LiquidO R&D and coming projects

IRN Neutrino - KIT Karlsruhe

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for the LiquidO Collaboration

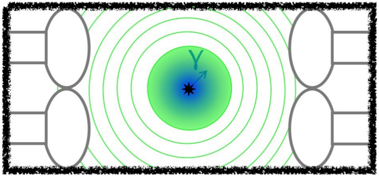
November 27, 2023

Liquid scintillators neutrino detectors

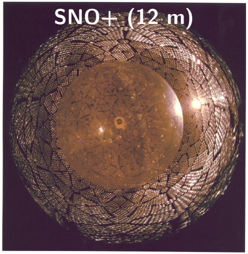
Neutrinos interactions produce scintillation light which is wavelength shifted and transported to PMTs at the edges $\rightarrow$ **high transparency !**

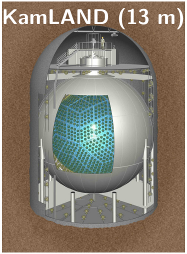
Many advantages:

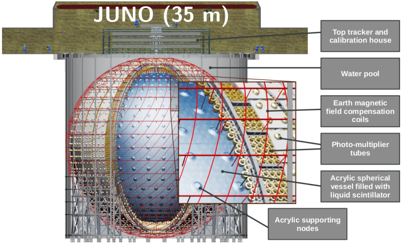
- homogeneous target
- scale and cost
- energy resolution
- radio-purity & self-shielding
- isotope loading ($\sim$3%)



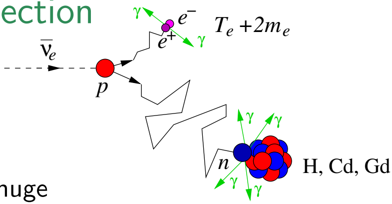
But PMT timing resolution (1-5 ns)
and photo-coverage wash out the events topology $\lesssim$ 0.5 m.







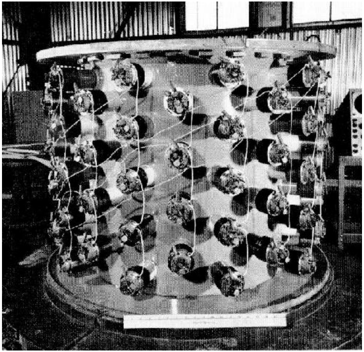
Reactor electron anti-neutrinos detection



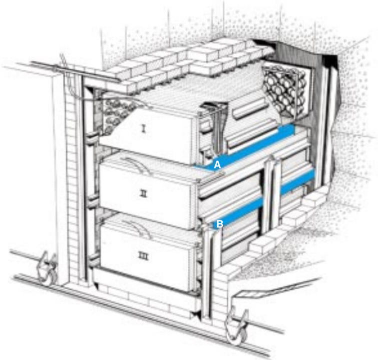
Inverse beta decay: $\bar{\nu}_e \; p \rightarrow e^+ \; n$

At shallow depth the cosmic background is huge

Hanford - 1953



Savannah River - 1956



10 times more cosmic rays than $\bar{\nu}_e$

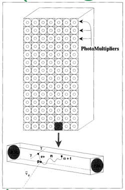
Discovery of the neutrino !

Segmented neutrino detectors

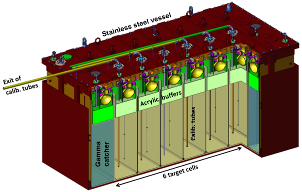
Shallow depth neutrino detectors use segmentation

- e^{+} n : time and space coinc + 2 γ 511 keV
- particle tracking for high energy neutrinos

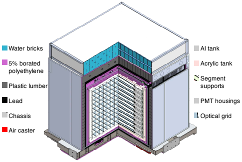
Bugey-3 (500 kg - 8.5 cm)



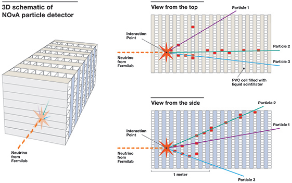
STEREO (1.6 t - 36 cm)



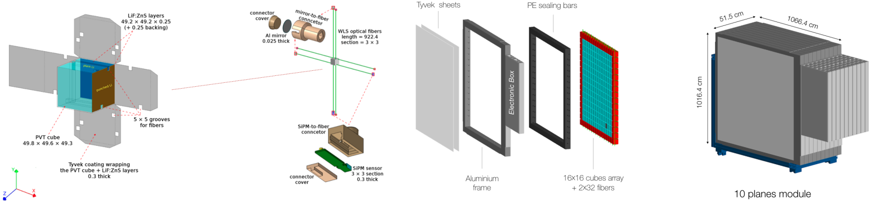
PROSPECT (3.7 t - 15 cm)



Noνa (14 kt - 6×4 cm)

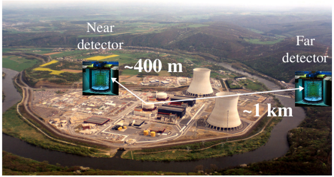


SoLid (1.6 t - 5 cm)



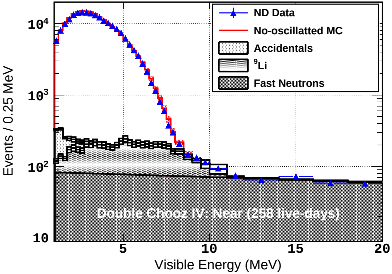
Dead materials introduced to build the segmented volumes

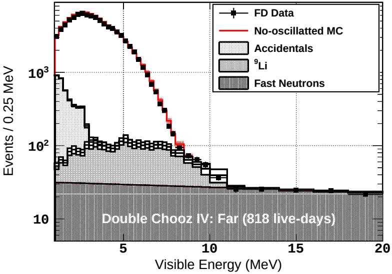
Double Chooz energy spectra



Example of Double Chooz background:

- Accidentals: $\gamma - n$ fortuitous coincidences
- Cosmogenics: $\beta^- - n$ decays (mostly ^{9}Li)
- Fast neutrons: p-recoil + n-capture or two n





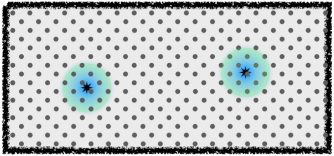
[Nature Physics 16, pages 558–564 (2020)]

None of these backgrounds has a positron-like prompt event !

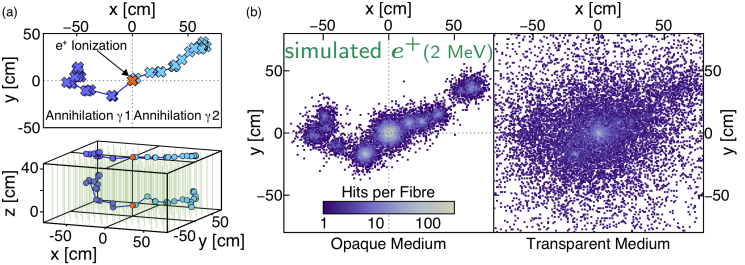
LiquidO principle

Opaque liquid scintillator to preserve local information of interactions

Dense network of **wavelength shifting fibers** to collect the scintillation light at the interaction points and transport it to the **SiPMs**



Preserve spatial precision ($\sigma_{xy,z} < 1$ cm) and fast timing ($\sigma_t \sim 0.1$ ns)

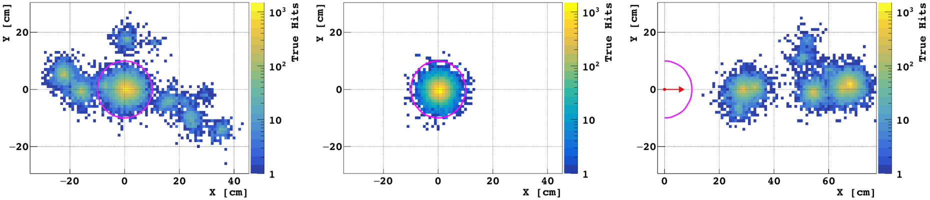


[Nature Comm. Phys. 4 (2021) 273]

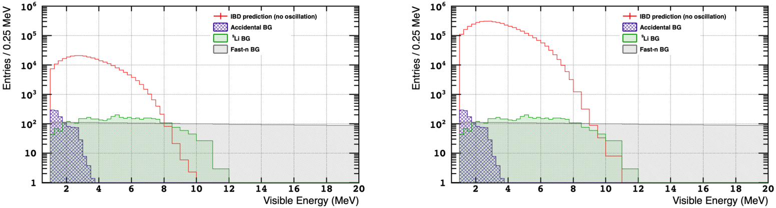
PID and background rejection

Unprecedented particle identification (PID) at MeV scale

e^+ (2 MeV) - e^- (2 MeV) - γ (2 MeV)

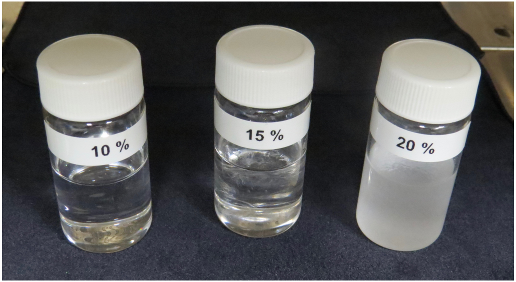


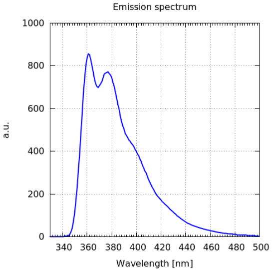
Double Chooz near (400 m) - AM-OTech (35 m) bkg / 10



Opaque liquid scintillator

Our first opaque scintillator: **NoWash** scintillator [arXiv:1908.03334]
(80% LAB + 20% paraffin wax + 0.3% PPO)



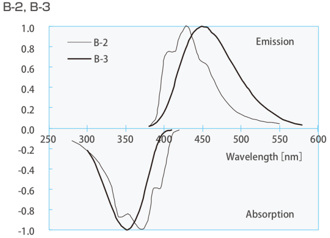


- Short scattering length ($<$1 cm) and moderate absorption length ($>$2 m)
- Opacity depends on the paraffin concentration or temperature

Other candidates being investigated: μ-crystals [arXiv:1807.00628], emulsion, water-based [arXiv:2301.09608]...

LiquidO light collection

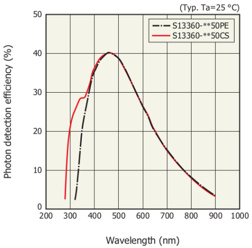
Kuraray B3 fibers produced in Japan



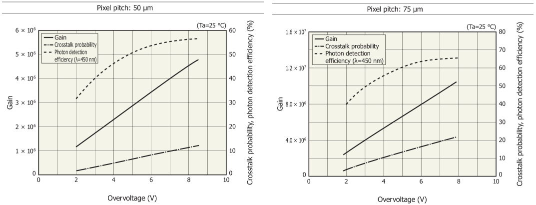
Materials

		Materials	Refractive index	Density (g/cm³)
Core		Polystylene(PS)	n_D=1.59	1.05
Cladding	for single cladding inner for multi-cladding	Polymethylmethacrylate (PMMA)	n_D=1.49	1.19
	outer for multi-cladding	Fluorinated polymer (FP)	n_D=1.42	1.43

SiPMs Hamamatsu MPPCs S13360-1350 or 1375



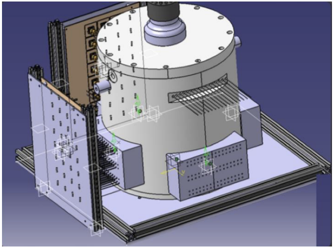
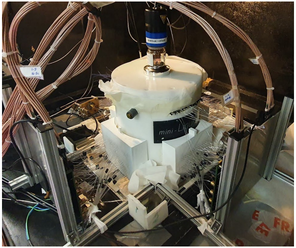
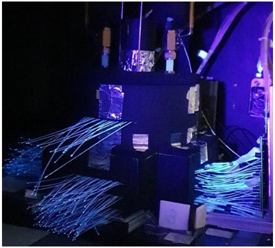
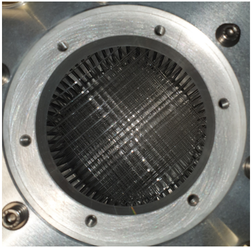
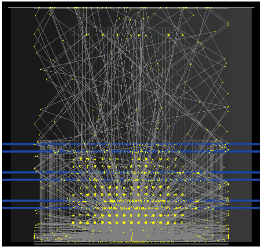
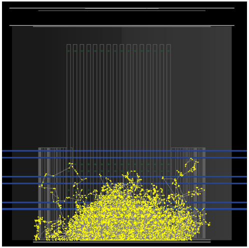
SPTR < 190 ps [NIM A 695 (2012) 354-358]



*SPTR: single photon time resolution FWHM

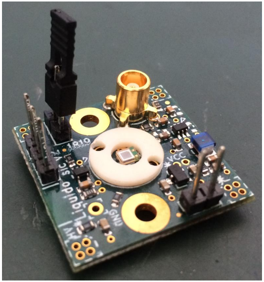
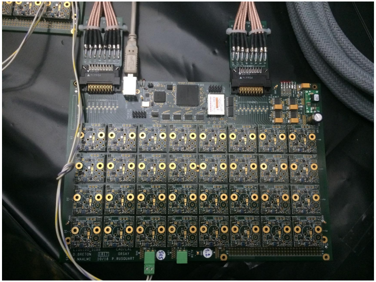
Mini-liquido: experimental demonstration since 2021

- 10 L prototype + thermal control [5-40°C]
- 64 fibers + 1 PMT + WaveCatcher (3.2 GS/s)
- Mono-energetic electron beam (^{90}Sr spectrometer 0.4-1.8 MeV)

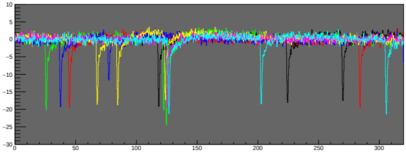







Mini-liquido: electronics

- SiCs boards: SiPM - 20-dB RF amplifier - T°C probe
- SiBB: 32 ch - LV & HV - DACs and T°C HV loop - interfaces

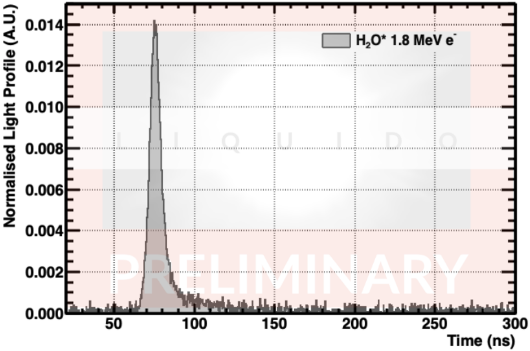



Digitization with WaveCatcher [NIM A 629 (2011) 123-132]



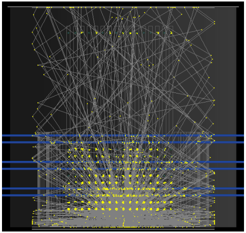
Mini-liquido: water phase

First data taken with water to test the detector timing



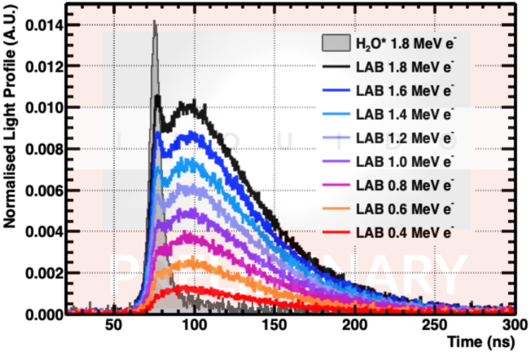
Transparent medium

- low light level due to Cherenkov only



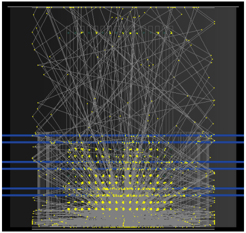
Mini-liquido: LAB phase

Timing potential: Cherenkov vs scintillation



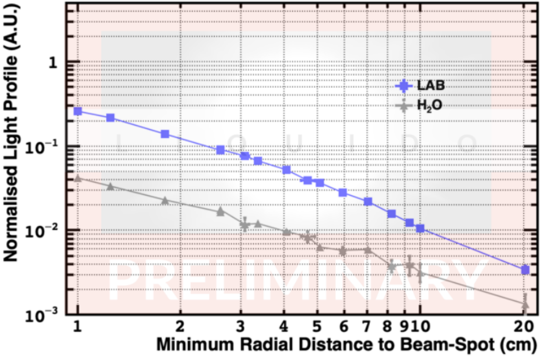
Transparent medium

- LAB without shifter (slow)
- Cherenkov peak in agreement with H_2O
- Cherenkov threshold visible



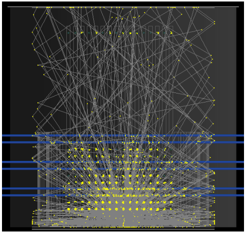
Mini-liquido: LAB phase

Light collection as a function of fiber distance to e^- beam



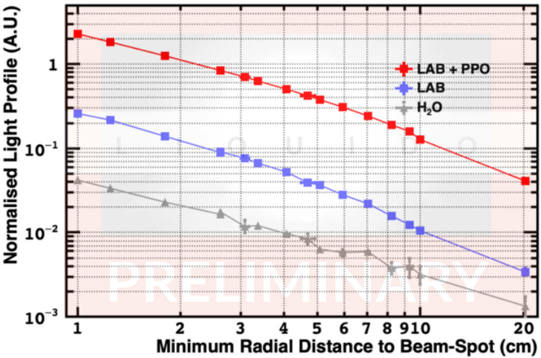
Transparent medium

- LAB without shifter (slow)
- more light than H_2O
- low acceptance
- similar pattern



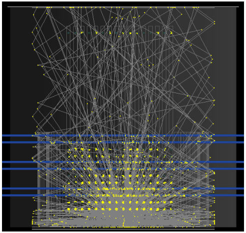
Mini-liquido: LAB + PPO

Including wavelength shifter PPO (≤3 g/L)



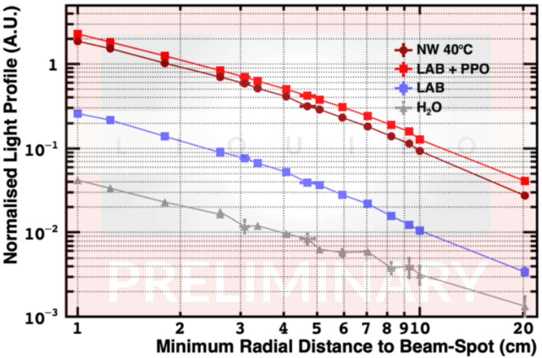
Transparent medium

- LAB + PPO
- more light collected by the fibers
- similar pattern



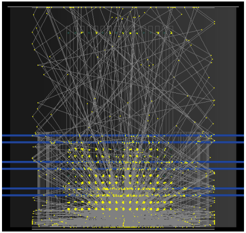
Mini-liquido: NoWash 40°C

NoWaSH scintillator at high temperature



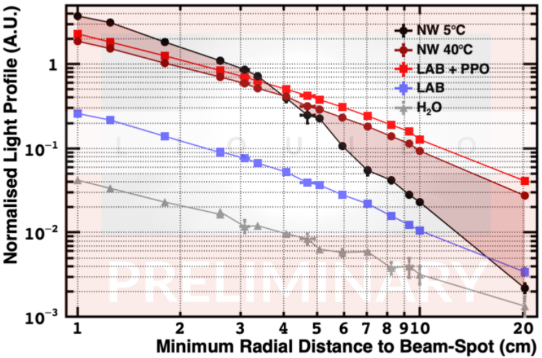
Transparent medium

- NoWaSH 40°C
- light-loss due to 20% paraffin
- no sign of absorption compared to LAB



Mini-liquido: NoWash 5°C

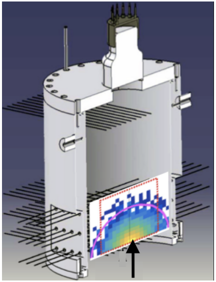
NoWaSH scintillator at low temperature



Demonstration of the light confinement with opaque scintillator!

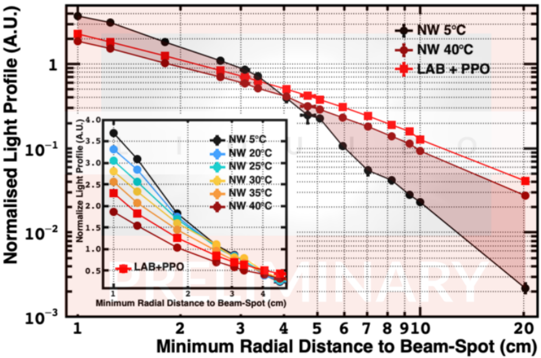
Opaque medium

- changing pattern
- more light close to the beam
- less light far from the beam
- light-ball ~ 4 cm



Mini-liquido: NoWash 5°C

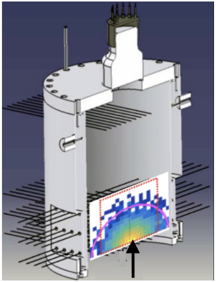
NoWaSH scintillator at low temperature



Publication coming soon

Opaque medium

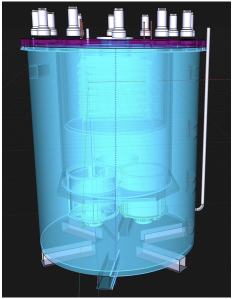
- regular transition from transparent to opaque
- almost twice more light in the first fibers



Coming projects

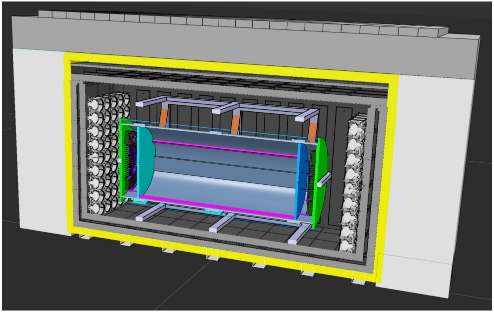
Two new projects in preparation

Mini-γ @ IJCLab
(under construction)



$\sim$100 kg
256 fibers ($\times$2 SiPMs)
Reconstruction 511 keV γ's
Demonstration of PID
Test different scintillators

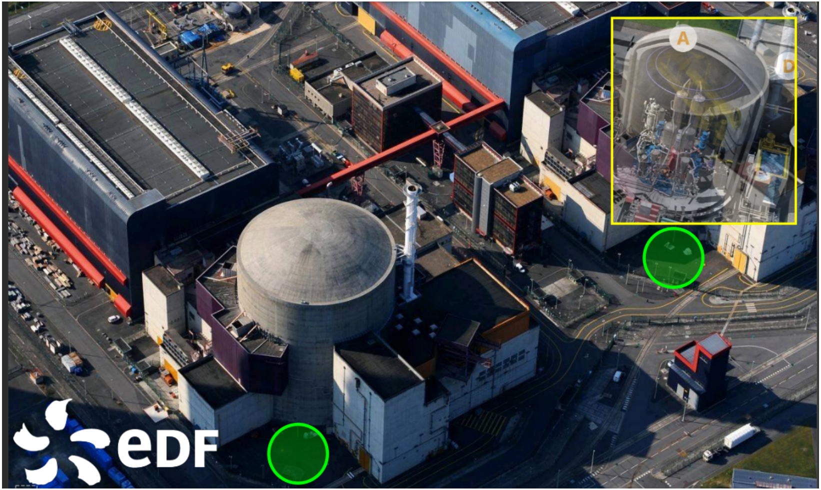
AM-OTech @ Chooz
(under preparation)



[5-10] tons target
$\sim$10000 fibers
EIC - UKRI funded
Reactor physics + innovation
2022-2027

AntiMatter-OTech

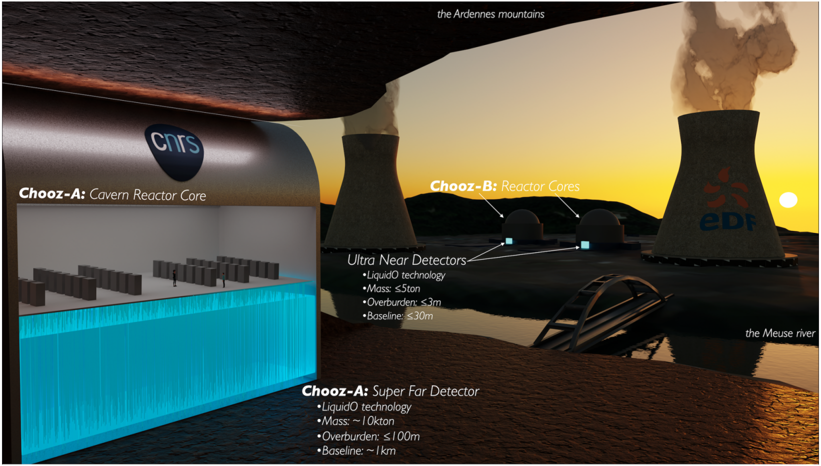
Ultra-near site @ Chooz 2×4.2 GW$_{\text{th}}$ - $L_\nu \approx 35$ m



Expected rate 25000 $\overline{\nu}_e$ / day - 10M $\overline{\nu}_e$ / year + some reactor off data

Future prospects

SuperChooz project $\sim$10 ktons - after 2030

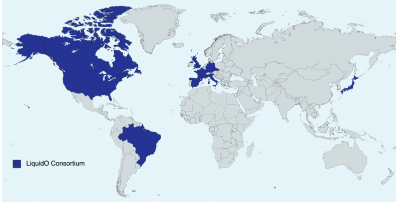


Physics program: improve precision on θ_{13} and Δm^2_{31}, indirectly improve δ_{CP}, test unitarity of PMNS matrix

Conclusion and perspectives

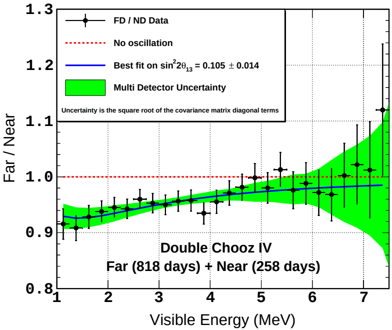
- Large neutrino detectors very efficient thanks to transparancy but are blind to the event topology
- Segmented neutrino detectors try to detect the positron and the annihilation γ's with more or less success
- LiquidO technology tries to gather the advantages of both techniques using an opaque liquid scintillator
- Thanks to R&D effort the confinement of the scintillation light has been demonstrated in two prototypes
- New projects are coming: mini-γ (liquidO PID) and AM-OTech (reactor anti-neutrinos)
- Possible demonstration for future project SuperChooz

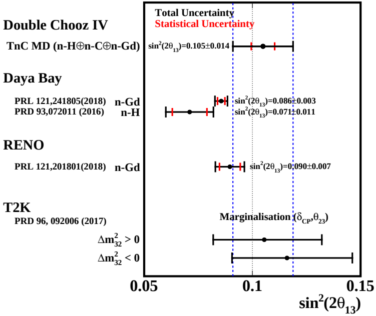
https://antimatter-otech.ijclab.in2p3.fr/
https://liquido.ijclab.in2p3.fr/



Thank you for your attention

Double Chooz θ_{13}

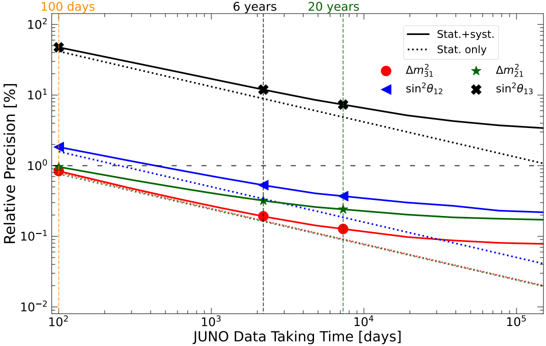




JUNO precision measurements

Sub-percent precision will be obtained by JUNO, except for θ_{13}

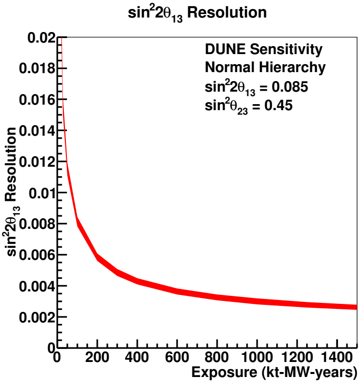
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)	± 0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	± 0.0007 (3.2%)	± 0.010 (47.9%)	± 0.0026 (12.1%)	± 0.0016 (7.3%)

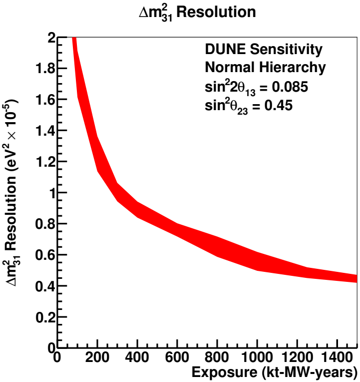


Chin.Phys.C 46 (2022) 12, 123001 - [arXiv:2204.13249]

DUNE θ_{13} and Δm^2_{31}

The precision on θ_{13} will be comparable to the actual precision of reactor experiments





PMNS unitarity triangle