Challenges in Liquid Scintillator and Water Detectors

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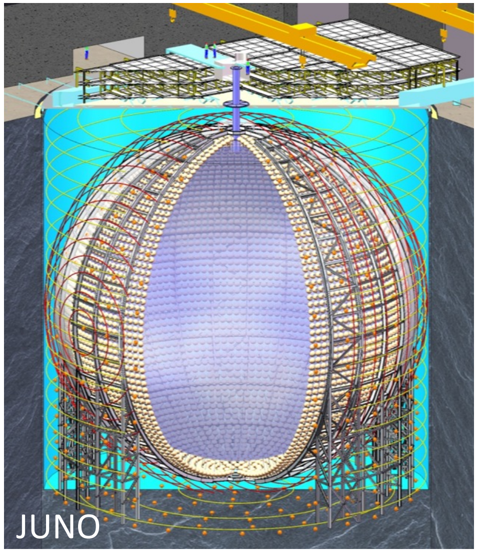
R&D for water and LS projects

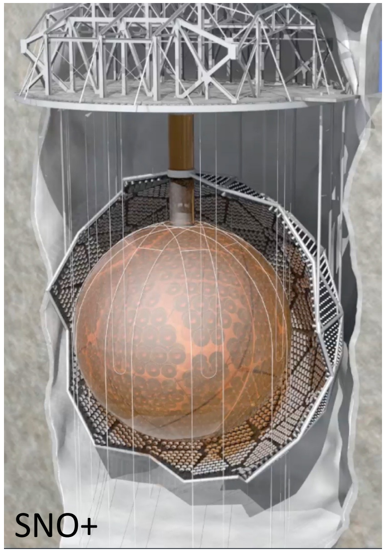
Well-established techniques and projects currently in the development phase

- large-volume water(+Gd!) detectors → HyperK
- ultrapure LS detectors → JUNO
- metal-loaded (Te) LS detectors for 0νββ → SNO+
- efficient veto detectors (water, LS, Gd-doped) → Darwin, SHiP …

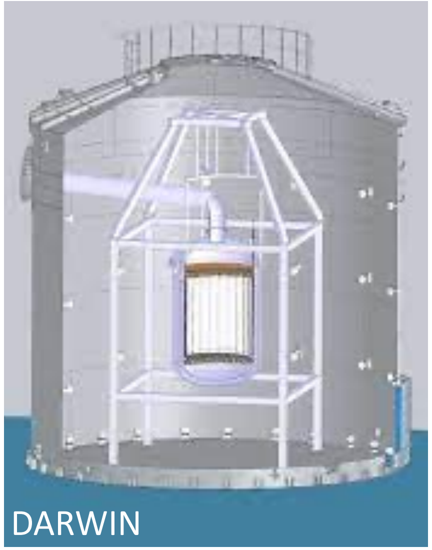
HyperKamiokande



JUNO

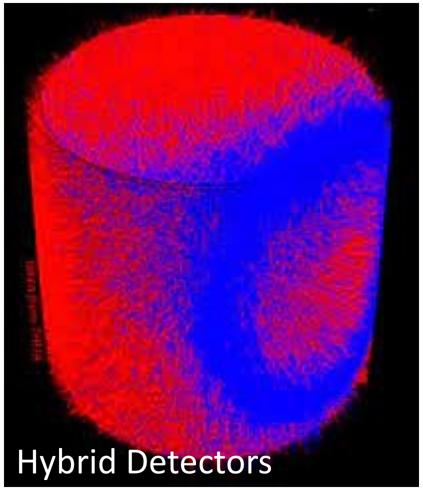


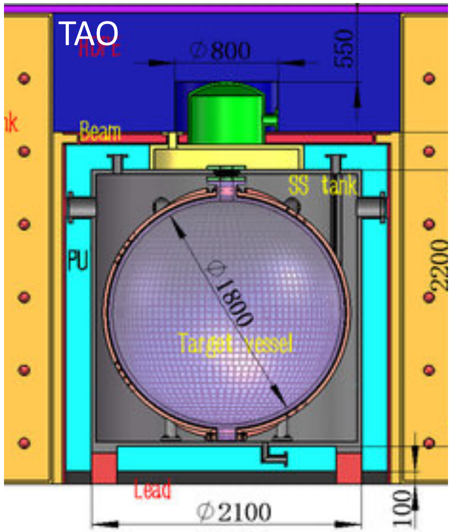
SNO+

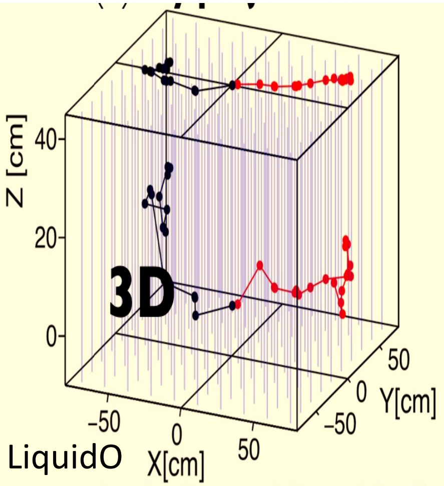


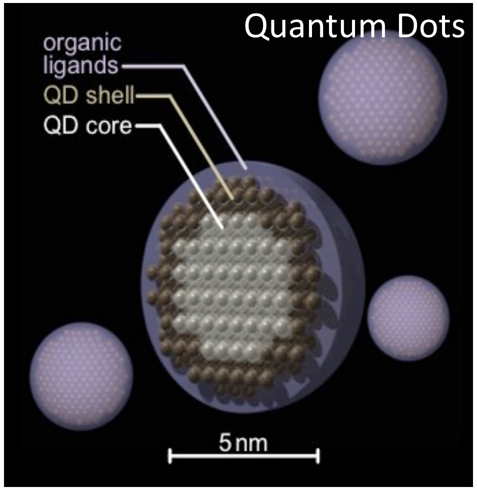
DARWIN

R&D for water and LS projects









New concepts: New techniques that go beyond the present state-of-the art and are entering demonstration phase

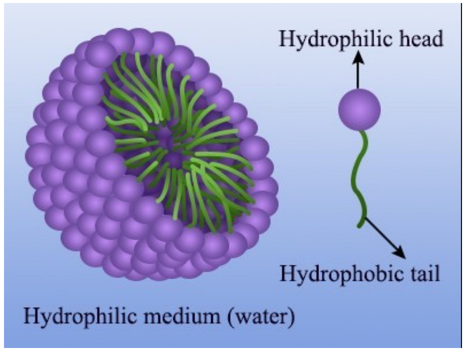
- hybrid Cherenkov/scintillation detectors → Theia
- cold LS with SiPM read-out → TAO
- opaque LS with fiber read-out → LiquidO
- LS doped with quantum dots for 0νββ searches → NuDot

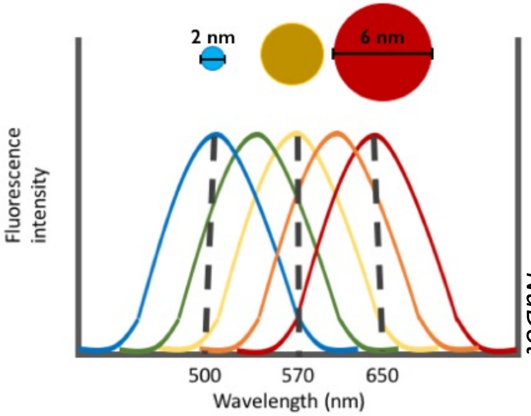
→ different requirements but common R&D topics!

Concrete R&D Topics

- liquid composition
    - bulk material
    - (metal) doping
- light emission properties
    - fluorescence times
    - spectrum
- optical transparency
- radiopurity
- coupling to new photo sensors
- advanced event reconstruction

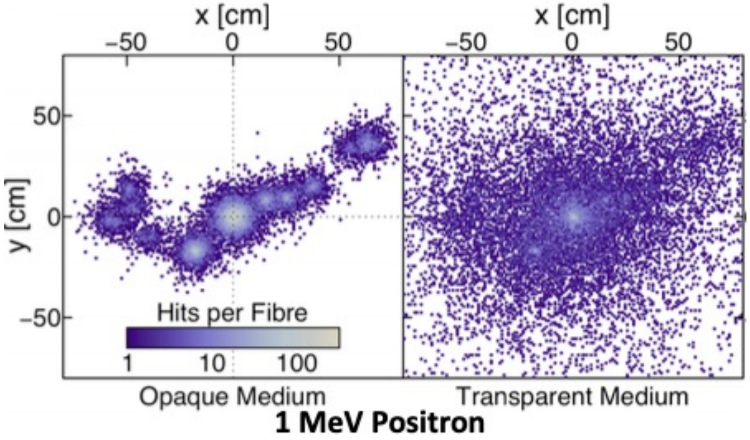
Water-based Liquid Scintillator
organic mycels suspended in water
with surfactant interface





NuDot

Quantum Dots
emission spectrum depends
on size & elemental composition



LiquidO

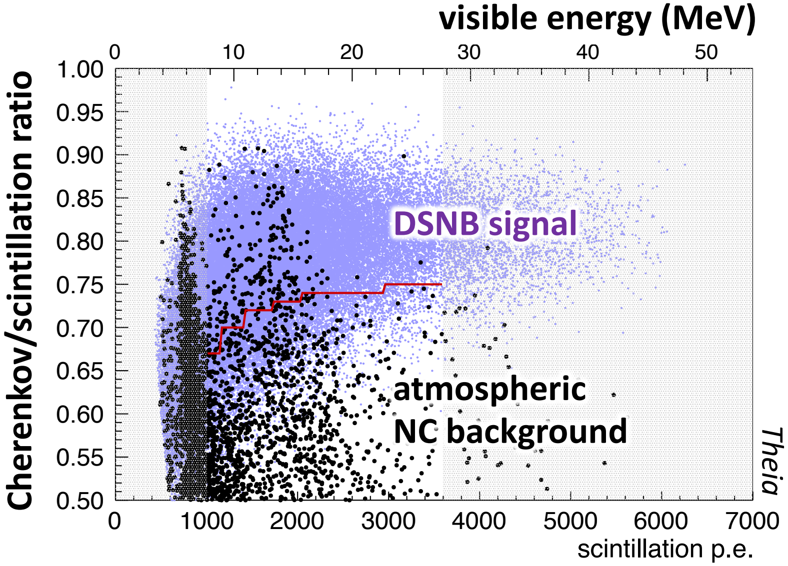
Opaque scintillator
short scattering length permits
better localization of light source

Example 1: Hybrid optical detectors

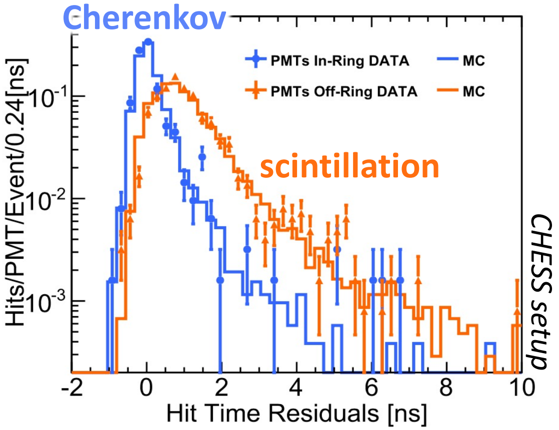
- **basic idea:** simultaneous readout of scintillation and Cherenkov signals
- **performance benefits**
  - improved energy and vertex reco
  - particle ID via C/S ratio
  - simplified metal loading
- **new detector requirements**
  - very transparent target medium
  - either fast timing (WbLS) and (sub-)nanosec photo sensors
  - or slow timing (slow fluors, solvents) in fully organic LS

→ trade-off between costs, timing, light yield …

- **R&D challenges**
  - transparency: Rayleigh scattering off mycels
  - purification of dual-phase liquid
  - complex event reconstruction (dual signal)



Particle ID based on the ratio of Cherenkov-to-scintillation (C/S) photons



nanosec timing for C/S separation

Example 2: Cold organic scintillators

- **basic idea**

  LS detector at -50°C
  - read-out by SiPMs (high QE)
  - enhanced light yield

  → maximize light collection

- **performance benefits**

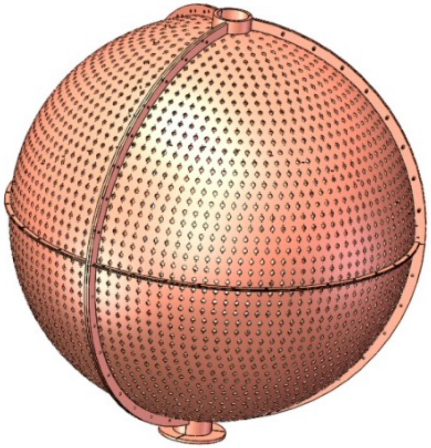
  several 10^3 p.e./MeV collected

  → energy resolution <2% @ 1 MeV

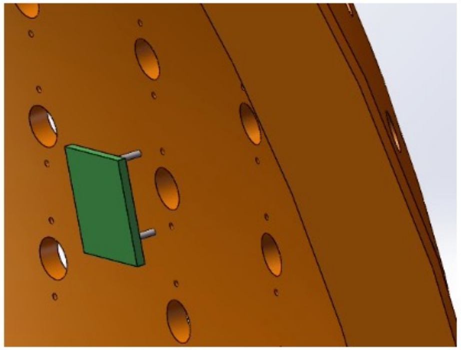
- **new detector requirements**
  - optical transparency
  - chemical stability

  at very low temperatures

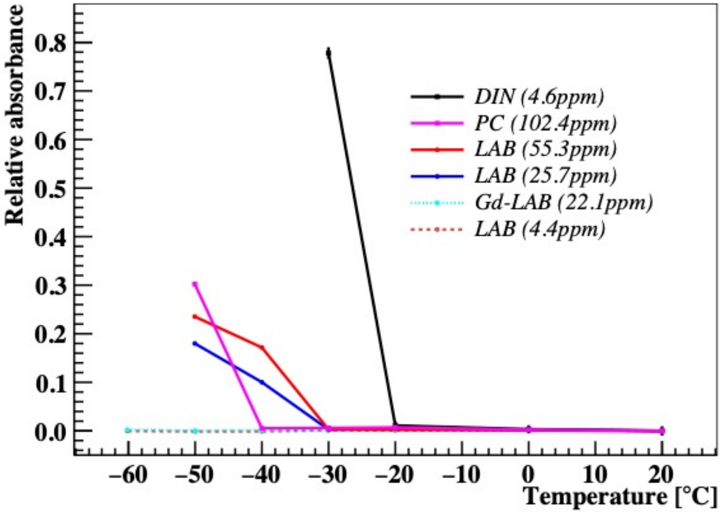
- **R&D challenges**
  - freezing out of water & organic components
  - large number of channels for full optical coverage



Cold LS permits large-scale deployment of SiPMs (TAO)



TAO



TAO

Absorption vs. LS temperature (different LS and bulk materials)

Improving Purification & Characterization

Water

radiopure water of benefit for whole community:

- direct for water-based neutrino detectors
- indirect for water/steam extraction of LS

→ new techniques to go below 10^{-15} g/g U/Th?

WbLS/metal-loaded organic LS

- purification of composite detector materials
- pioneered for Gd+water: divide and purify

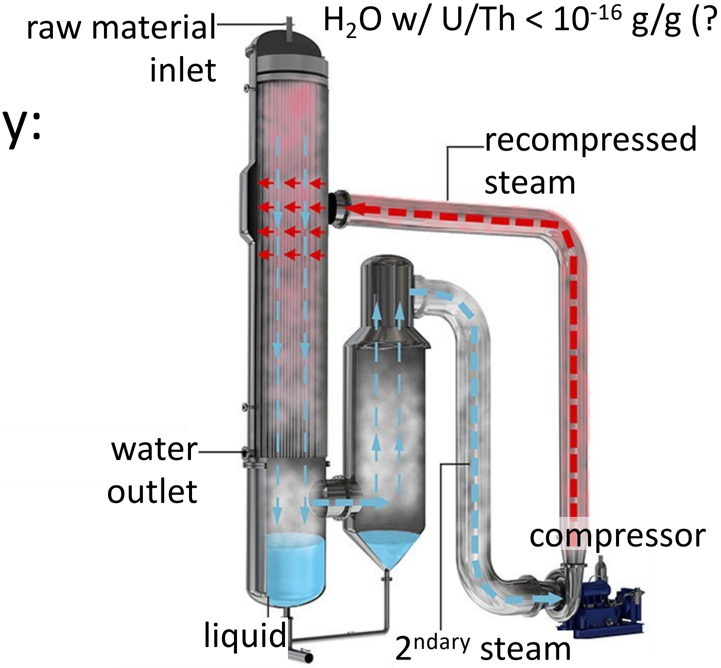
Challenges in Characterization

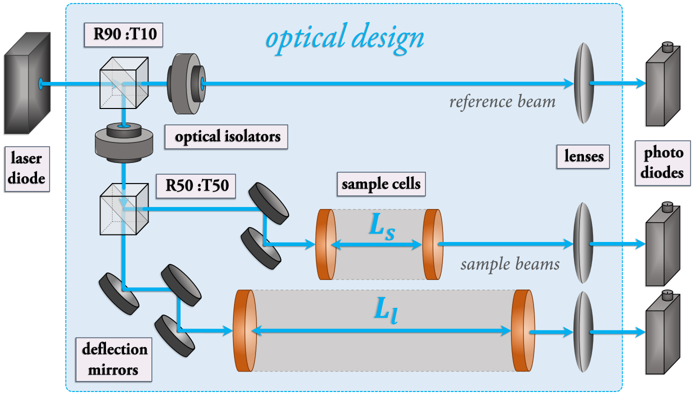
- measure optical attenuation length ≥30m
- table-top → long-arm setups (several meters)
- alternatives?

  e.g. CELLPALS: interferometry of intensity-modulated light pulses in reflective cavities

Mechanical Vapor Recompressor

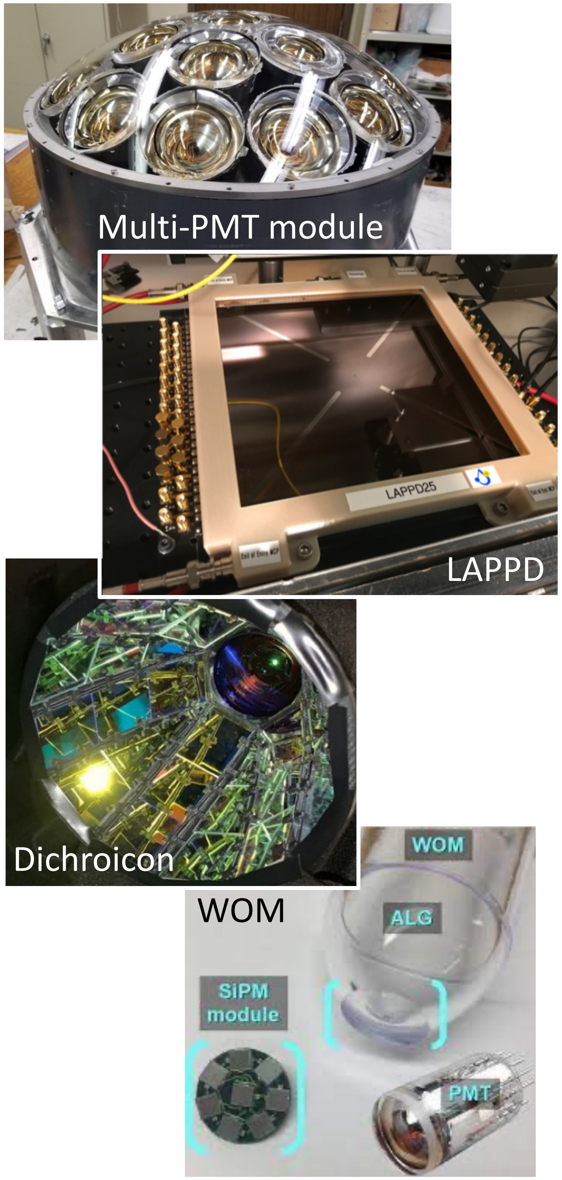
H_2O w/ U/Th < 10^{-16} g/g (?)





CELLPALS interferometry setup (U.Tübingen)

Interfacing new photosensors



Photosensor	**Features**
Large-area PMTs (high-QE & MCP-PMT)	Enhanced light collection
M-DOMs, Multi-PMT modules in water	Exploit granularity for reconstruction
LAPPDs in water/WbLS	ps-timing for improved vertex reco and Č/S separation
Dichroicons in WbLS	Wavelength-separation for hybrid-reconstruction
WOMs in water/LS	Large light collection area optical coupling and emission/absorption spectra
SiPMs in LS	High QE/granularity but cooling for dark noise

+ enhanced light collection:
mirrors/cones, (active) light guides, fibres, metalenses …

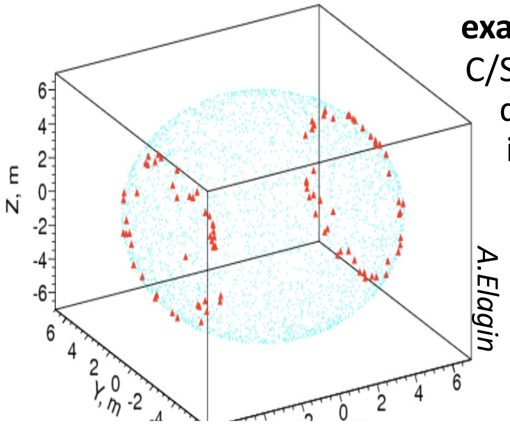
Need for new reconstruction techniques

Challenges

- resolving complicated topologies
  - GeV energies: multi-π/NC events
  - MeV range: 2-track events for 0νββ
- reconstruction of hybrid signals (Cherenkov+scintillation)
- large amounts of high-resolution or wavelength-dependent data

Approaches

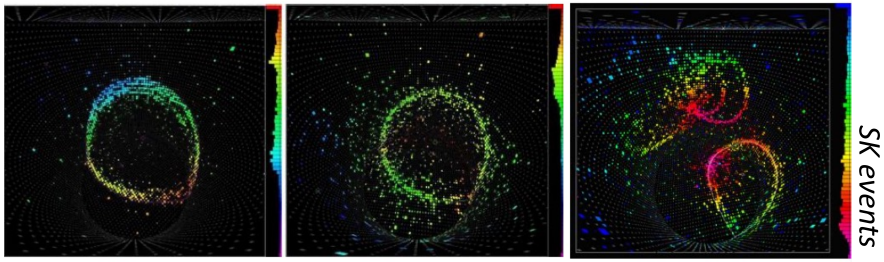
- “standard” likelihood methods
- machine-learning techniques
- topological reconstruction



A.Elagin

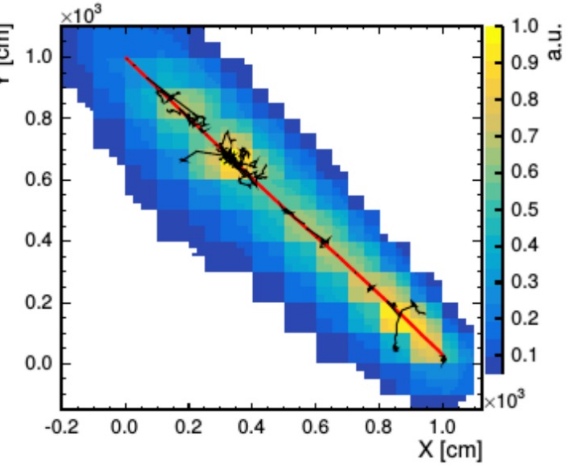
example: hybrid C/S signal for BG discrimination in 0νββ decay

ring topologies vs. machine learning



Muon Electron Multi-ring

SK events

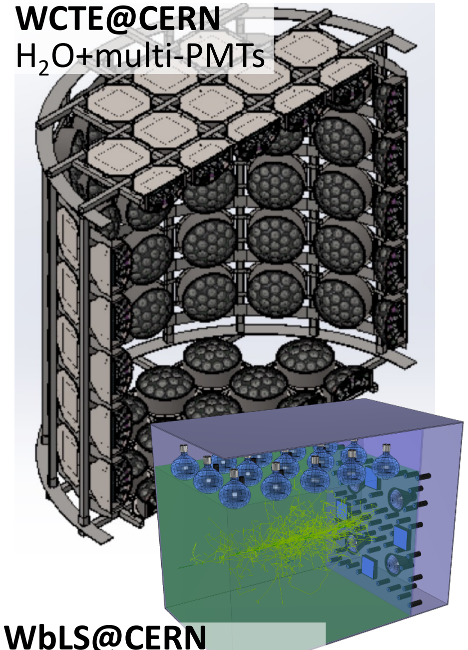


topological reconstruction of light emission along a 3-GeV muon track in LS (Wonsak et al.)

Conclusions and Outlook

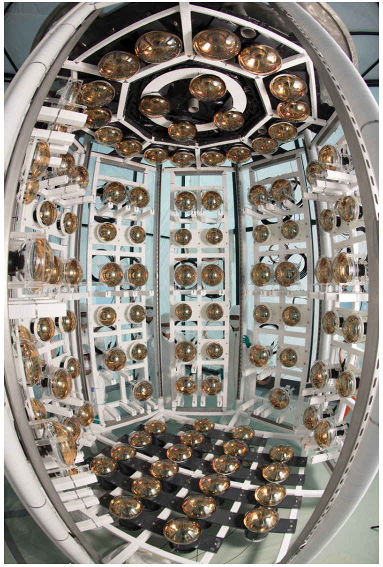
- substantial progress over the last few years:
  - refinement of existing techniques
  - entirely new experimental concepts
  - new “auxiliaries”, e.g. photo sensors, reconstruction
- **next years:** put new concepts to the test in ton-scale setups in underground labs, particle beams …

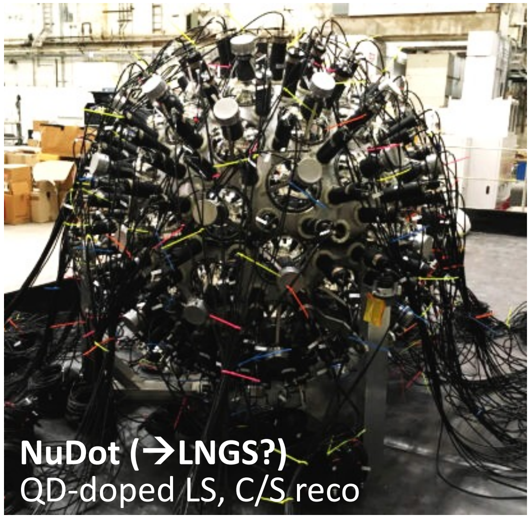
WCTE@CERN
H_2O+multi-PMTs



WbLS@CERN
LAPPDs/Dichroicons

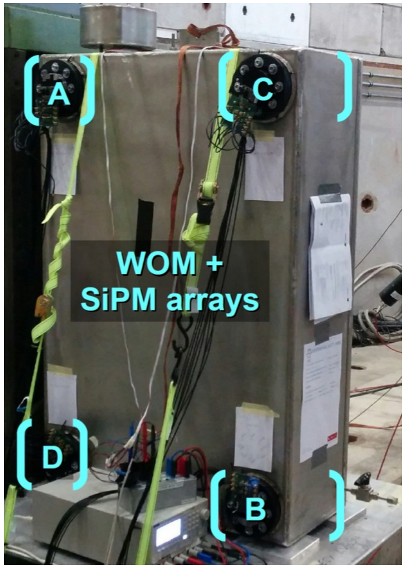
ANNIE@FNAL
LAPPDs, H_2O+Gd, WbLS





NuDot (→LNGS?)
QD-doped LS, C/S reco

SHIP-SBT test cell @CERN
LS+WOM+SiPM readout



Questions for the panel discussion

- **too large:** What is the maximum size and attenuation length we can achieve for scintillator detectors?

- **too little:** Can metal-loaded scintillator detectors hope in the long run to compete with other 0νββ experiments?
  And what is the best way to optimize energy resolution?

- **too much:** Are hybrid detectors combining Cherenkov and scintillation signals getting the best or the worst of two worlds?

Thank you for your attention!