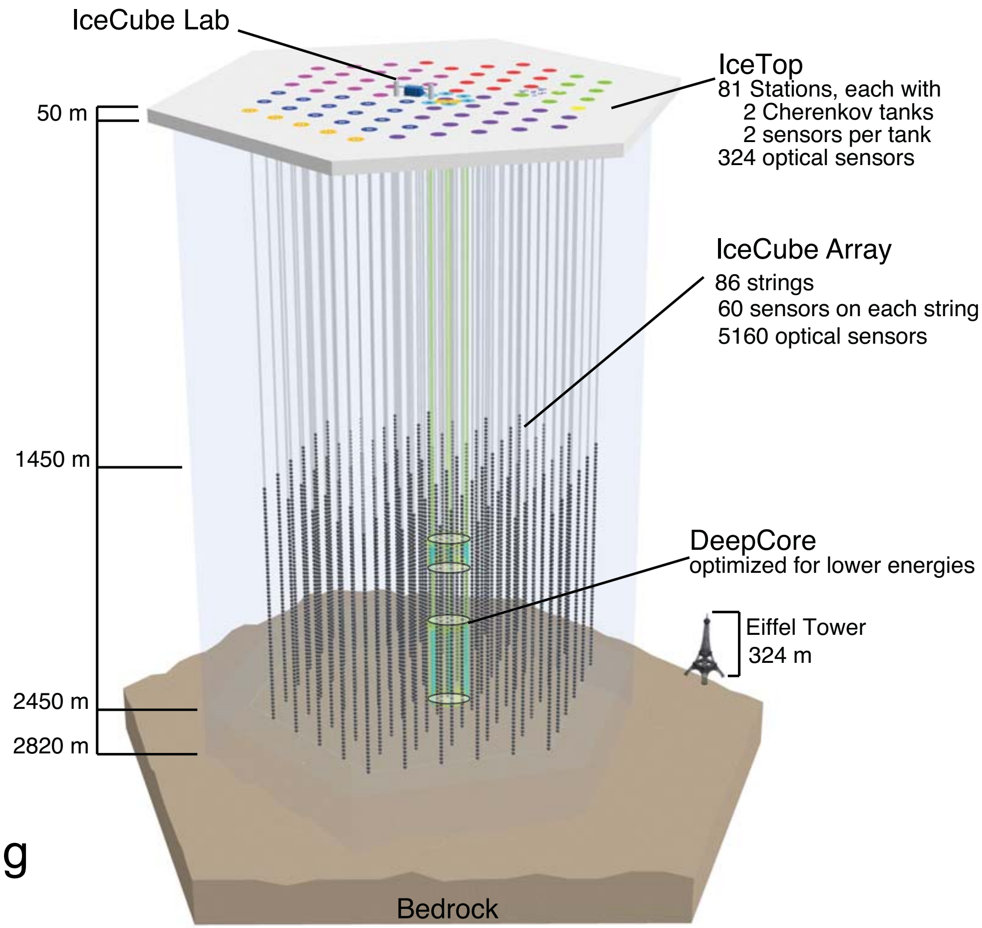
- +20 string, 25m / 4m spacing
- E_{thresh} ~ 1GeV

  ➔ ν mass hierarchy, WIMPs,…

MICA (envisioned)

- +100 strings, 15-25m / 0.5m spacing
- E_{thresh} ~ few MeV

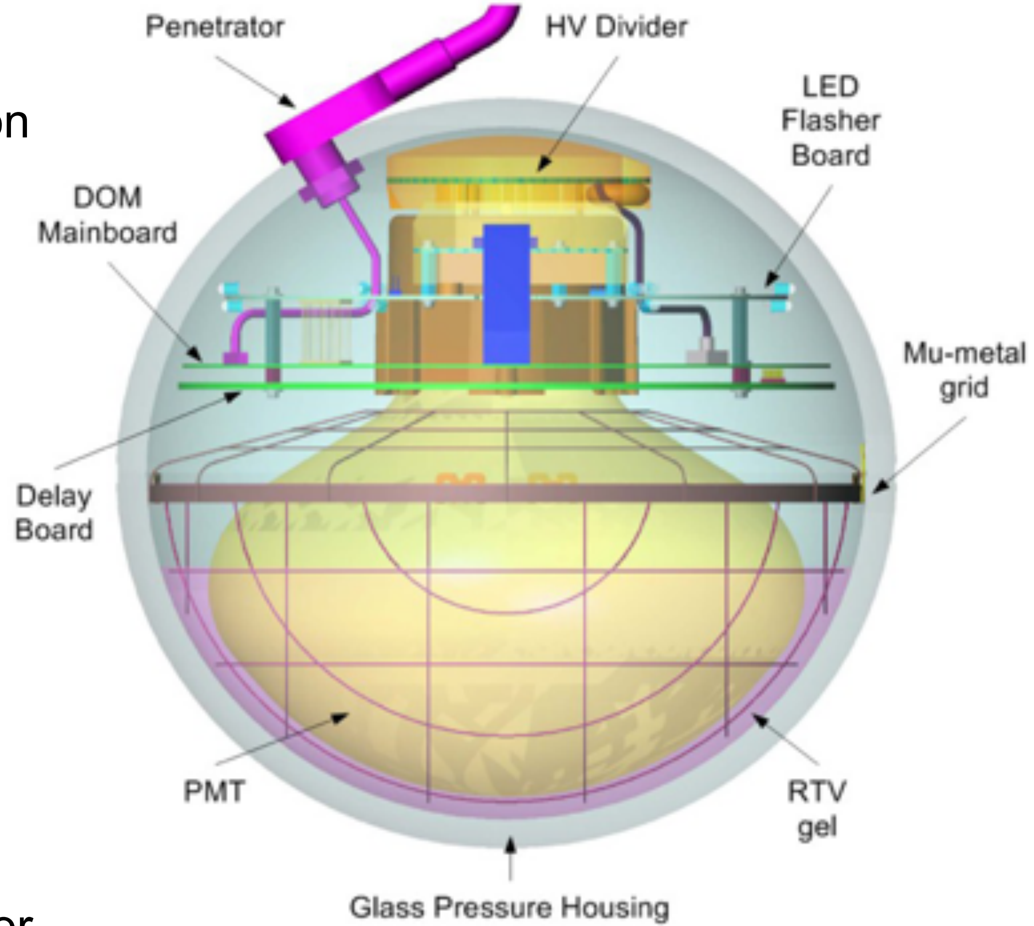
  ➔ Supernova ν, proton decay,...



Motivation

Sensor requirements

- largest photosensitive area
- low noise rate
  - ➔ energy threshold and resolution
- robust
  - ➔ high pressures Ø(kbar)
  - ➔ low temperatures



IceCube optical module

- bialkali photo-cathode
- pressure housing
- digital readout & comms
- A_{eff} ~ $20cm^2$
- f_{noise} ~ 500Hz @ -30ºC
  - ➔ cost ~5k$ / module
  - ➔ size constraint by hole diameter

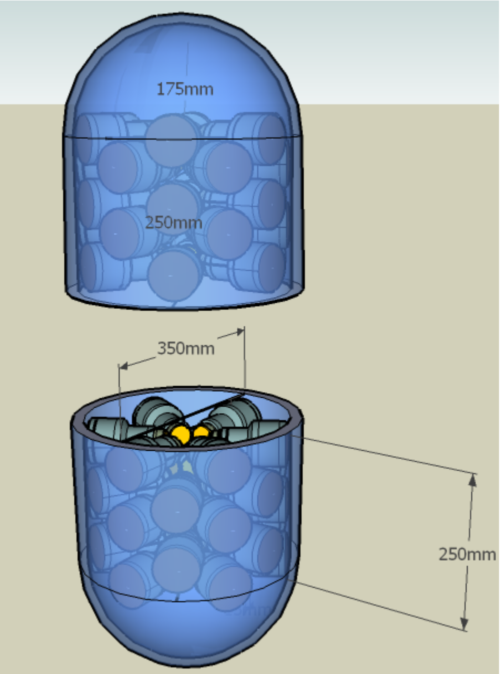
Multi-PMT concept

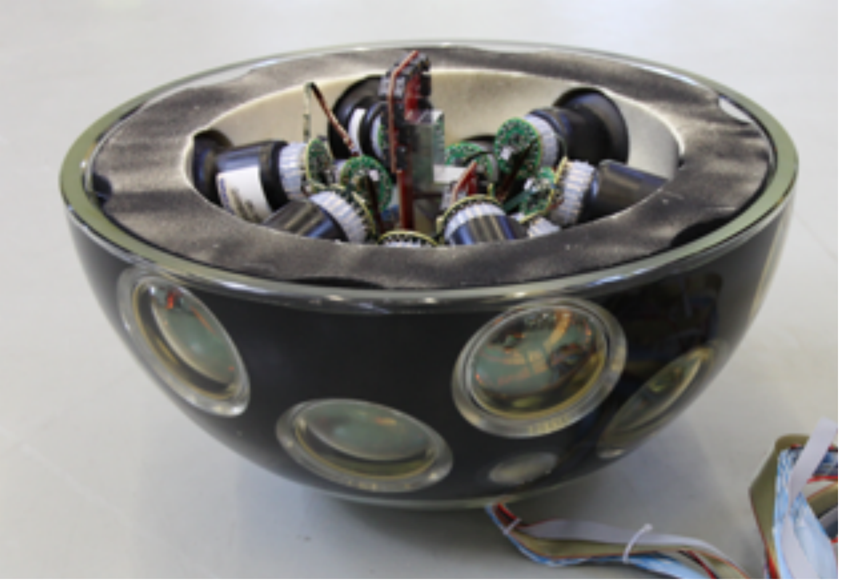
KM3Net

- 17'' pressure sphere
- 31x 3'' PMT
  - ➔ ~3x larger A_{eff}
  - ➔ directional sensitivity

South Pole adaption

- cylindrical pressure housing





But...

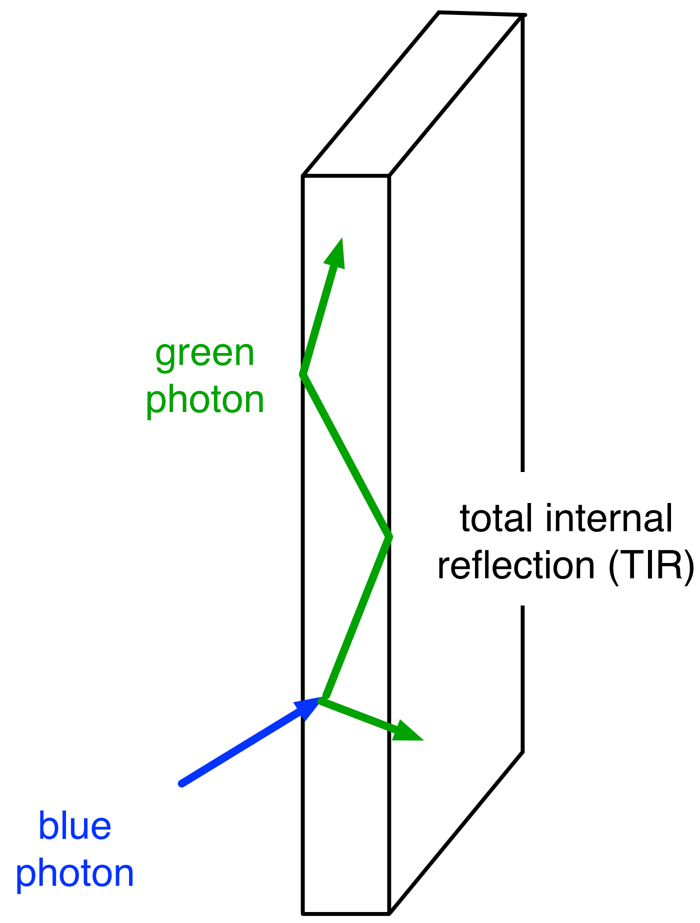
- High noise rate
  - ➔ ~ 1 kHz total
- High power density
  - ➔ Ø(100W) vs. 4W
- Cost
  (scales with photocathode area)
- Complexity
  (readout channels)

Basic concept

- Wavelength shifters (WLS)
  ➔ concentrate light

WLS bars

- large sensitive area
- inexpensive
- low noise rate (< 1Hz/kg)



Wavelength shifting optical module (WOM)

Basic concept

- Wavelength shifters (WLS)
  ➔ concentrate light

WLS bars

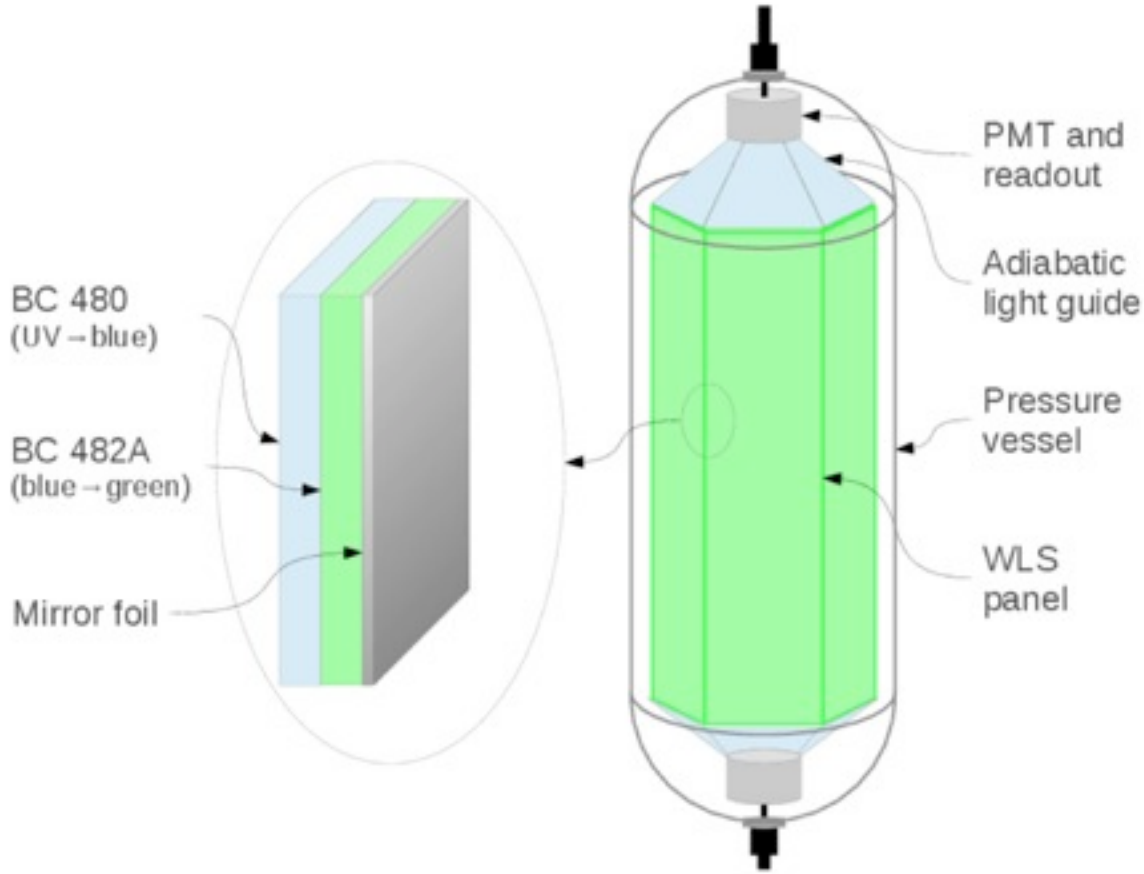
- large sensitive area
- inexpensive
- low noise rate (< 1Hz/kg)

Readout

- small PMT(s)
  ➔ low noise (~ few Hz)

Pressure vessel

- fused silica (quartz)
  ➔ UV transparent
  ➔ low noise (<0.1 Hz/kg)



Tested WLS materials

Ingredients

- active material (wavelength shift)
- carrier (waveguide)

Active Material

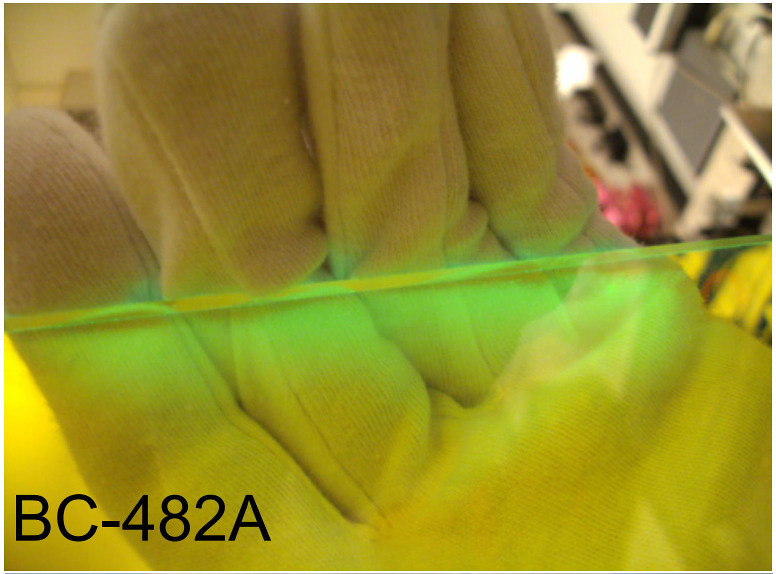
- BC-482A
  ➔ blue to green
- BC-480
  ➔ UV to blue

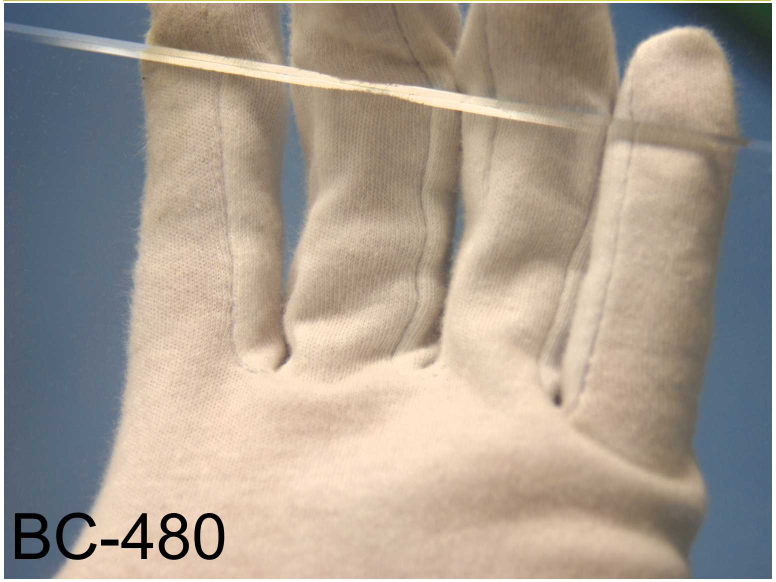
Carrier

- polyvinyltuolene (PVT)
  ➔ not UV transparent

Manufacturer

- Saint-Gobain



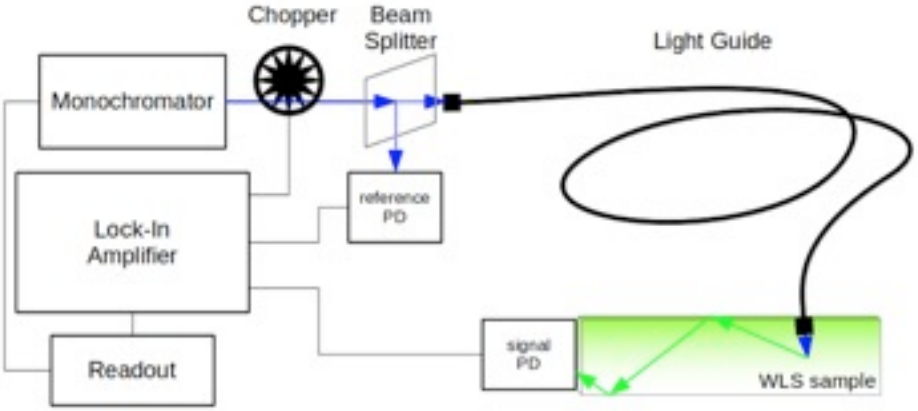


Determining WOM efficiency

Total efficiency

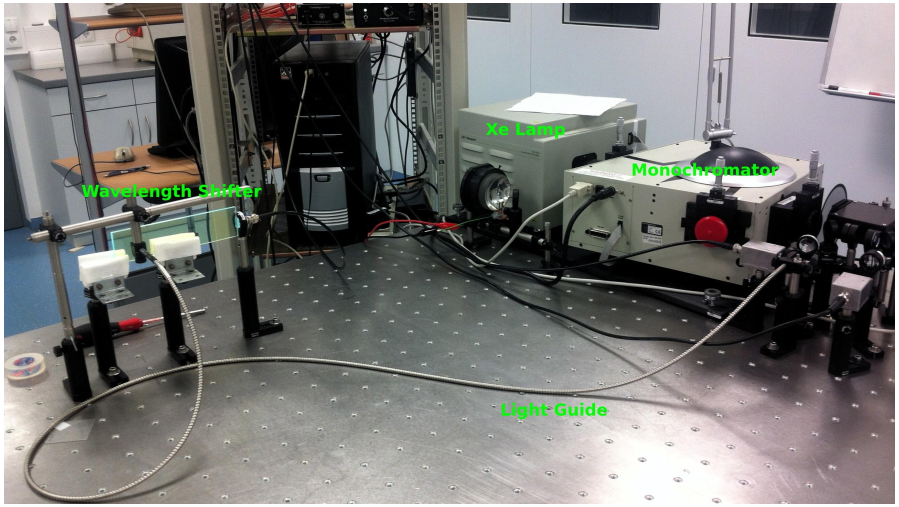
$$\varepsilon_{tot} = \varepsilon_{glass}(\theta) \cdot \varepsilon_{WLS}(\lambda) \cdot \varepsilon_{PMT}(\lambda)$$

- ε_{glass}: glass-air transition
  ➔ calculate (Fresnel)
- ε_{WLS}: capture efficiency
  ➔ lab measurement
- ε_{PMT}: quantum efficiency
  ➔ from manufacturer



Lab setup

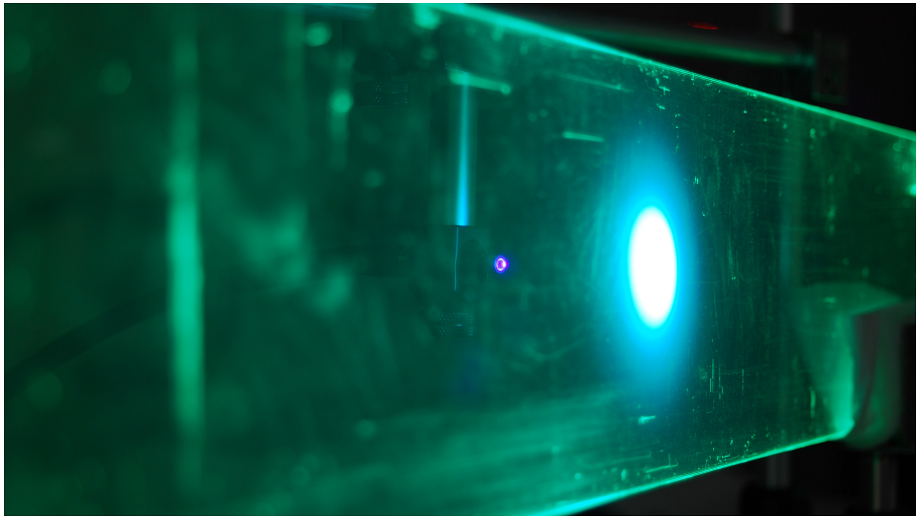
- reference photo diode
  ➔ identical to signal diode
  - relative calibration
- wavelength scan
  ➔ 5-10 min per sample



Results I: Emission spectra

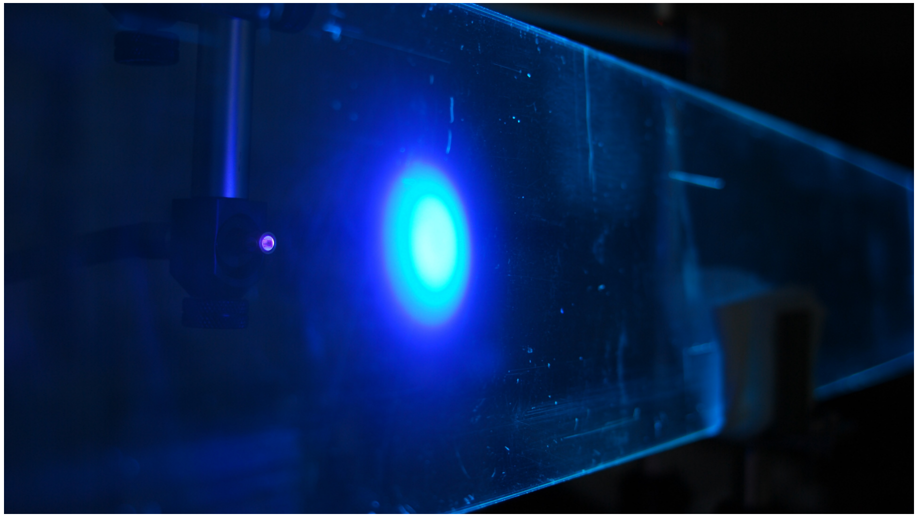
BC-482A

- blue to green



BC-480

- UV to blue



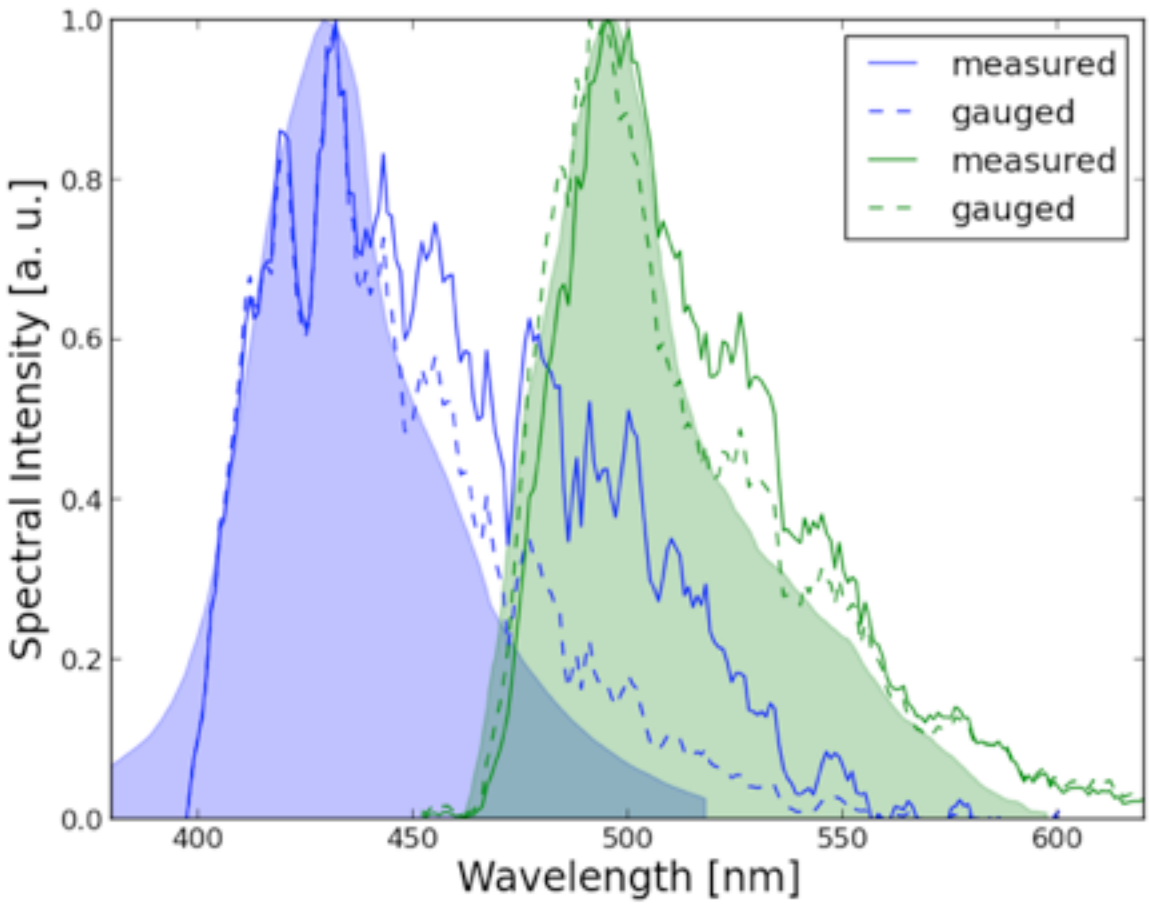
Results I: Emission spectra

BC-482A

- blue to green
- peak at 490nm
  ➔ good match

BC-480

- UV to blue
- peak at 430nm
  ➔ good match



Results II: Capture efficiency

Capture efficiency

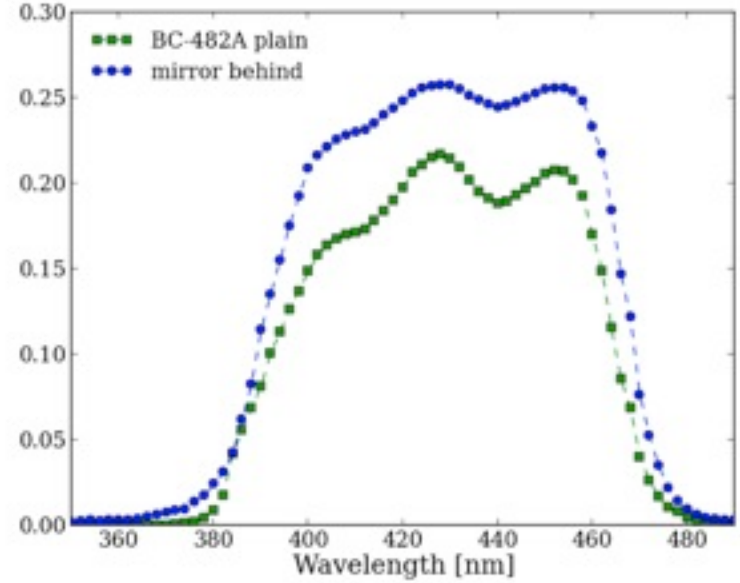
- $\varepsilon_{WLS} = N_\gamma(out) / N_\gamma(in)$
- includes
  - ➔ absorption
  - ➔ quantum efficiency
  - ➔ waveguide losses

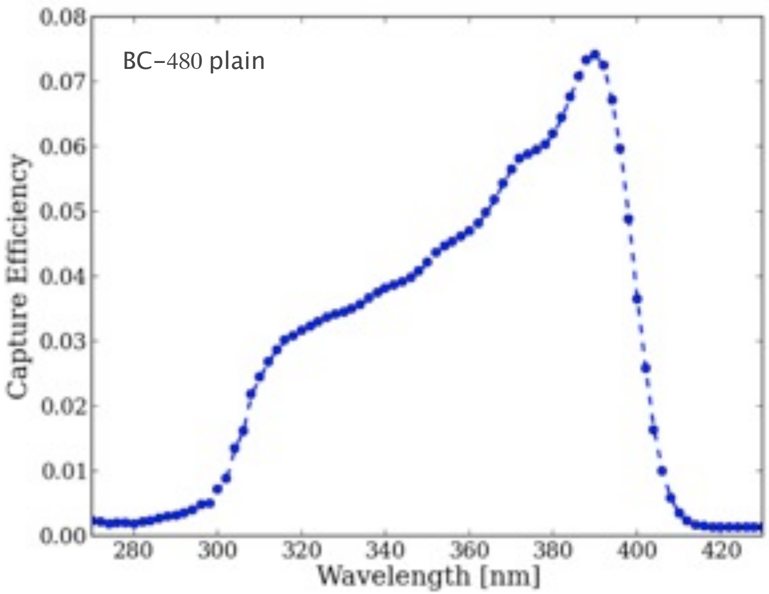
BC-482A

- Measured: $\varepsilon_{WLS} \approx 20\%$
- Toy-MC: $\varepsilon_{WLS} \approx 37\%$
- mirror increases ε_{WLS}
  - ➔ optical thickness low (λ_{abs} = 3.9±0.3mm)

BC-480

- Measured: ε_{WLS}(peak) ≈ 7.8%
  - ➔ absorption in carrier ?

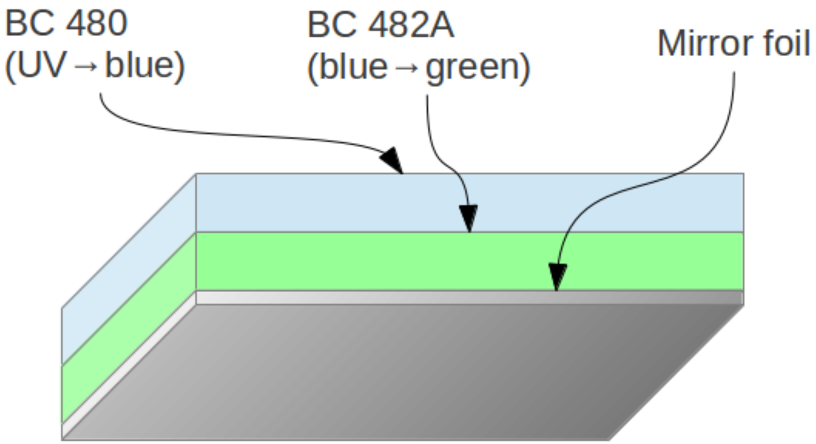




Result III: combined capture efficiency

Sandwich technology

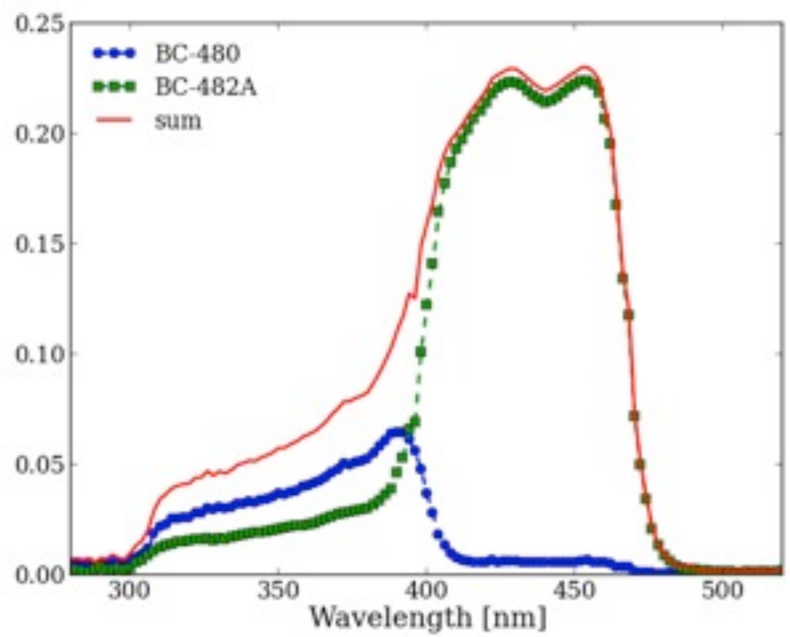
- each WLS acts as individual waveguide
- mirror foil
  ➔ increases optical thickness



Combined efficiency

- sensitivity range
  ➔ 300nm - 480nm

- overall efficiency
  ➔ ε(430nm) reduced due to absorption in BC-480
  ➔ ε(350nm) increased due to double converted photons



Glass vessel

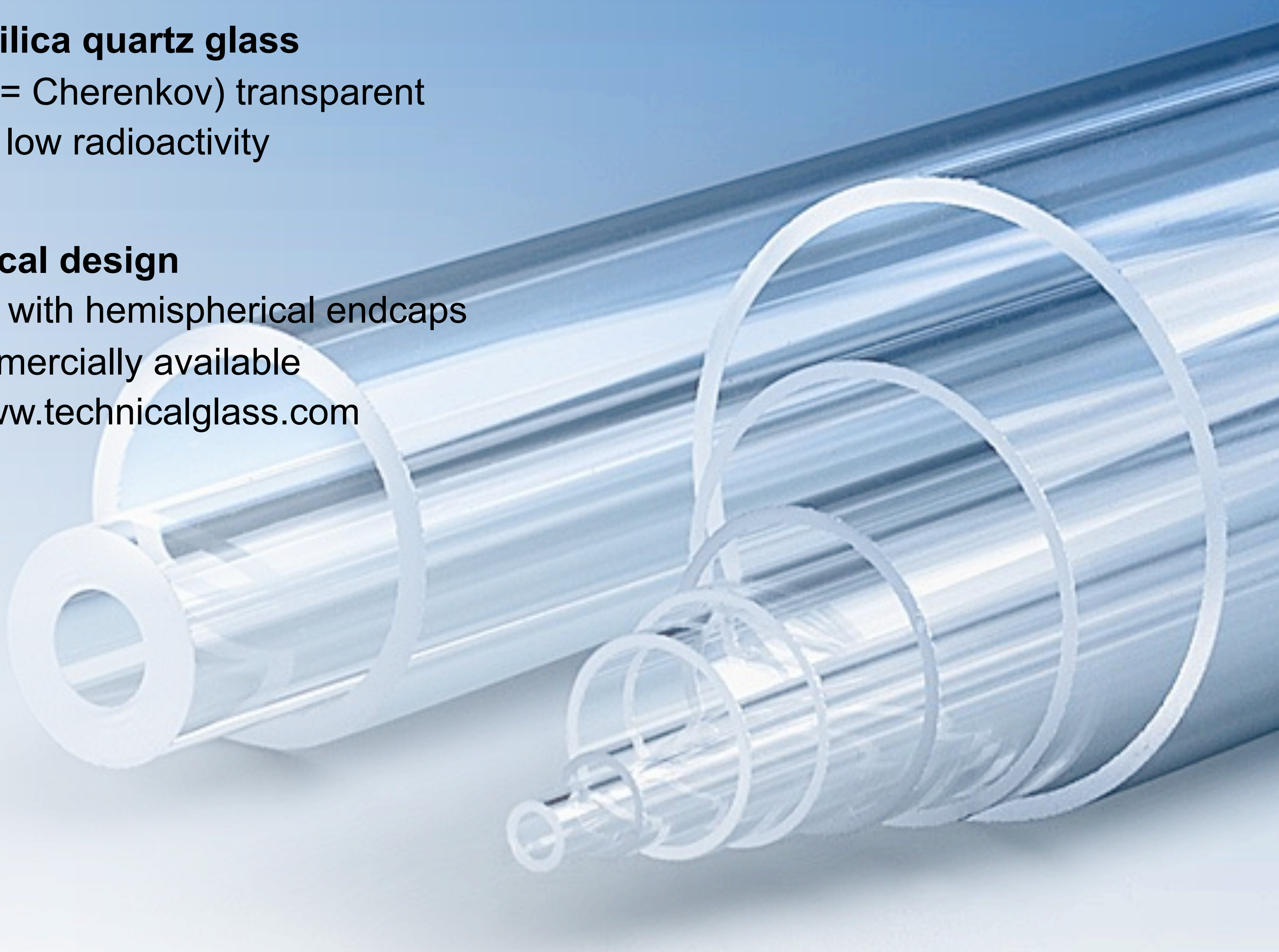
universität bonn

Fused silica quartz glass

- UV (= Cherenkov) transparent
- very low radioactivity

Cylindrical design

- tube with hemispherical endcaps
- commercially available
  ➔ www.technicalglass.com



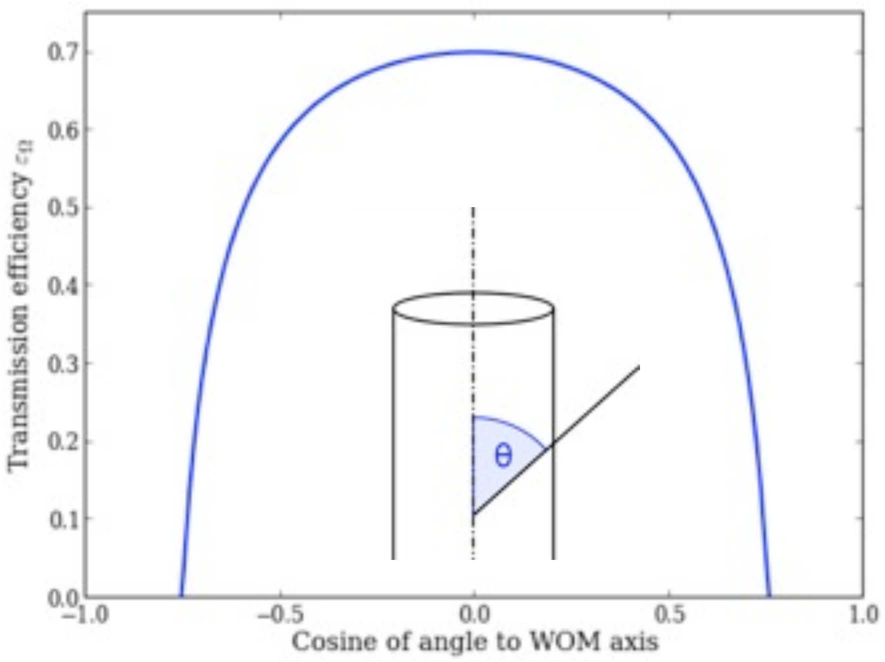
Transmission into WLS

- ice-glass-air transition
  - ice: n = 1.33
  - glass: n = 1.48
  - air: n = 1.0

  ➔ strong directional dependance
- average over all impact parameters

  ➔ peak transmission

  $\varepsilon_{glass}(\theta_{peak}) = 70\%$



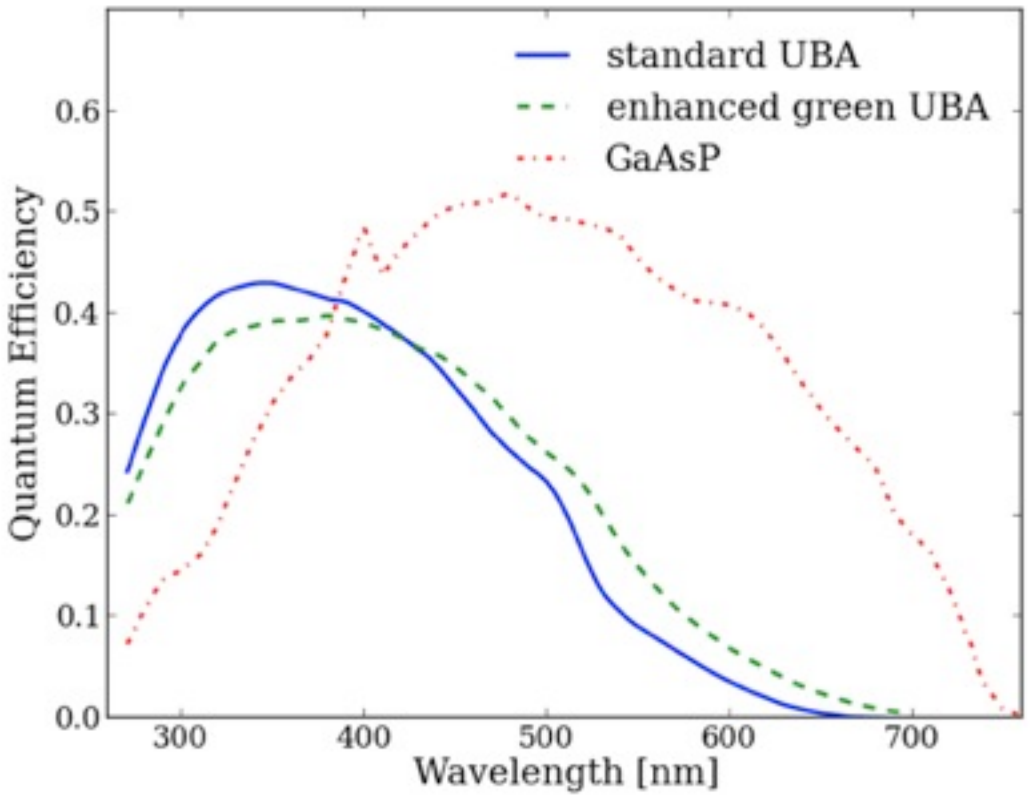
Readout PMTs

Requirements

- high green sensitivity
- low noise

Photocathodes (Hamamatsu)

- Ultra-bialkali (R7600-UBA)
  ➔ off-the-shelf
- 'enhanced green' (R7600-EG)
  ➔ off-the-shelf
- GaAsP (R9792U MHP119)
  ➔prototype for Magic-II
  (limited cathode size)



Overall quantum efficiency

IceCube DOM

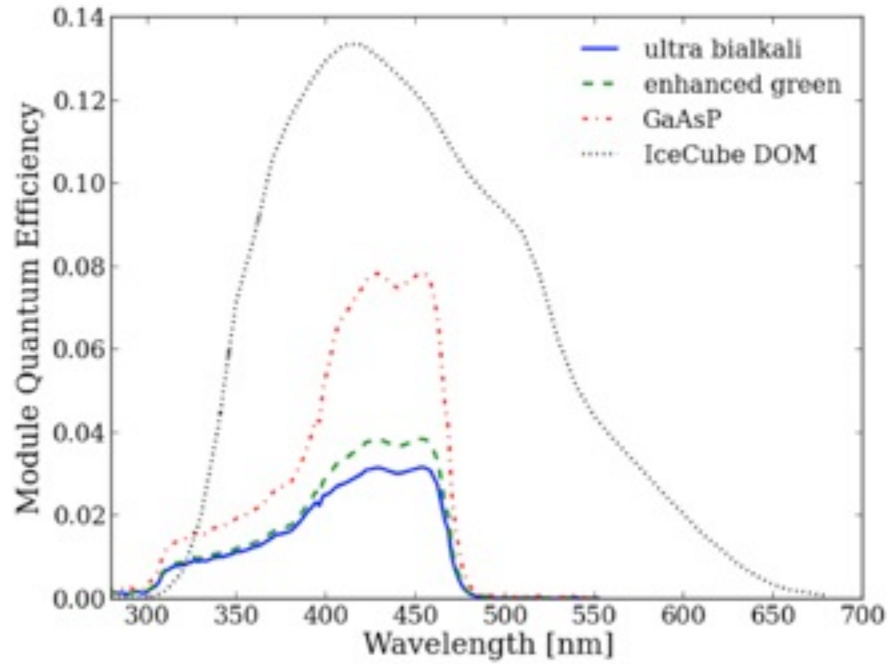
- as built

WOM parameters

- radius = 10cm
- length = 2m
- PMT(2'') = 25cm^2

Effective Area

- Cherenkov spectrum weighted
  ➔ range 300nm - 600nm
- averaged over all incidence angles



Module	Mean QE [%]	Peak QE [%]	A_{eff} [cm^2]	Noise [Hz]
UBA WOM	1..24	3.18	28.1	~ 10
EG WOM	1.43	3.86	32.4	~ 10
GaAsP WOM	2.64	7.86	59.7	10^6
IceCube DOM	7.49	13.4	18.0	800

Time resolution

Toy Monte Carlo

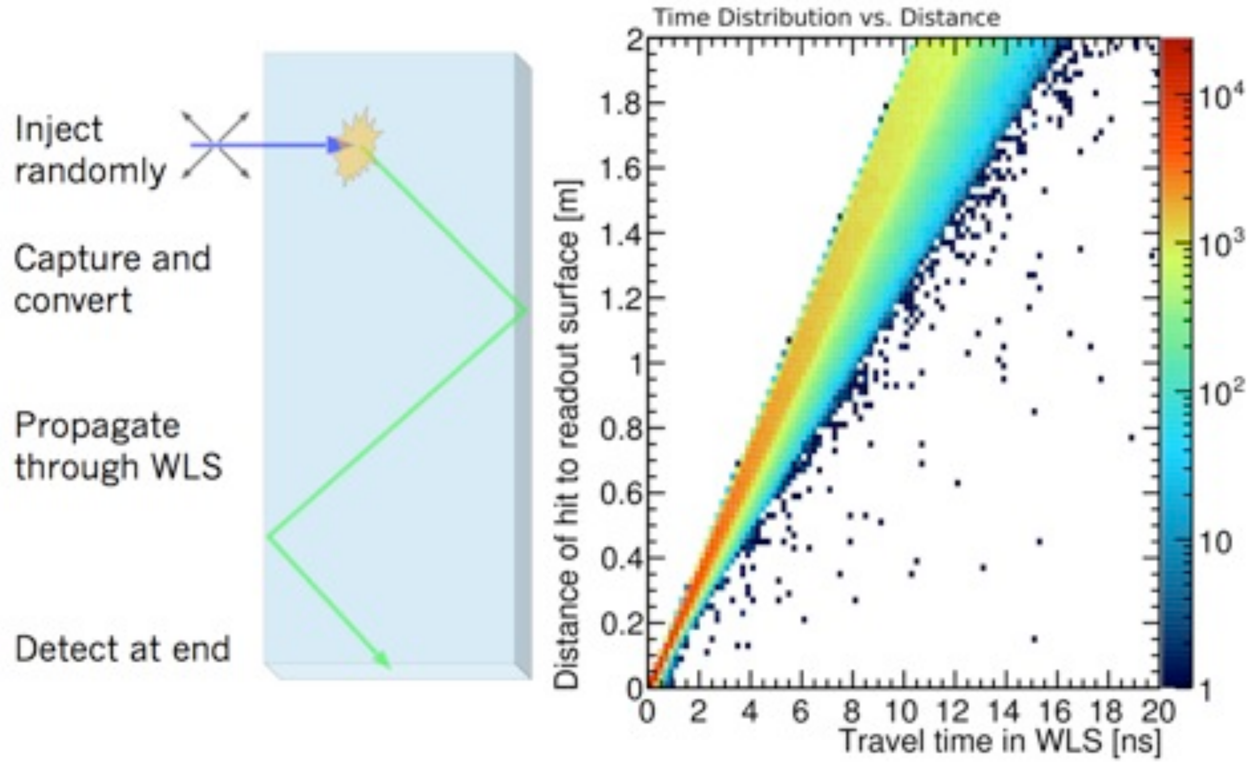
- random incidence
- photon capture
- re-emission
  ➔QE ~ 85%
- propagation

Results

- Capture efficiency (with mirror)
  ➔ε_{WLS} = 35 %
- Time resolution (2m bar)
  ➔RMS(τ) = 2.74 ns

Re-emission time

- 8.5 ns
  ➔dominates over propagation



Prospective developments

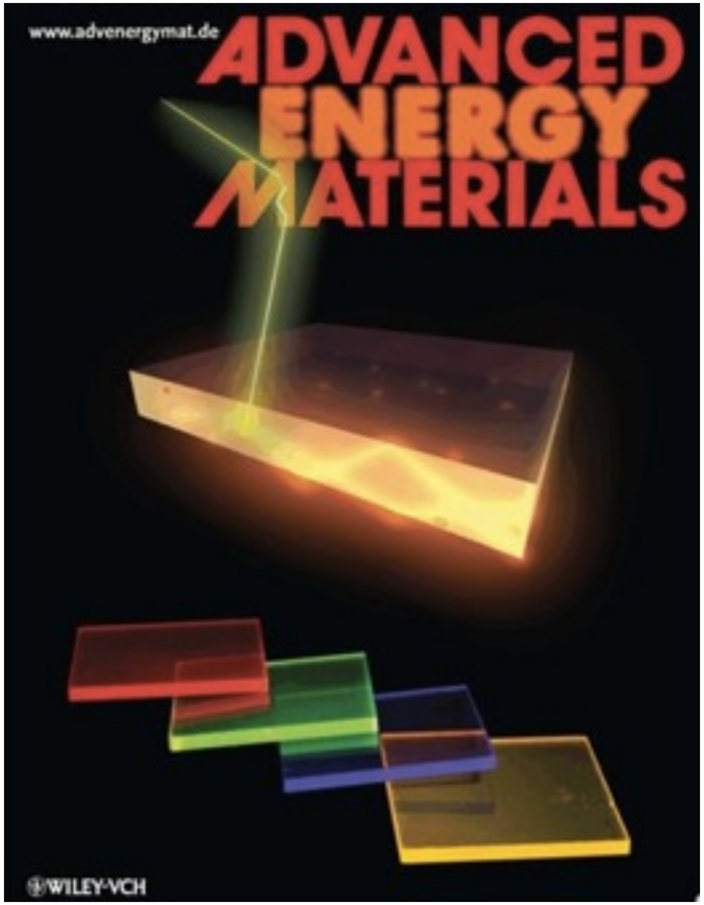
Related research field

- Luminescent solar concentrators (LSC)
  - capture solar light in WLS
  - concentrate on solar cell
  - ➔ solar energy

Explored technologies

- Organic thin films
- Custom made luminosphores
- Alignment of luminosphores
- Selective mirrors
- Quantum Dots
- Geometry
- ….

➔ Can improve A_{eff} by large factor



Technique used to capture solar energy
e.g. Debije & Verbunt, 2011
Baldo et al., Science 2008

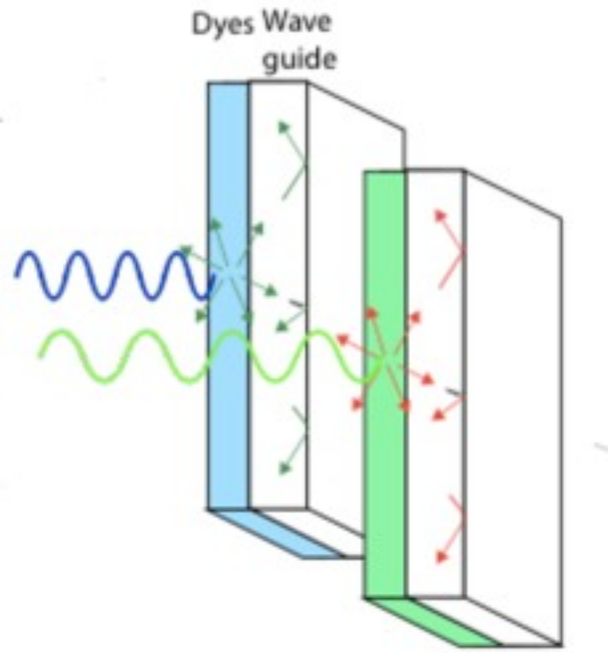
Prospects I: UV extension

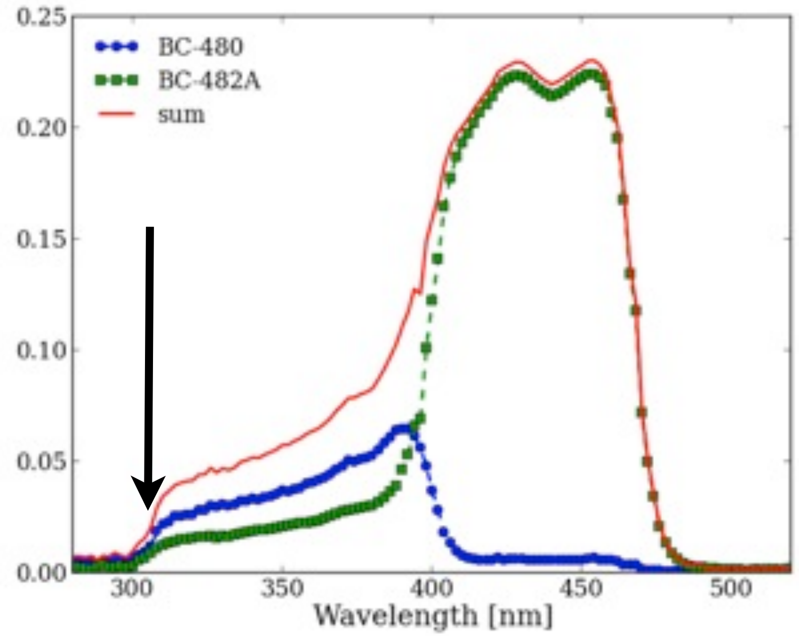
Problem

- PVT (and PMMA) hosts
  ➔ not transparent to UV light

Solution

- thin WLS film on clear light guide
  ➔ avoid absorption





Prospects II: reabsorption

Problem

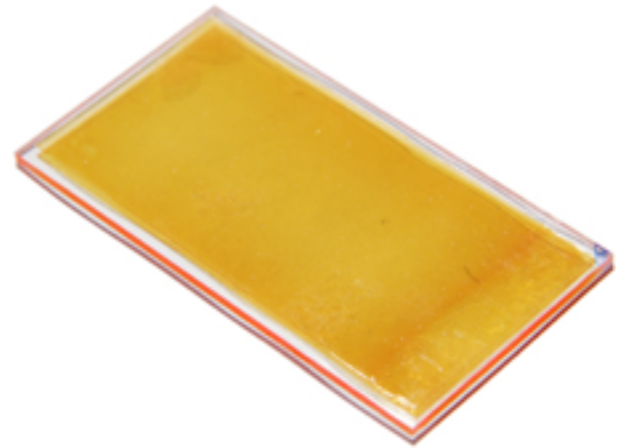
- shifted photons reabsorbed in dye

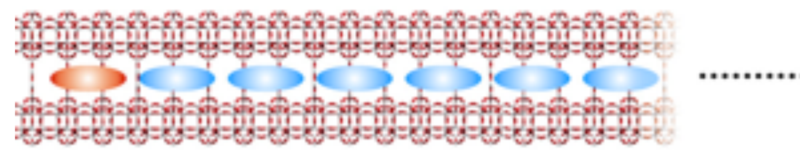
Solution

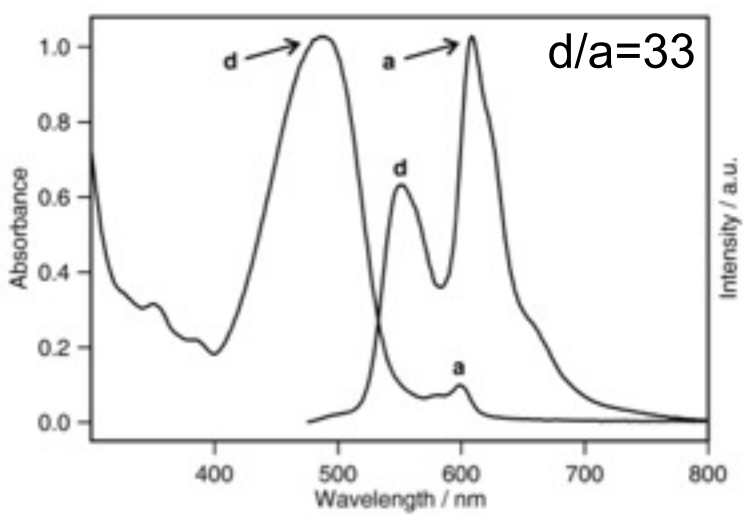
- dyes arranged in zeolite nanotubes
- Förster Resonant Energy Transfer (FRET)

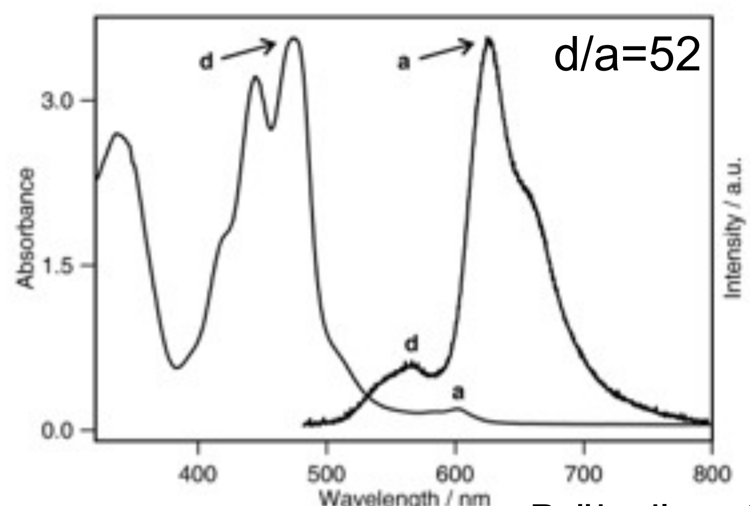
  ➔Luminophores with taylored stokes shift
- commercially available

  ➔ ZeoFRET http://www.optical-additives.com/



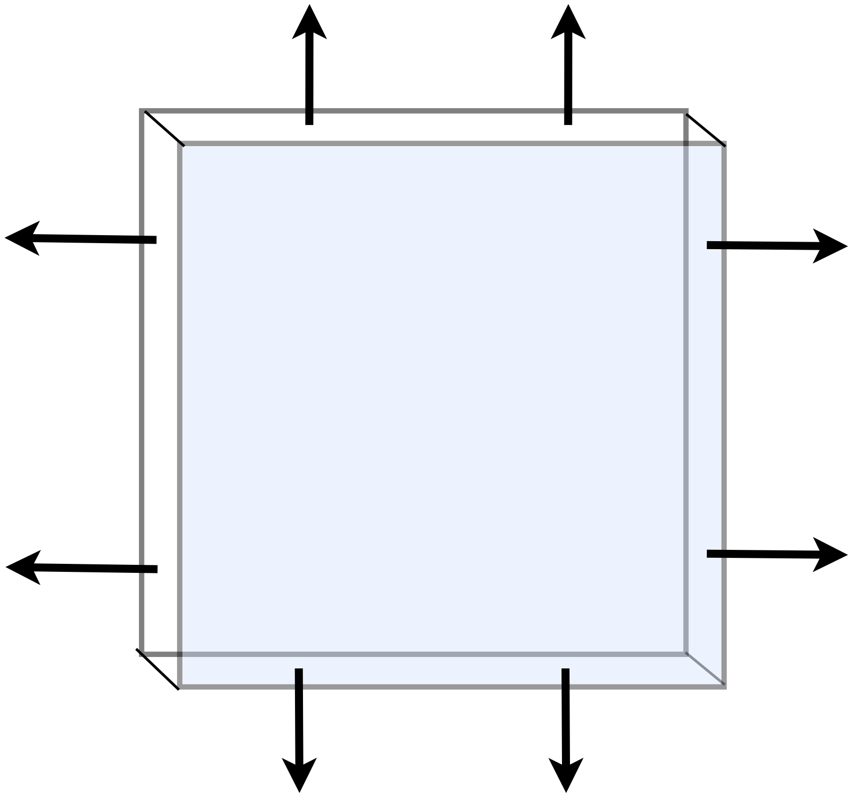


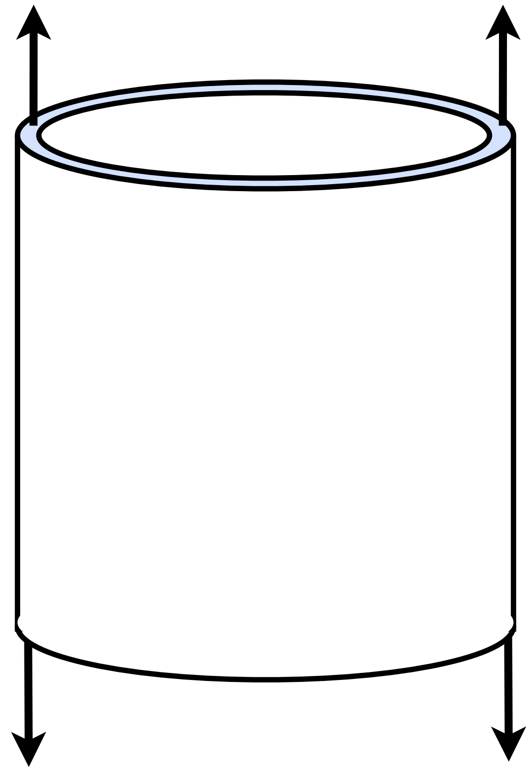




Brühwiler et al., 2011

Prospects III: geometry





Bar

- photon loss on 4 edges

Tube

- photon loss on 2 edges only
  ➔double efficiency

Summary

WOM concept offers several promises

- current estimated sensitivity ≥ DOM
- noise rate <10 Hz due to passive WLS
- boost due new photonics technology
- directional resolution by segmentation
- adaptible size (e.g. 10 cm diameter tubes)
- small PMT surface
  ➔ new technologies?

Next step

- build prototype with
  off-the-shelf components