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ICECUBE

Studies on dark rates induced by radioactive decays in the multi-PMT digital optical module

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living.knowledge

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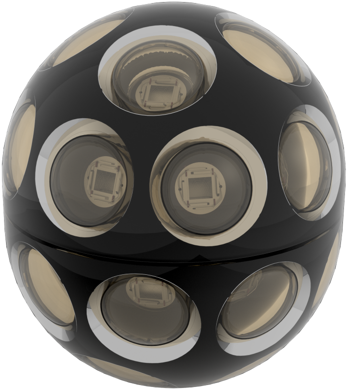
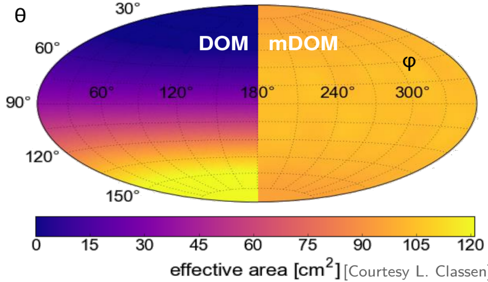
Overview

- The mDOM and its background mechanisms
- Background parameter determination
- Simulation of background in the optical modules

The multi-PMT digital optical module



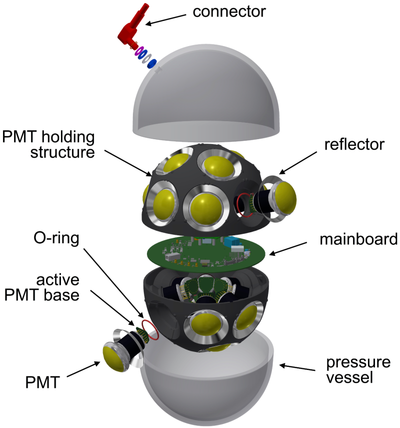
[IceCube-Collaboration]



[Courtesy L. Classen]

- 24×3 inch photomultiplier tubes (PMTs)
- 4π angular acceptance
- Directional sensitivity
- Larger effective area

Background sources in the mDOM



Ice features no optical activity
→ Module main background source.

- Dark rate of PMTs
  - Enhancement by conductive objects in proximity of photocathode (reflector)
  - Optical cross-talk between PMTs
- **Radioactive decays in pressure vessel (gel+PMT glass)**

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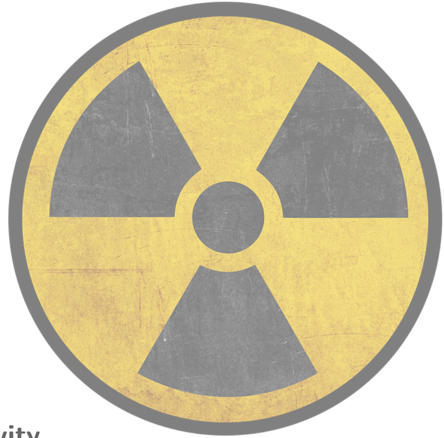
Radioactivity inside glass and gel

- Vitrovex and Benthos glass:
  - ^{238}**U chain** ($4\text{-}9\ \frac{\text{Bq}}{\text{kg}}$)
  - ^{232}Th chain ($1\text{-}2\ \frac{\text{Bq}}{\text{kg}}$)
  - ^{235}U chain ($0.5\text{-}0.8\ \frac{\text{Bq}}{\text{kg}}$)
  - ^{40}K ($0\text{-}70\ \frac{\text{Bq}}{\text{kg}}$)



- QSI gel feature **no measurable activity**

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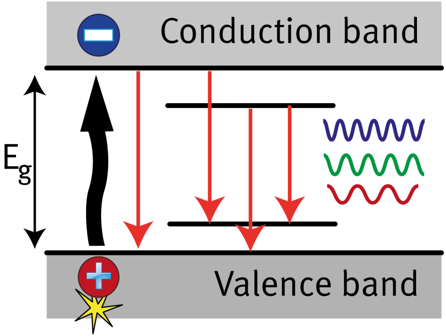
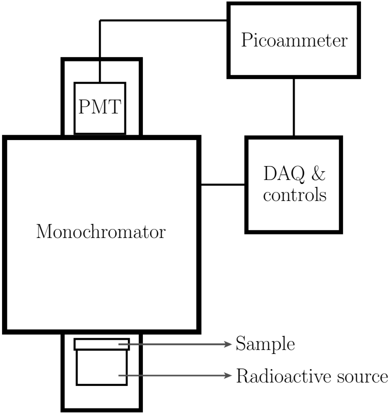
Scintillation basics



Empirical parametrisation:

- Spectrum
- Lifetime τ: $I(t) \propto e^{-t/\tau}$
- Yield (amount of photons per deposited energy)

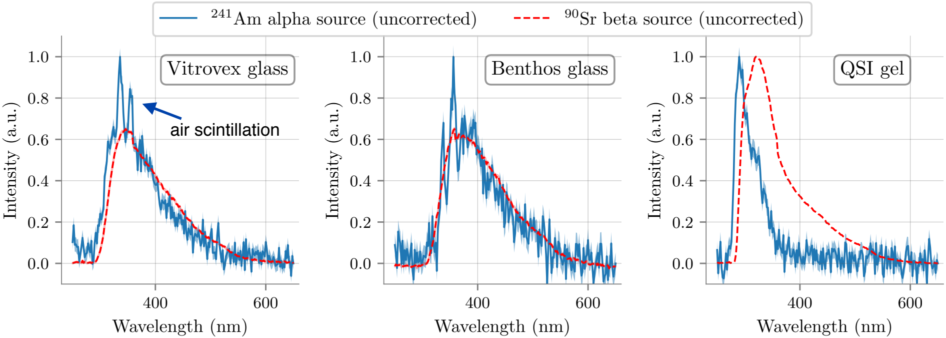
Measuring the scintillation spectra



- Glass excitation with radioactive source
- Wavelength selection with monochromator
- Photon detection with small PMT

[Hamamatsu R7600U-200 Datasheet]

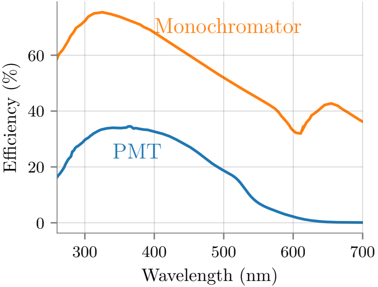
Spectra with ^{90}Sr-β and ^{241}Am-α-source

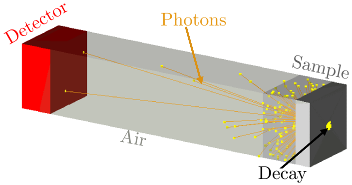


Shift in UV cutoff caused by different sample thicknesses

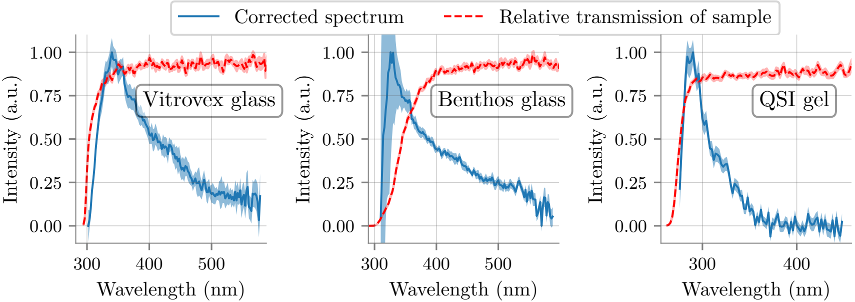
Correcting the spectra

- Efficiency of monochromators diffraction grating
- Quantum efficiency of PMT
- Photon absorption in sample
  → Simulation (Geant4)





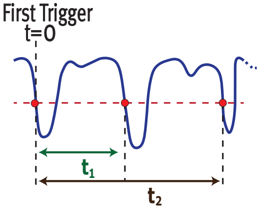
Corrected spectra

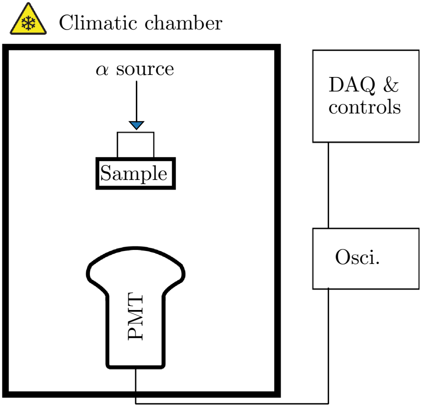


- Probably most of the luminescence in UV-region is absorbed in the samples!

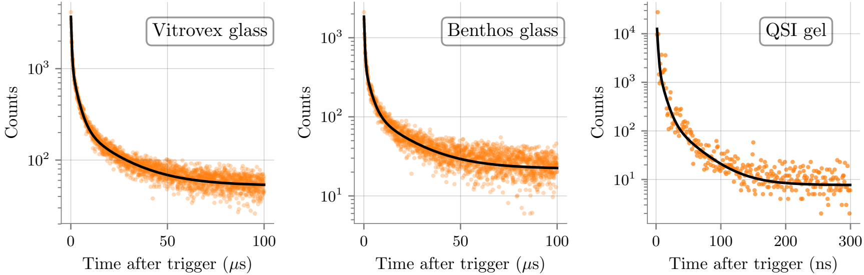
Measuring the scintillation lifetime

- Excitation with weak ^{241}Am-α-source ($\sim 2.83\,$kBq)
- Measurement of $100\,\mu$s waveforms after trigger event
- Save hit time of all photons inside waveforms





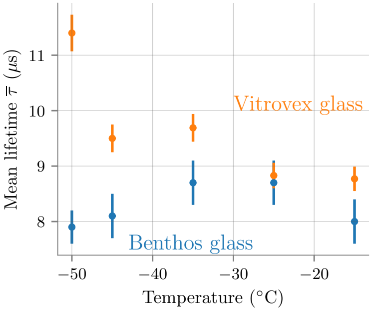
Time distribution of all samples

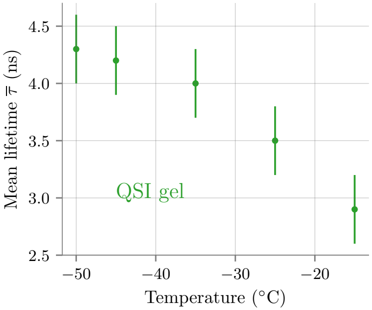


- Multi-exponential decay fit: $I(t) = \sum_i \alpha_i \exp(-t/\tau_i)$
  $\rightarrow$ All samples feature 3 decay constants

Lifetime temperature dependence

Mean lifetime: $\overline{\tau} = \frac{\sum_i \alpha_i \tau_i^2}{\sum_i \alpha_i \tau_i}$

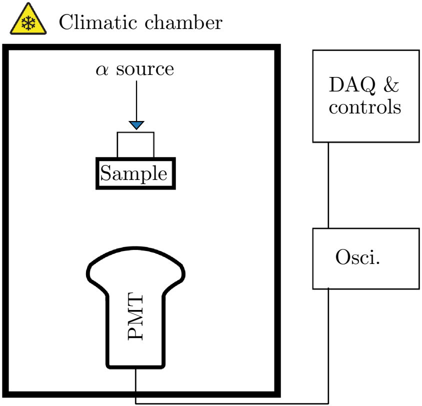




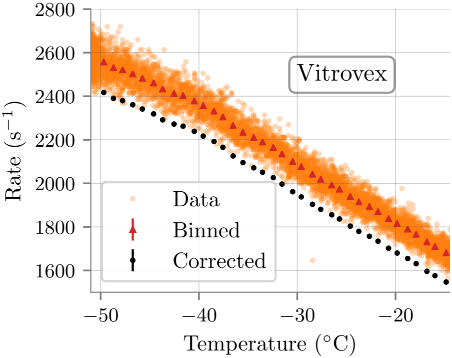
Determination of scintillation yield

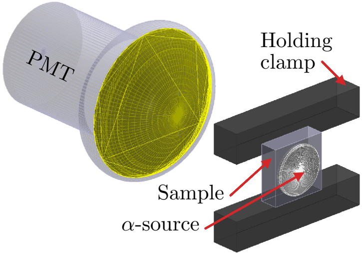
$$\text{yield} = \left\langle \frac{\#\text{emitted photons}}{\text{dep. energy}} \right\rangle$$

- Measure rate from excited sample
- Simulate the setup using different yields and interpolate for measured rate
- Correct for PMT dark rate and **air scintillation**



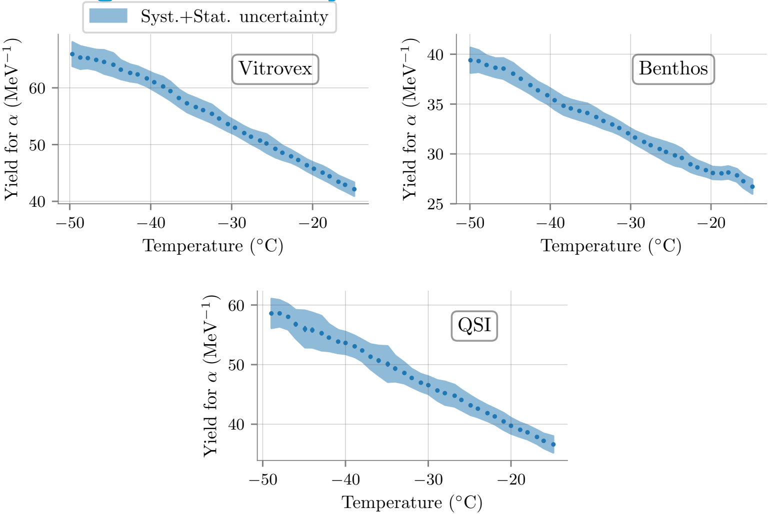
Glass and gel scintillation yield: Rate



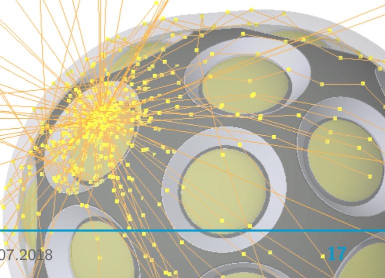


Rate caused by air luminescence simulated and corrected

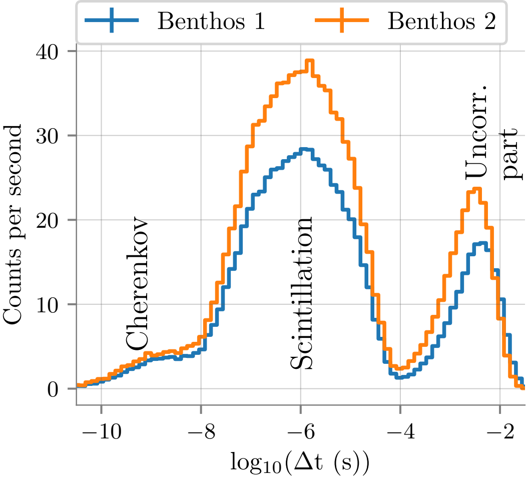
Glass and gel scintillation yield

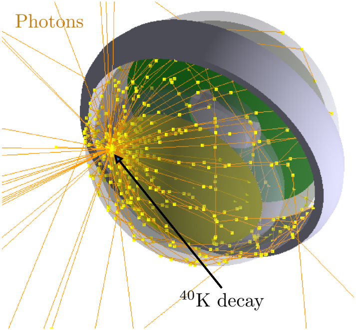


Simulating the background in the optical modules



Simulation results for the IceCube optical module

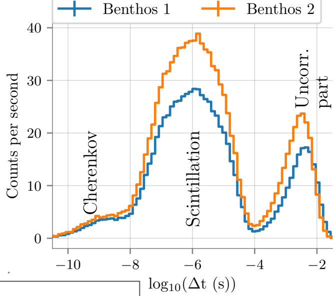


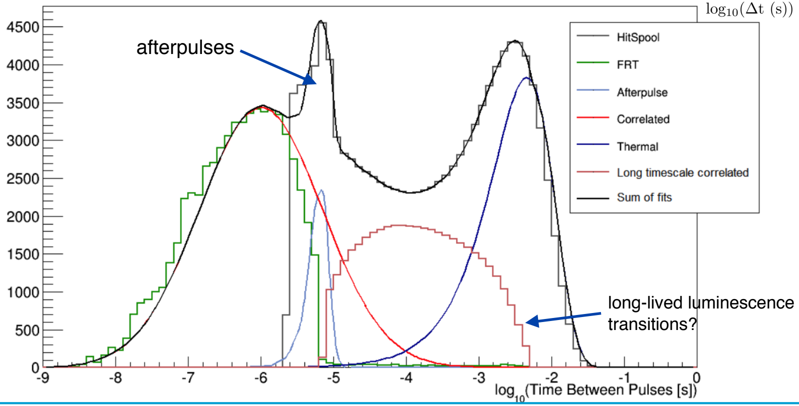


- In Benthos 2 42 % higher ^{238}U activity than Benthos 1

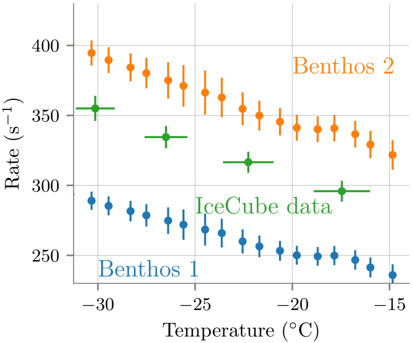
Comparison with IceCube data

[N. Stanisha, Bachelor Thesis, SHC, 2014]



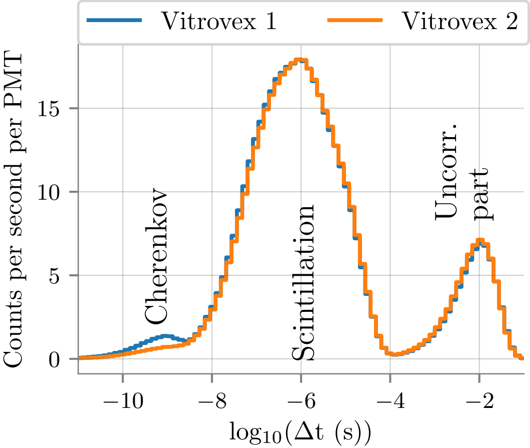


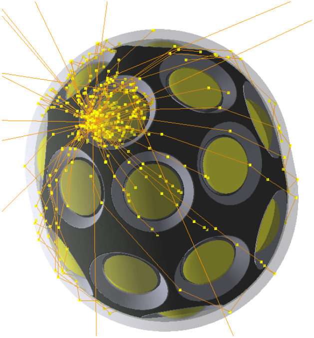
Correlated rate temperature dependence



- Temperature dependence of simulated rate in well agreement with experimental data

Simulation results for mDOM

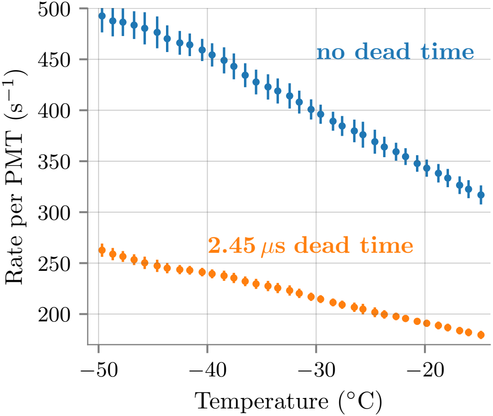




^{40}K:

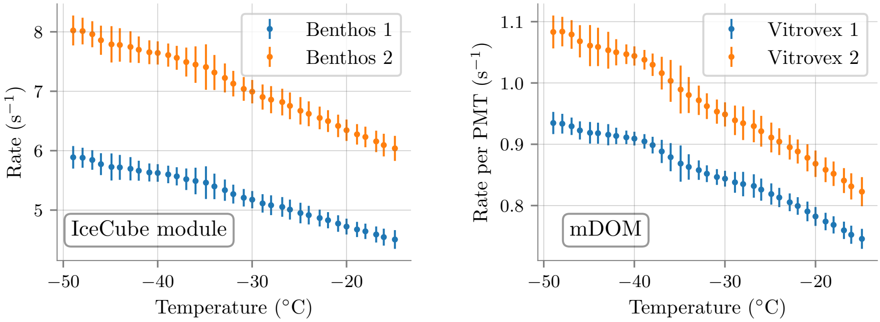
- Vitrovex 1 $(61 \pm 1)\ \frac{\mathrm{Bq}}{\mathrm{kg}}$
- Vitrovex 2 $(1.0 \pm 1.4)\ \frac{\mathrm{Bq}}{\mathrm{kg}}$

mDOM rate as a function of temperature



@ $-30\,°$C expected background rate of $401 \pm 10\,s^{-1}$ per PMT

Gel influence on rate



Summing up...

- Decays in glass produce Cherenkov and scintillation photons
- Scintillation most important background component
- Scintillation can be fully parametrized
- Scintillation spectrum is absorbed in UV-region
- Long lifetime for glass, short for gel
- Scintillation yield strongly temperature dependant
- Background from gel scintillation neglectable
- Simulation in good agreement with IceCube data

Thank you for your attention!

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Radioactivity inside glass and gel

	Mass-specific activity (Bq/kg)			
	VV 1	VV 2	VV 3	VV vessel
^{238}U-Chain	4.53 ± 0.10	4.61 ± 0.19	4.69 ± 0.10	8.42 ± 0.13
^{232}Th-Chain	1.39 ± 0.09	1.34 ± 0.09	1.07 ± 0.10	2.27 ± 0.10
^{235}U-Chain	0.56 ± 0.07	0.61 ± 0.07	0.62 ± 0.16	0.75 ± 0.08
^{40}K	53.6 ± 1.7	57.5 ± 1.8	66.2 ± 1.2	<0.99

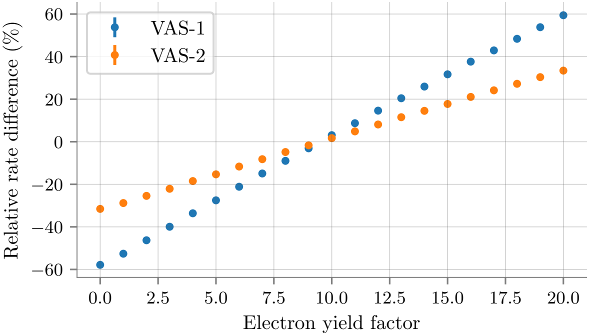
VV: Small Vitrovex samples from 2016

VV Vessel: Old Vitrovex prototype vessel for IceCube (production year ~ 2000)

- QSI and Wacker gel feature **no measurable activity**

Scintillation after beta decay

- Yield calculated only valid for α particles. The yield is normaly higher for e^-. In my simulations I used for e^- a factor 9.5 higher from the determined yield (following 'Radiation Detection and Measurement', Glenn F. Knoll)

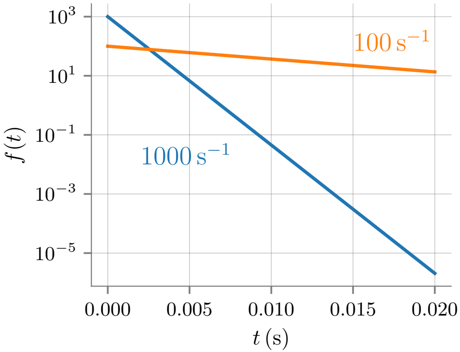


VAS: Vitrovex isotope activity set

Background rate will change depending on true value of glass yield for electrons

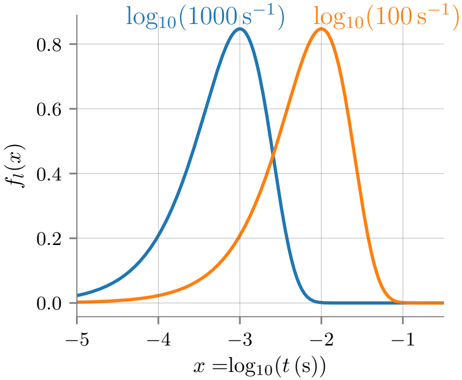
Random (uncorrelated) noise

- Poissonian process
- $f(t) \propto \exp(-\mu \cdot t)$
  $\rightarrow$ Rate given by slope

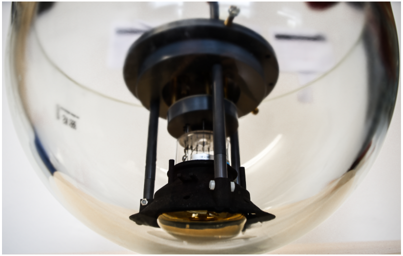


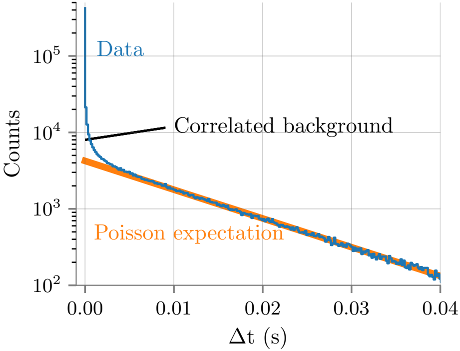
Random (uncorrelated) noise

- $x = \log_{10}(t)$
- $f_l(x) \propto 10^x \cdot \exp(-\mu \cdot 10^x)$
  $\rightarrow$ Rate given by maximum

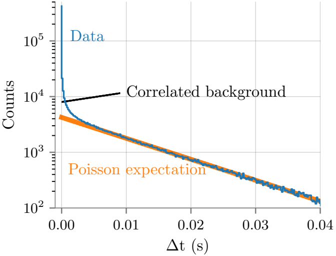


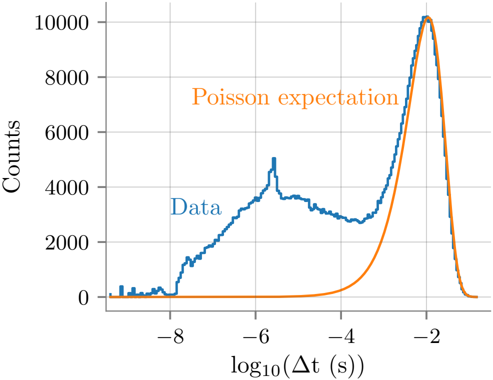
Correlated and random noise



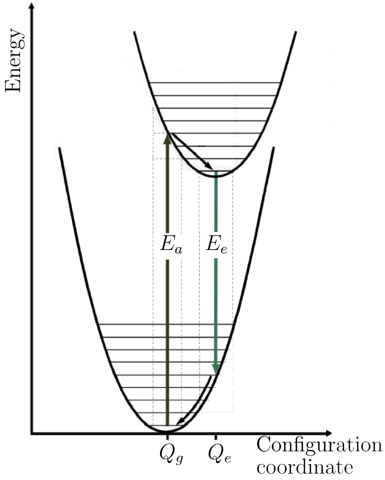


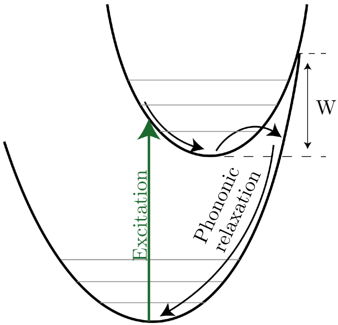
Correlated and random noise



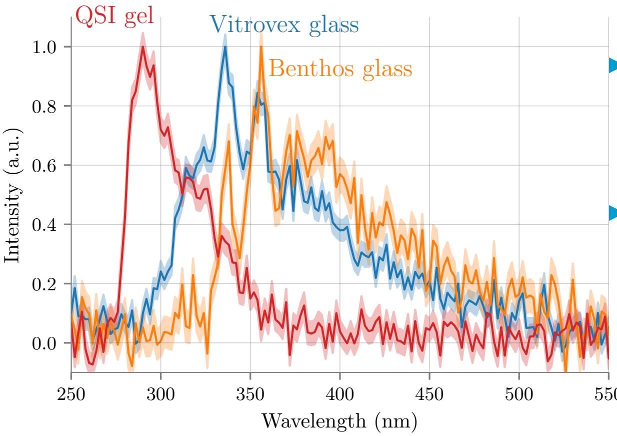


Thermal quenching



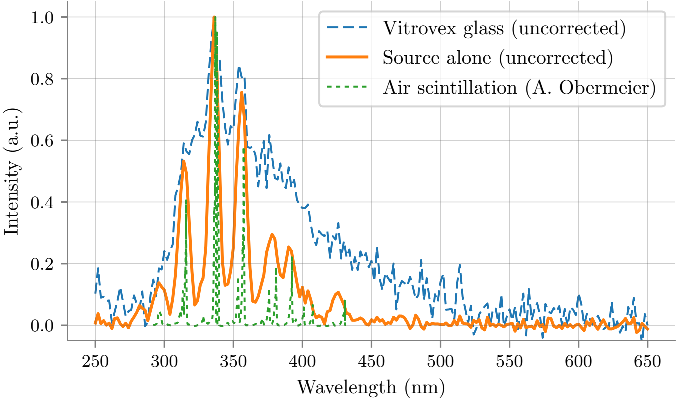


Spectra with ^{241}Am-α-source



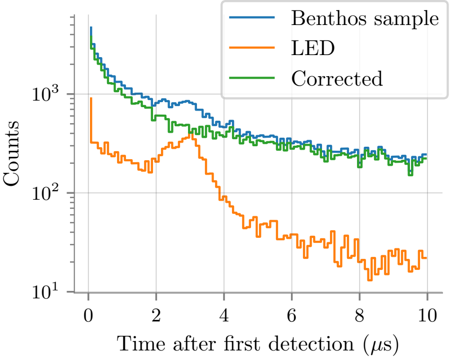
- Excitation with $\sim 250\,$kBq ^{241}Am-source ($\overline{E_\alpha} = 5.48\,$MeV)
- Glass samples show peaks at $\sim 337\,$nm and $\sim 358\,$nm

Air luminescence contamination



- Short range of α leads to air luminescence contamination and low activity of the source to poor SNR
- β-source may circumvent these problems $\rightarrow$ ^{90}Sr of $\sim 0.4\,$GBq

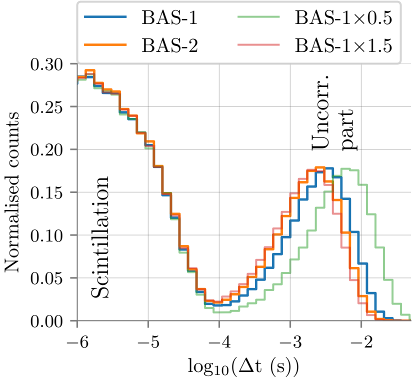
Correcting for PMT effects



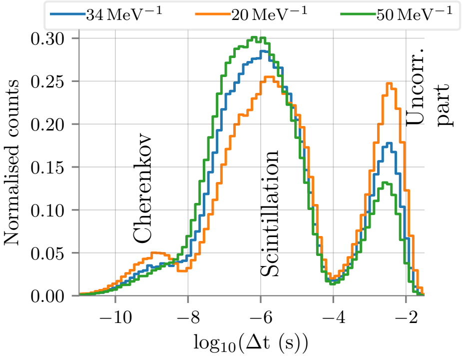
- Correlated noise from PMT has to be corrected
- Measure PMT response with LED light instead of scintillation light

Impacts on time distribution

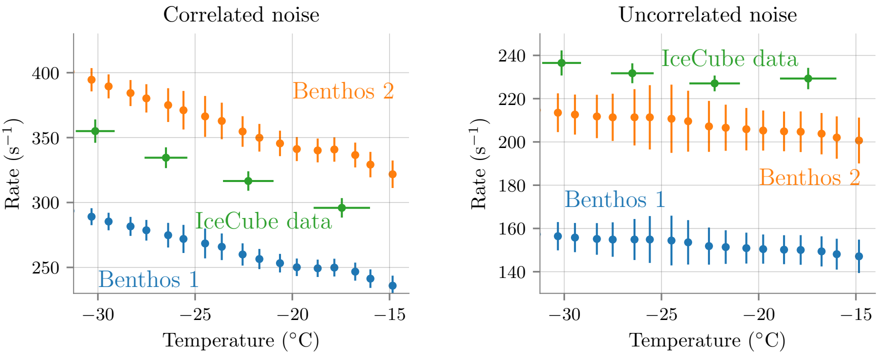
Activity variation



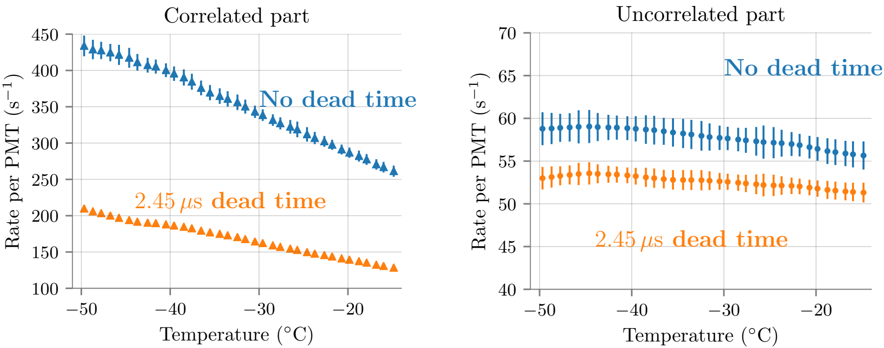
Yield variation



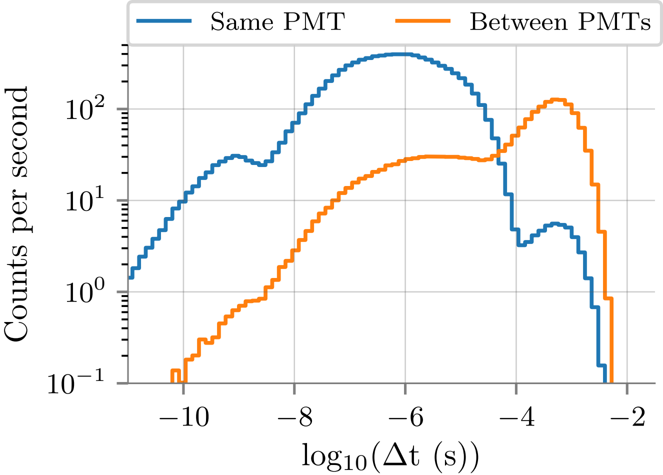
DOM rate temperature dependence



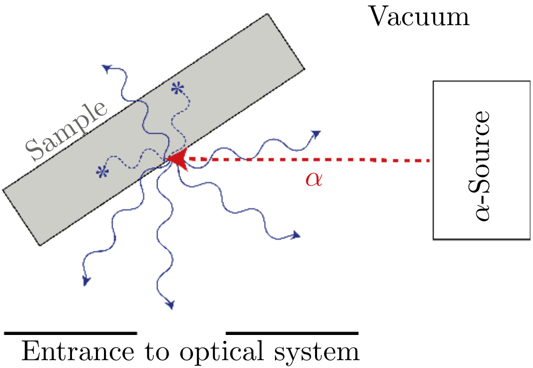
mDOM rate as a function of temperature



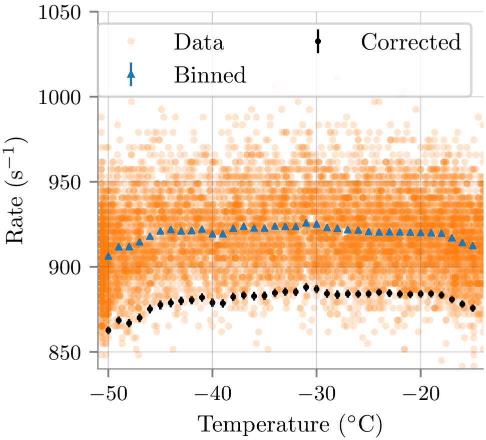
Coincidences between PMTs



Improved spectrum measurement

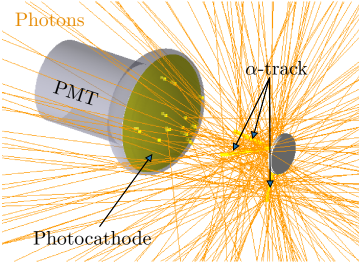


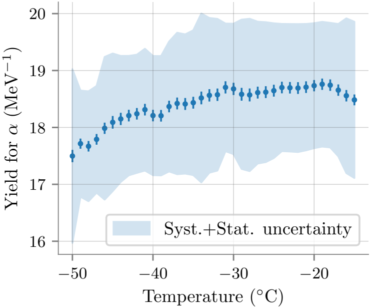
Air scintillation yield



- Rate measured with source alone
- Correct for PMT effects

Air scintillation yield





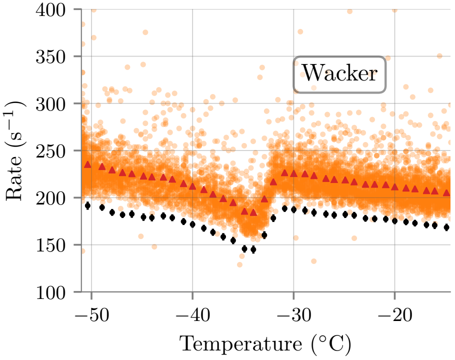
Mean yield between $-30\,^{\circ}$C and $-15\,^{\circ}$C: $(18.7 \pm 1.2)\,\mathrm{MeV}^{-1}$

Reference ($20\,^{\circ}$C):

$(19 \pm 3)\,\mathrm{MeV}^{-1}$ [J. Sand et al., New Journal of Physics, Vol. 16, 053022, 2014]

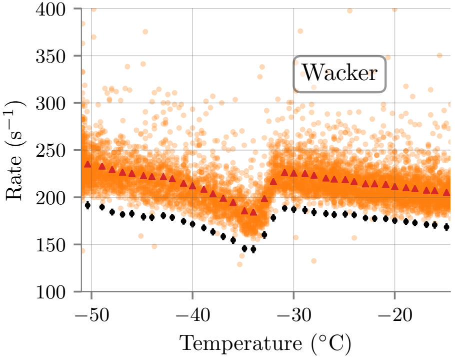
$(18.9 \pm 2.5)\,\mathrm{MeV}^{-1}$ [C. Thompson et al., Radiation Measurements, Vol. 88, p. 48-54, 2016]

The case of Wacker gel

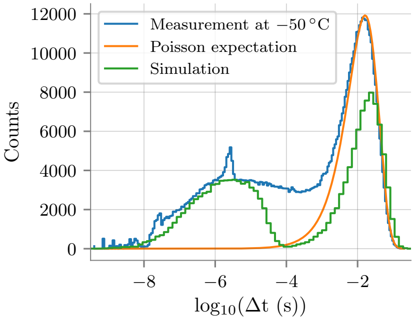


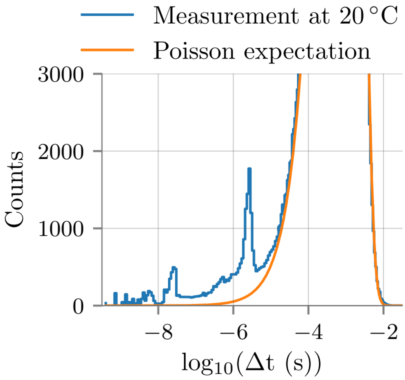
- No meaningful yield calculation possible
- Crystallisation at low temperatures

The case of Wacker gel

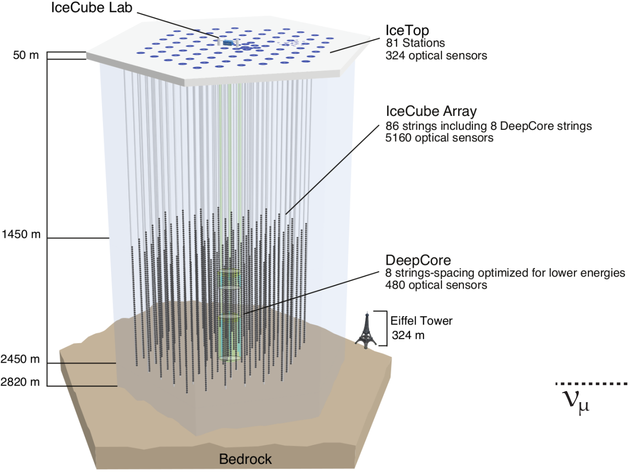


dT dark rates PMT in front of Vitrovex vessel



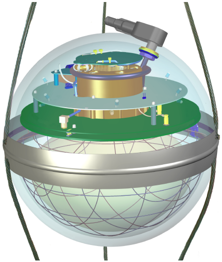


IceCube Observatory

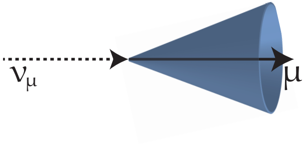


[IceCube-Collaboration]

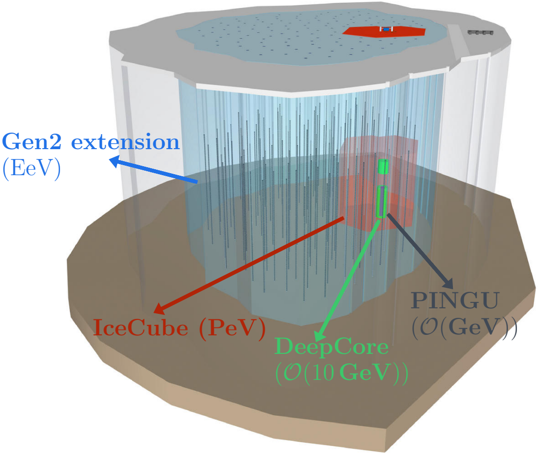
Digital Optical Module



[IceCube-Collaboration]



IceCube-Gen2



[IceCube-Collaboration]

- ~ 120 new strings with 80 modules each
- $5\text{-}10\,\mathrm{km}^3$ instrumented volume
- PINGU (Phase I) high string density