A Single Photon Sensor employing Wavelength-shifting and Light-guiding Technology

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Photo Sensors in current Neutrino Detectors

- Always PMT-only with no enhancement of collection area [1, 2]
- Sensitive area is given by PMT area
  - need lots of large high-efficiency PMTs
- PMT noise is proportional to photocathode area [3]
  - want to reduce cathode size
- Peak efficiency of PMTs usually in green or blue wavelength range
  - want to match Cherenkov peak in the UV (ice is UV-transparent)
- In dense arrays, module noise is crucial for energy threshold and energy resolution

New Wavelength Shifter (WLS) based Design Concept

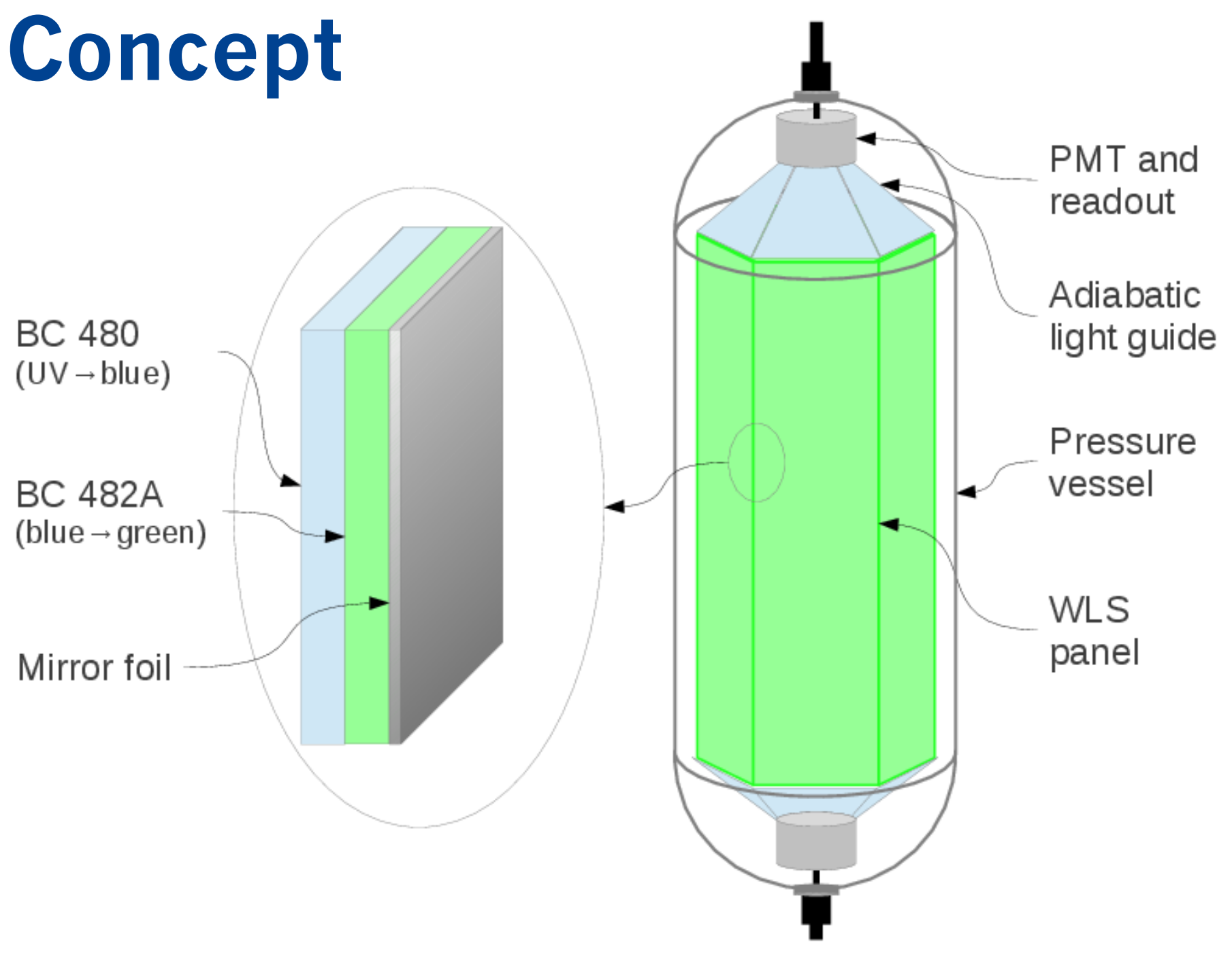


Fig. 1: Design concept of a Wavelength-shifting Optical Module (WOM)

- Cylindrical housing of UV-transparent quartz glass (high radiopurity)
- Sandwich of WLS bars (low-noise organic material) captures Cherenkov photons and converts them to larger wavelength
- Secondary photons are guided towards readout in end caps
- Readout with small (few cm²) off-the-shelf PMTs
- Dominating noise source: PMT cathode (~10 Hz for 2” PMT)

- Module efficiency $\varepsilon_{\mathrm{tot}} = \varepsilon_\Omega(\vartheta) \cdot \varepsilon_{\mathrm{WLS}}(\lambda) \cdot \varepsilon_{\mathrm{PMT}}$
  - ε_Ω: Transmission of incident photon into glass vessel → calculate
  - $\varepsilon_{\mathrm{WLS}}$: Capture efficiency → lab measurement
  - $\varepsilon_{\mathrm{PMT}}$: Mean PMT quantum efficiency for WLS output spectrum

Lab Setup

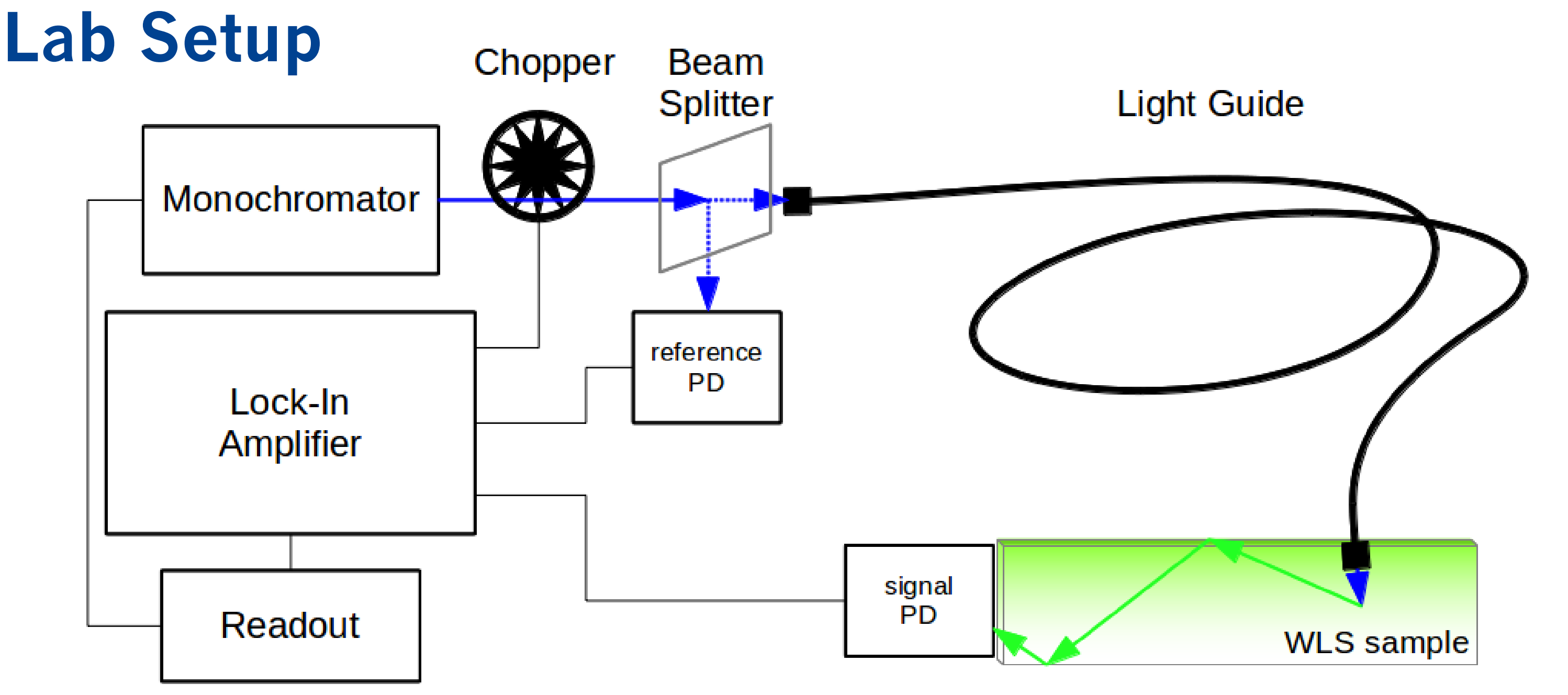
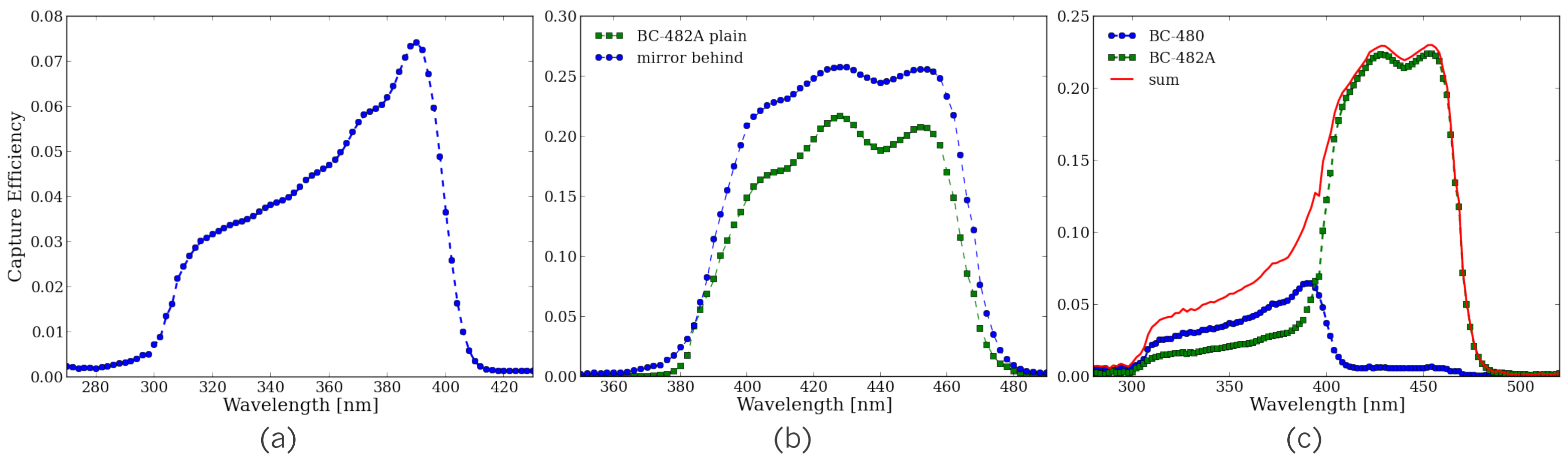


Fig. 2: Setup for measuring the capture efficiency ε_{WLS} of a WLS sample

- Capture efficiency = #incoming photons / #photons detected at short edges
- Accessible wavelength range: ~250 nm to well above 600 nm

Measurements



(a) (b) (c)

Fig. 3: Capture efficiency measured for (a) BC-480, (b) BC-482A, and (c) a sandwich of both materials (BC-480 in front)

- Two WLS materials have been tested (sample size: 1000 x 100 x 5 mm):
  - BC-480 [4]: UV → blue (absorption/emission peak: 395 nm/430 nm)
  - BC-482A [5]: blue → green (absorption/emission peak: 425 nm/495 nm)
- Peak capture efficiency: **7.5 %** (BC-480) and **25 %** (BC-482A)
- For BC-480, efficiency limited due to strong UV absorption of carrier
- For BC-482A, mirror behind WLS sample increases efficiency
  - sample thickness (5 mm) not optimal, absorption length 3.9±0.3 mm
- Sandwich has lower efficiency in blue, but higher efficiency in UV
  - absorption inside BC-480 (in front)
- escaping light from BC-480 bar captured in BC-482A bar

Time Resolution and Achievable Efficiency

- Created toy Monte Carlo to simulate photon capture and propagation
  - use same profile as lab samples (100 x 5 mm)
- Assuming photon conversion efficiency of 86 % for dye [6]

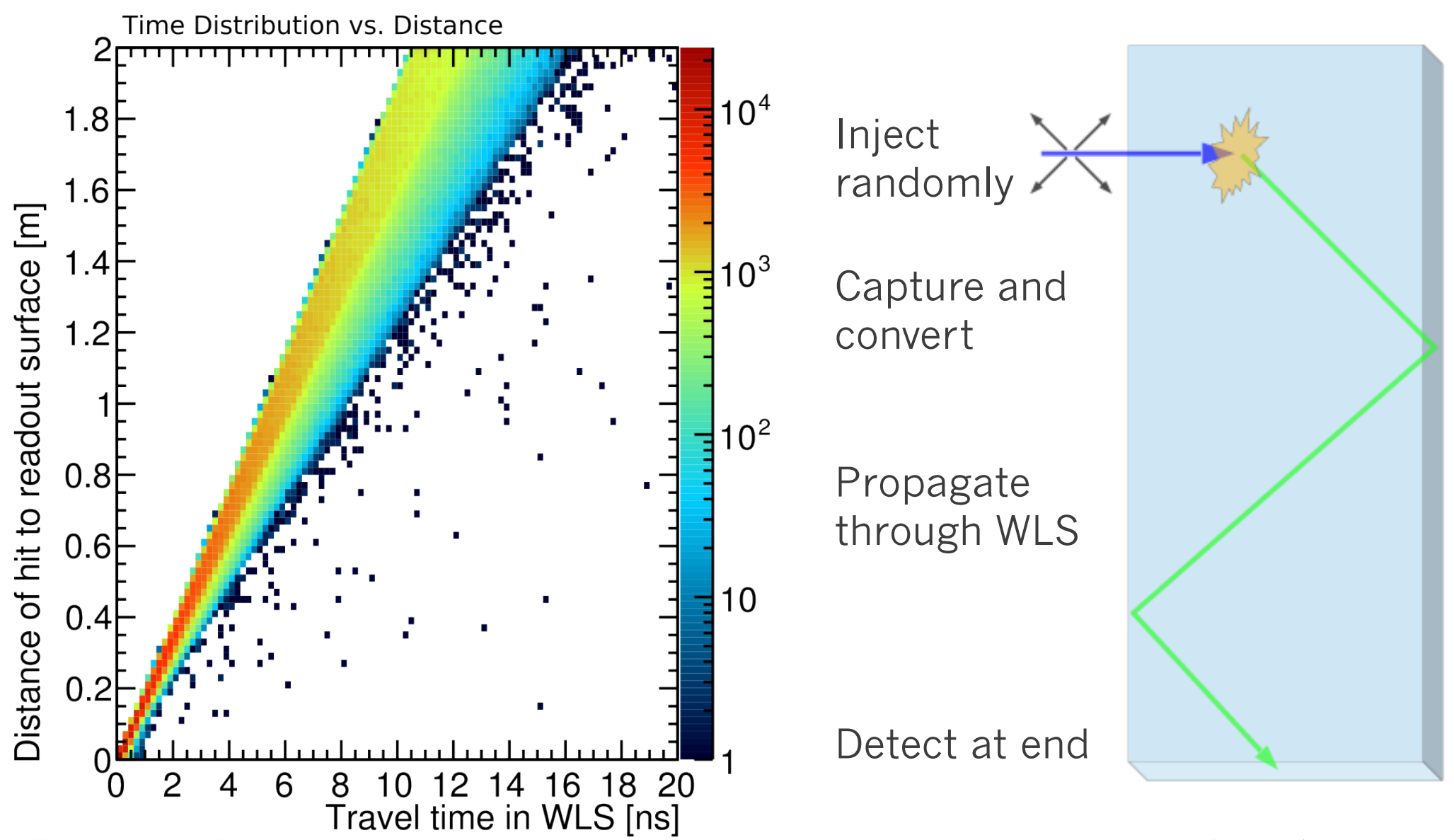


Fig. 4: Distribution of the photon travel time (left), schematic of the simulation algorithm

- Capture efficiency (with mirror):
  - 35 %
- Time resolution RMS for 2 m bar:
  - 2.74 ns / 2 m
- Re-emission time measured [6]:
  - 8.5 ns (dominates over propagation)

Angular Efficiency

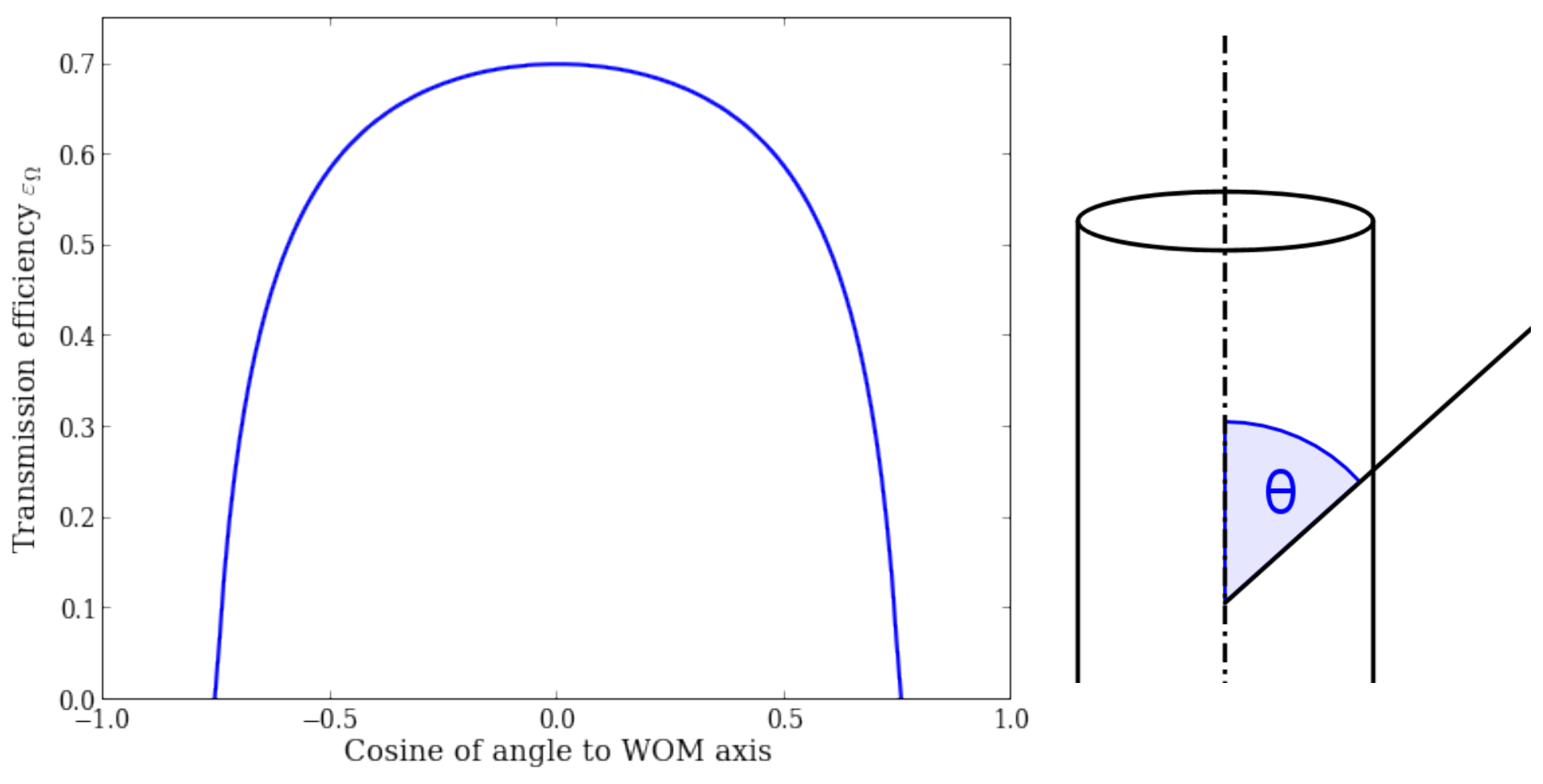
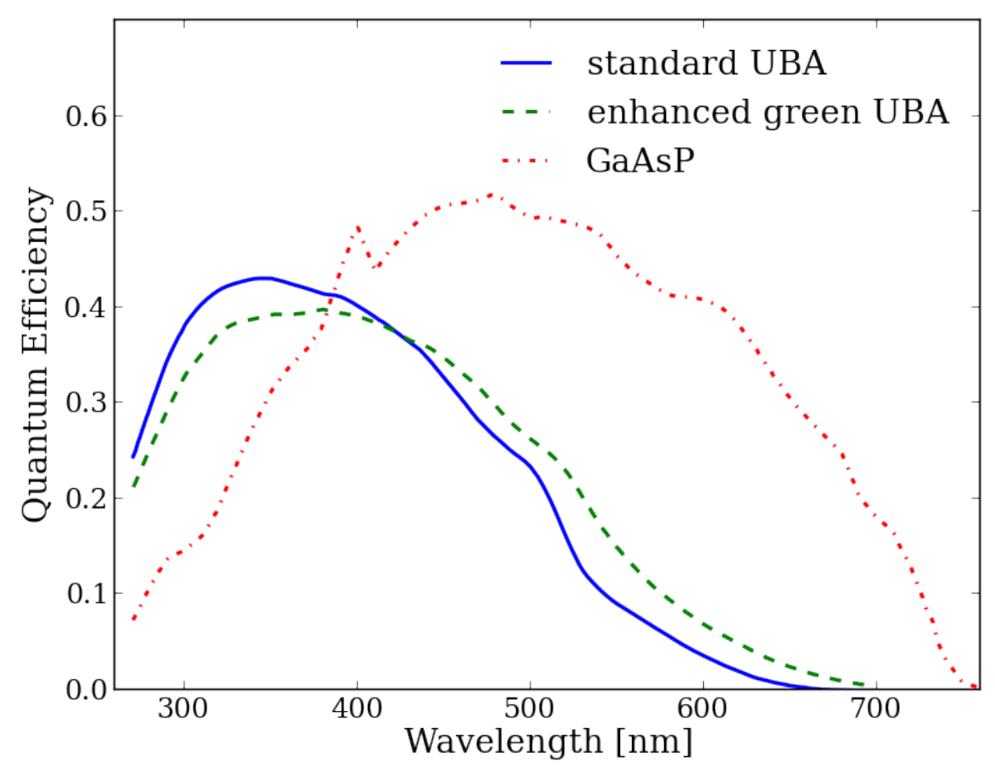


Fig. 5: Transmission into WOM interior (left), definition of angle ϑ (right)

- Probability for a photon to penetrate from surrounding ice into WOM interior
- Assume transition
  ice (n = 1.33) →
  glass (n = 1.48) →
  air (n = 1.0)
- Integrate Fresnel's formulae over all *impact parameters* for given angle ϑ between photon and WOM axis

PMT readout



- Consider three different prototype Hamamatsu PMTs:
  - R7600-UBA (ultra-bialkali cathode)
  - R7600-EG (enhanced green sensitivity)
  - R9792U MHP119 (GaAsP cathode)
- Calculate $\varepsilon_{\mathrm{PMT}}$ for both WLS materials by convolving quantum efficiency with respective output spectrum

Fig. 6: Quantum efficiencies of the considered PMTs Data provided by Hamamatsu [7]

Noise Budget

- Individual components' contribution:
  - Fused quartz glass housing [8]: 0.02 Bq/kg ≙ 0.5 Bq/m^2
  - WLS panel [8]: 0.4 Bq/kg ≙ 3.5 Bq/m^2
  - PMT (bialkali cathode [3]): < 1 Hz/cm^2 @ –50 °C
- Assuming WOM with R = 10 cm, L = 2 m (A ≈ 1.25 m^2) and ≈ 5 cm^2 PMT cathode, **noise rate of full module is only 10 Hz**!

Full WLS Optical Module Performance

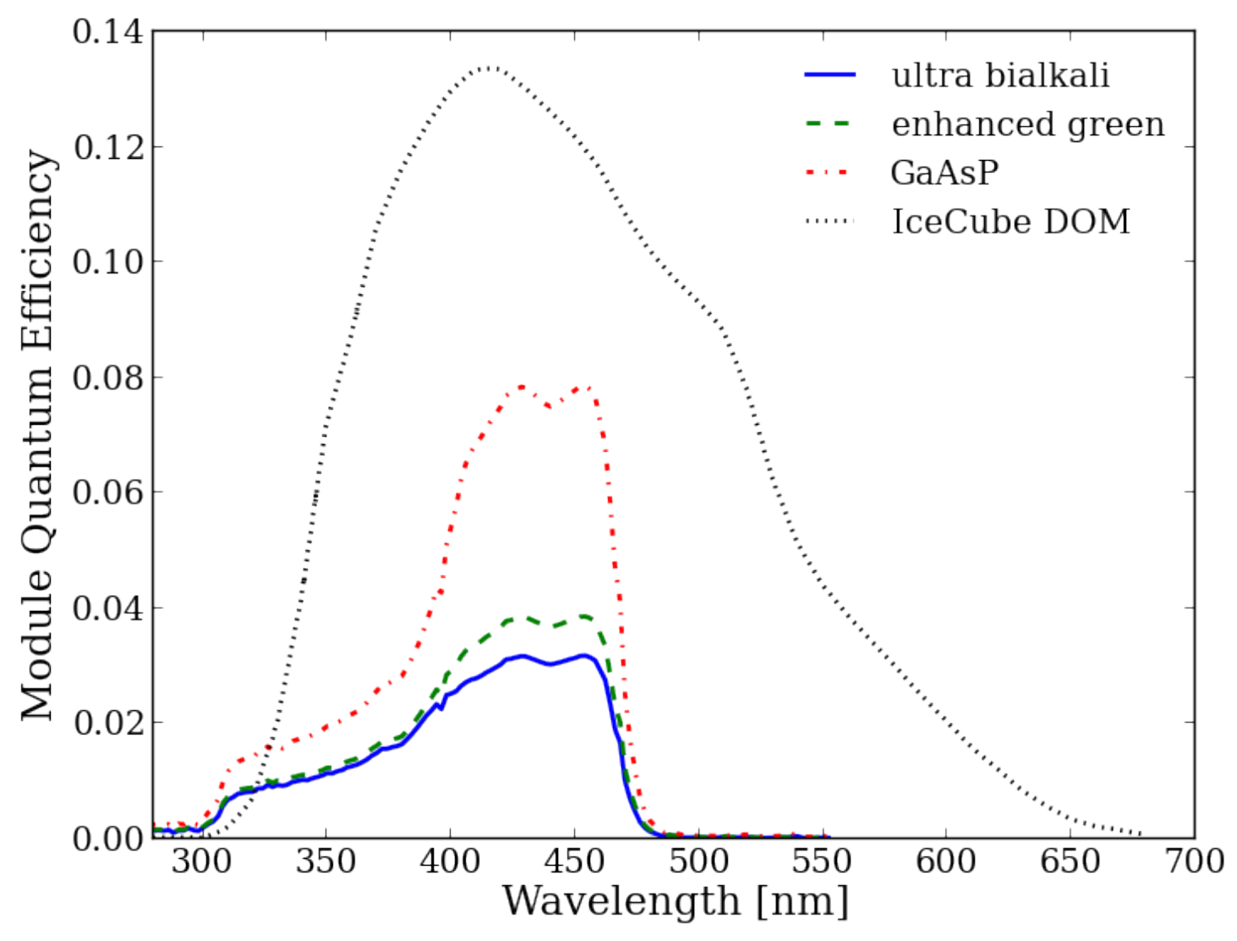


Fig. 7: Full quantum efficiency of a WOM with different PMTs compared to IceCube DOM [1], both at angle of optimal acceptance

- Multiply ε_Ω, $\varepsilon_{\mathrm{WLS}}$, and $\varepsilon_{\mathrm{PMT}}$ to get quantum efficiency of full module
- Calculate mean quantum efficiency for Cherenkov spectrum (~$1/\lambda^2$ between 300 nm and 600 nm) inciding isotropically

Module	Mean QE [%]	Peak QE [%]	Eff. Area [cm^2]	Noise [Hz]
UBA WOM	1.25	3.18	30.5	≈ 10
EG WOM	1.44	3.86	35.2	≈ 10
GaAsP WOM	2.65	7.86	64.7	10^6
IceCube DOM	7.10	13.4	19.4	800

- Can construct WOM with **50 – 75 % larger effective area** than IceCube DOM from available components
- Noise rate reduced by almost **two orders of magnitude**
- Large room for improvement by future R&D
- Can learn from other fields of physics, e.g. solar energy [10]

References

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