A New Reactor Neutrino Experiment at Chooz

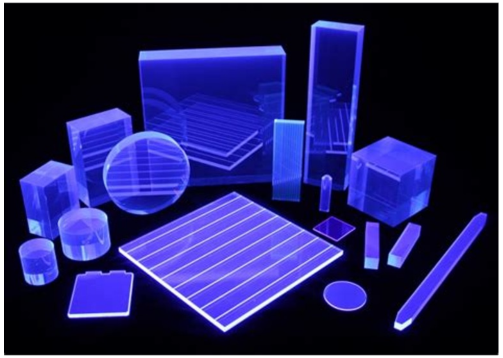
Thiago Bezerra, for the CLOUD Collaboration

Les Rencontres de Physique de la Vallée d'Aoste, LA THUILE 2024

9th March 2024

Quick review on scintillators

→ **Radiation detection with scintillators, 80 years "business"**



→ **Converts deposited energy into light**

→ **Light converted to electric signals**

→ Detection and calorimetry

→ ***<u>Requires transparent media for light propagation</u>***

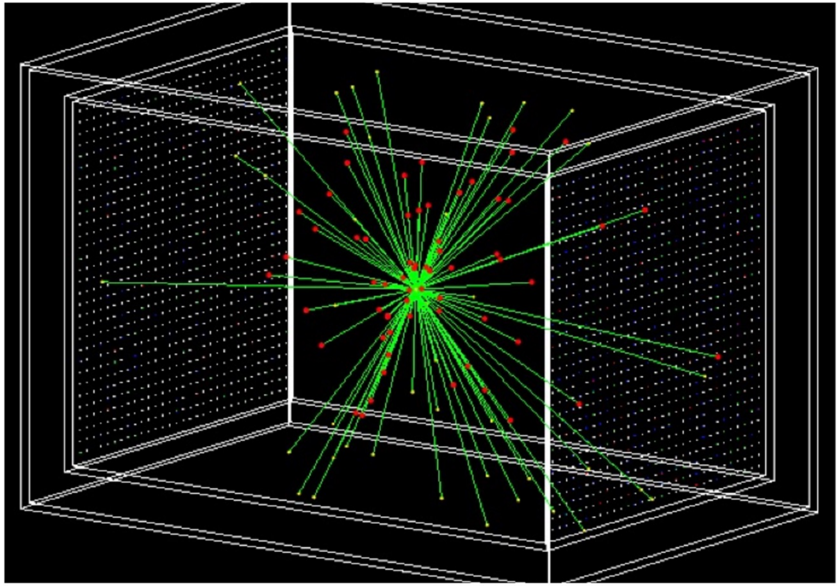
The <u>*novel*</u> opaque scintillation technique

Two types of opacity

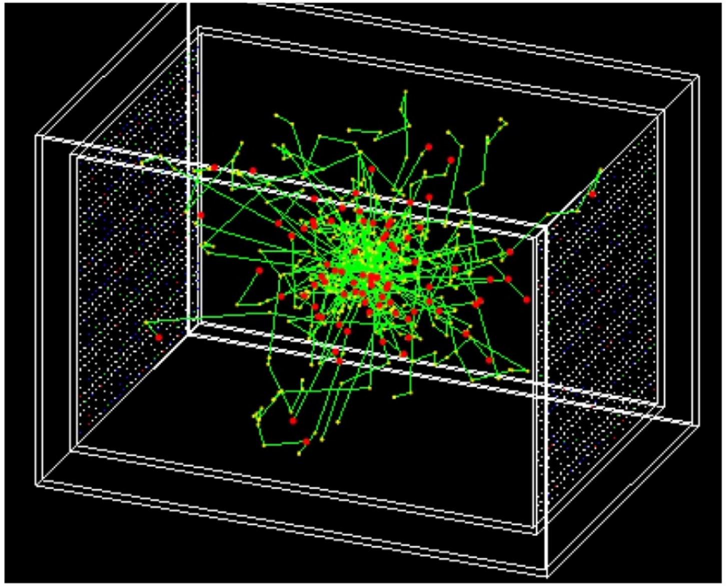
Short *absorption* length
Short scattering length

Long *absorption* length
Short scattering length

Light paths

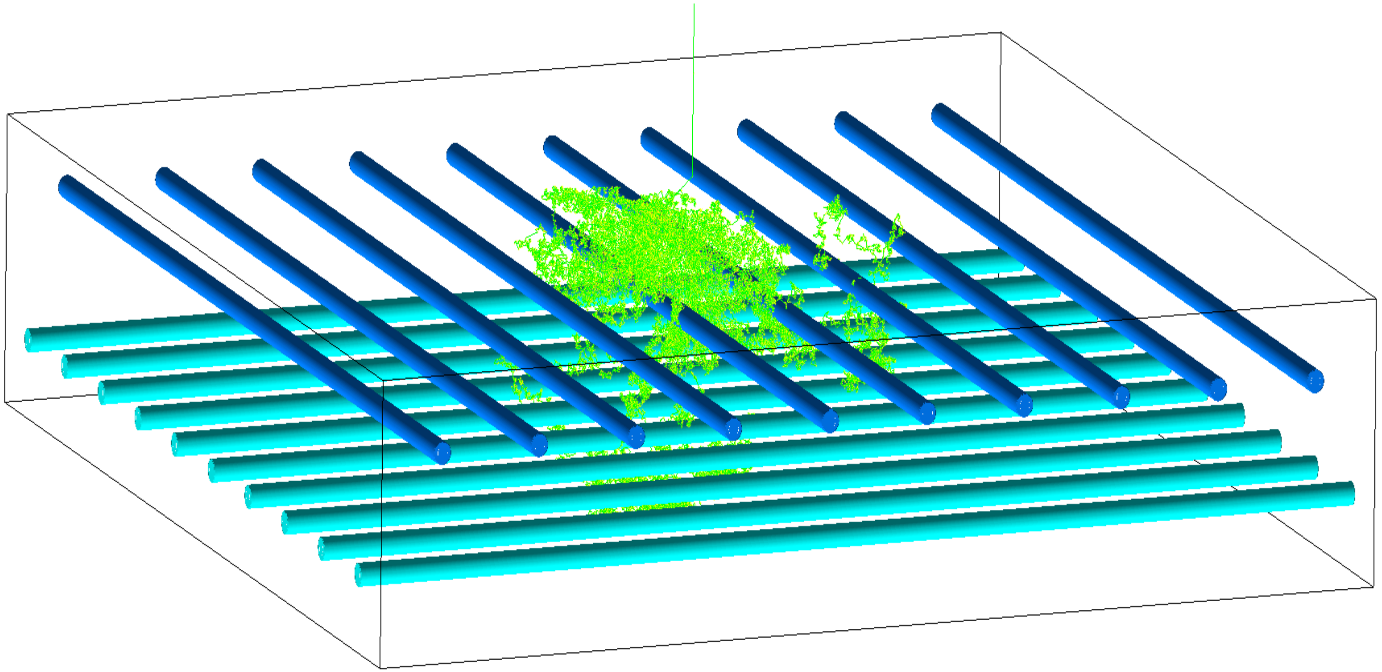


Transparent scintillator
Straight paths

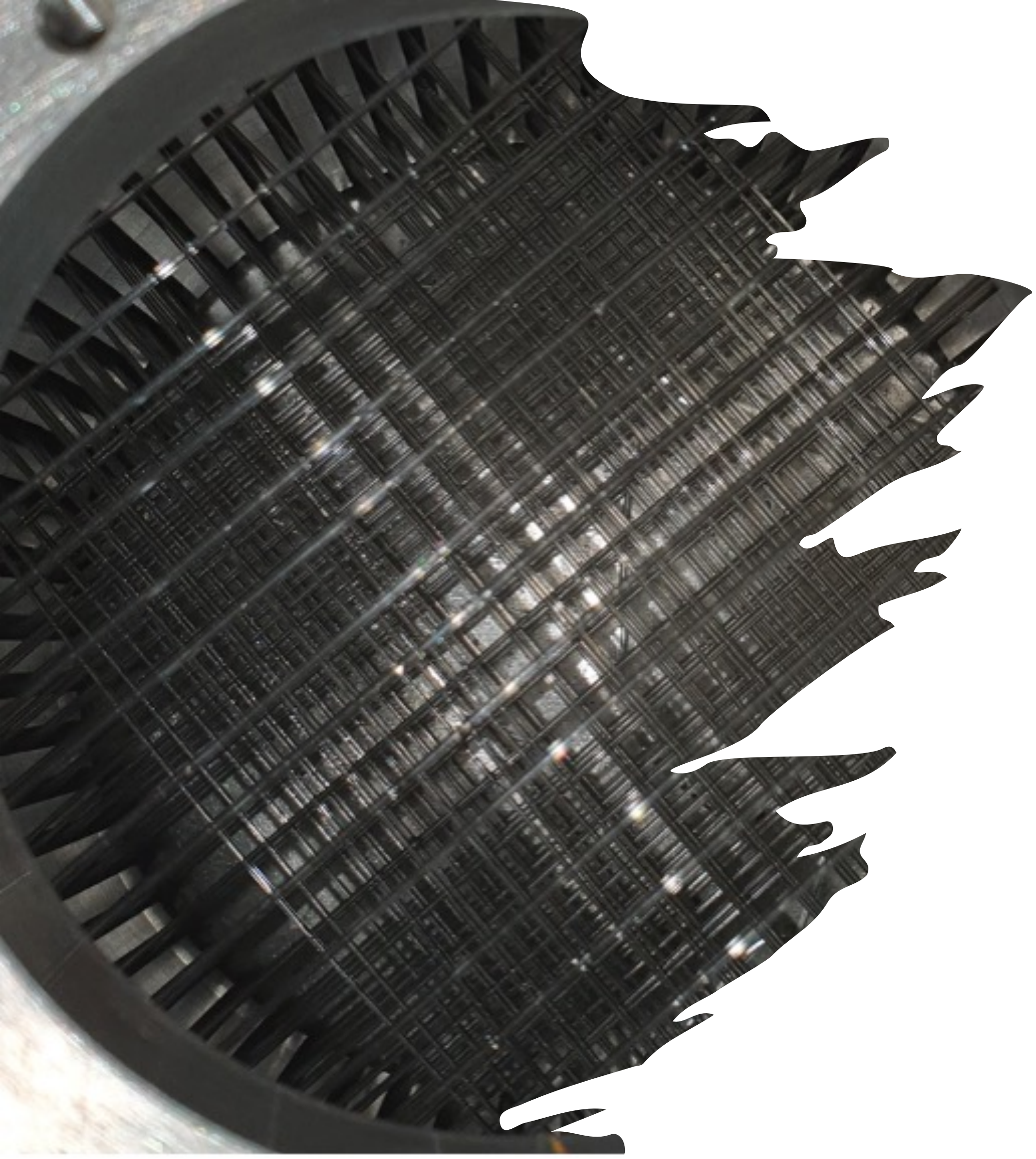


Opaque scintillator
Random walk

Confine energy deposition locally



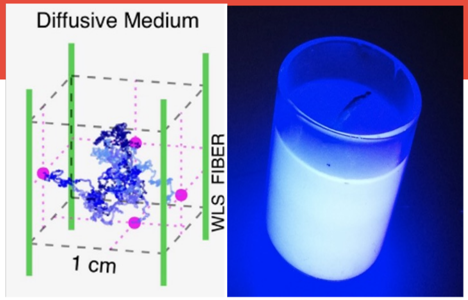
Readout: wavelength shifting fibres + SiPMs

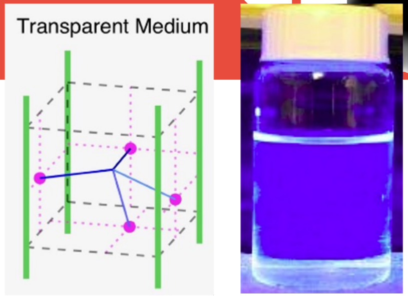


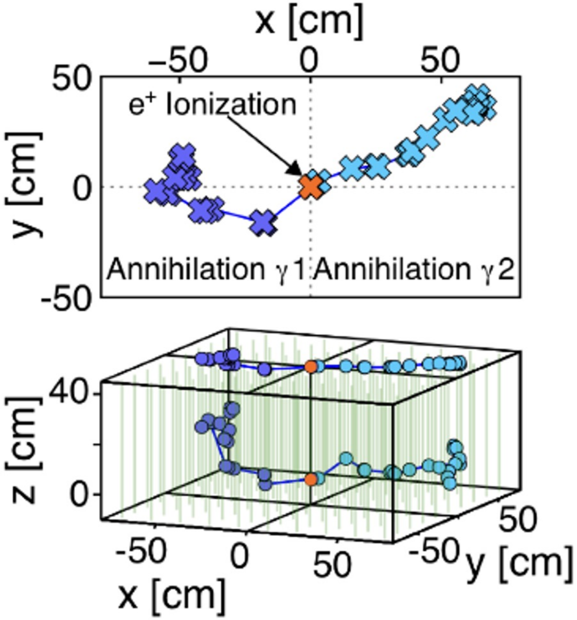
How does it compare to traditional particle detection?

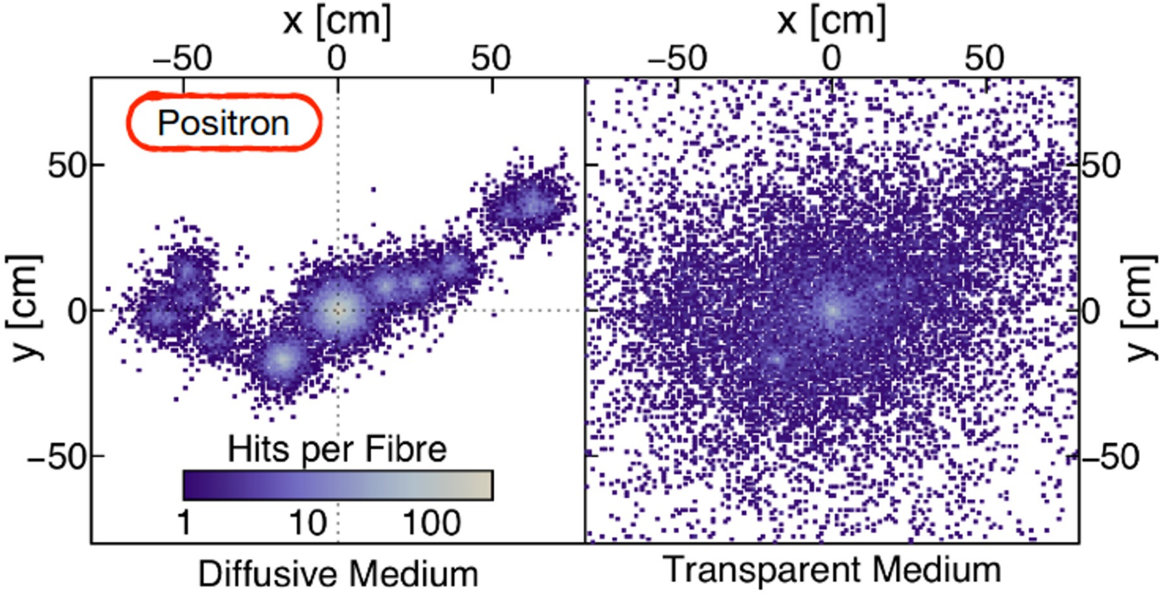
A new approach: LiquidO

Positron **(e⁺)** of 1 MeV

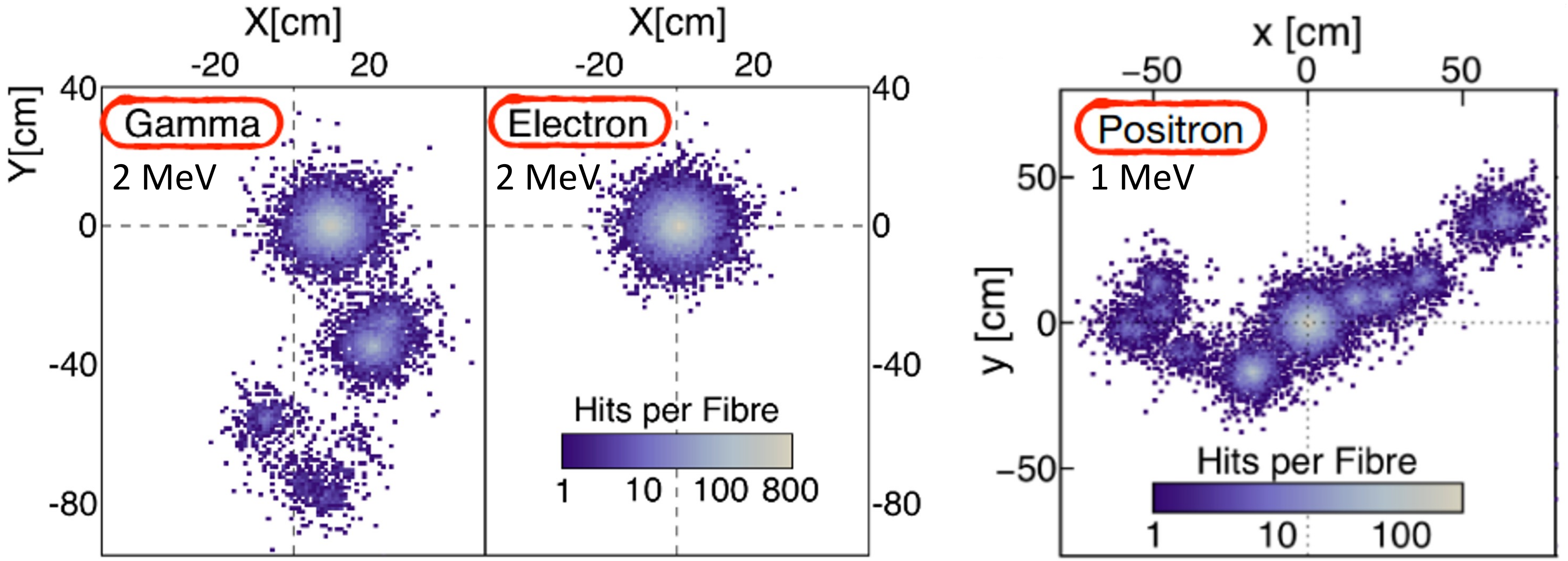






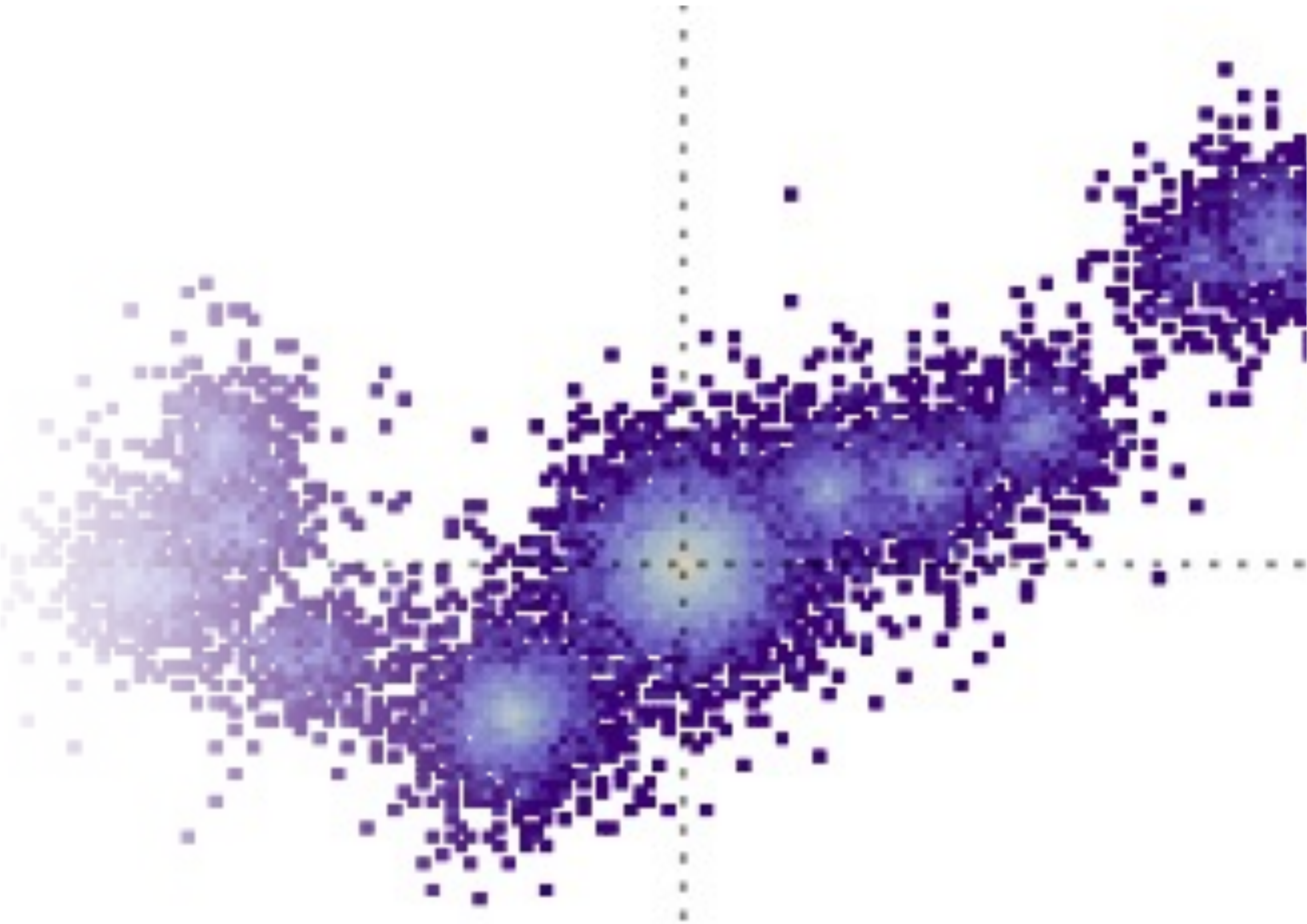


Powerful particle identification



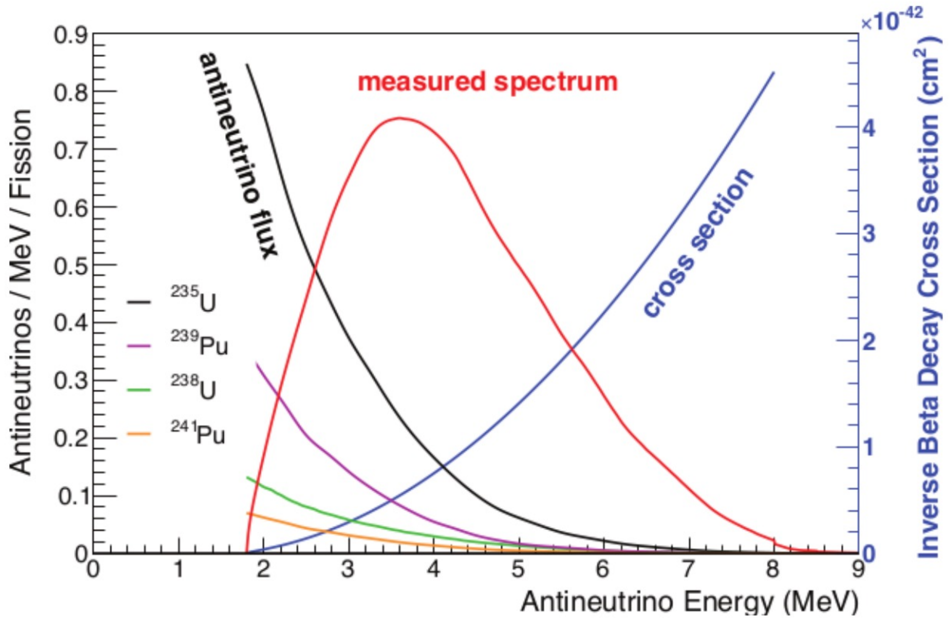
Cannot separate these 3 on an event-by-event basis with transparent scintillator!

Implications of High Resolution Imaging

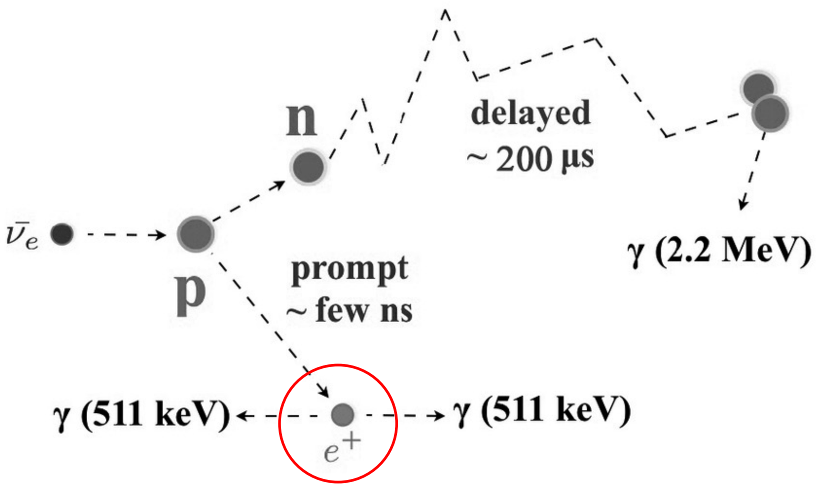


Impact on reactor neutrino detection

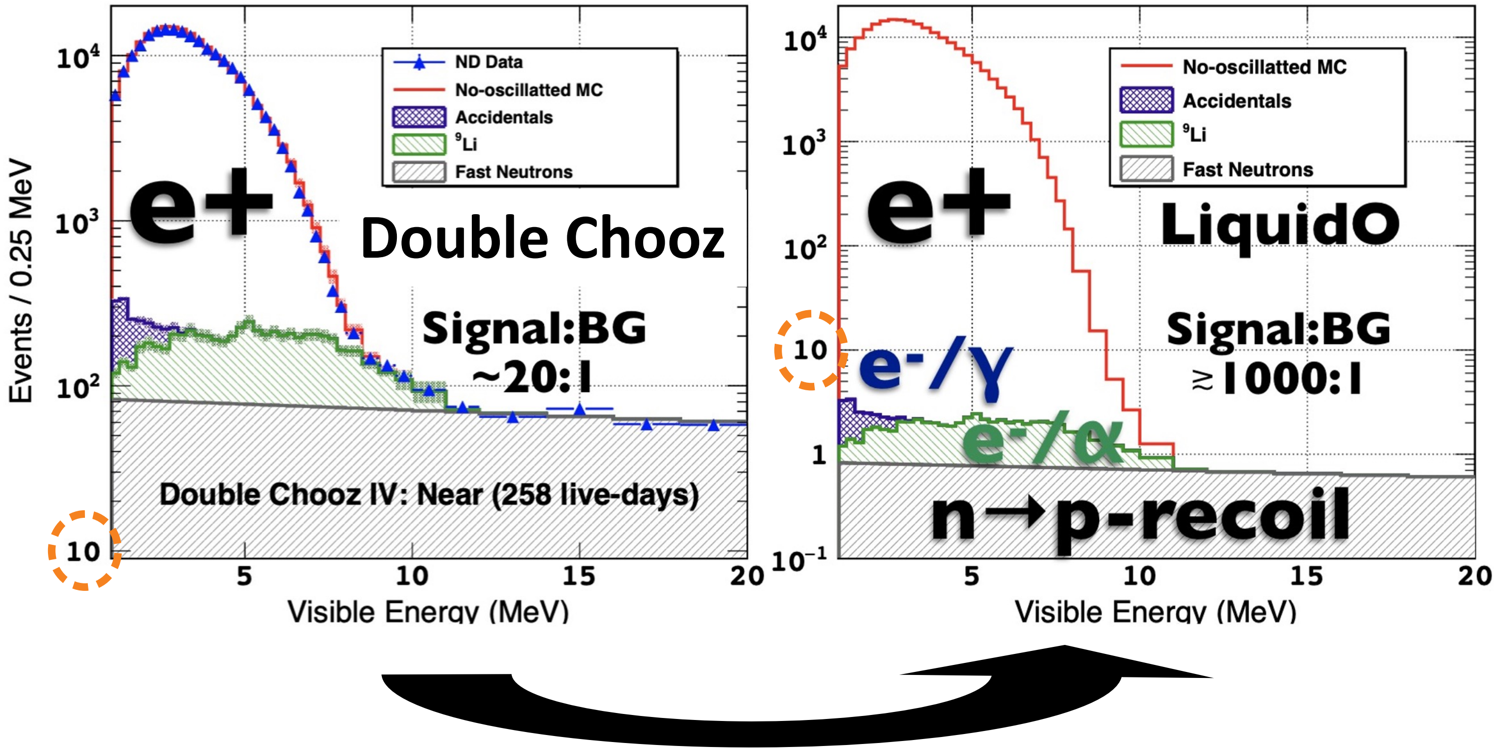
Nuclear reactors are a powerful anti-ν_e source!



Inverse Beta Decay reaction:



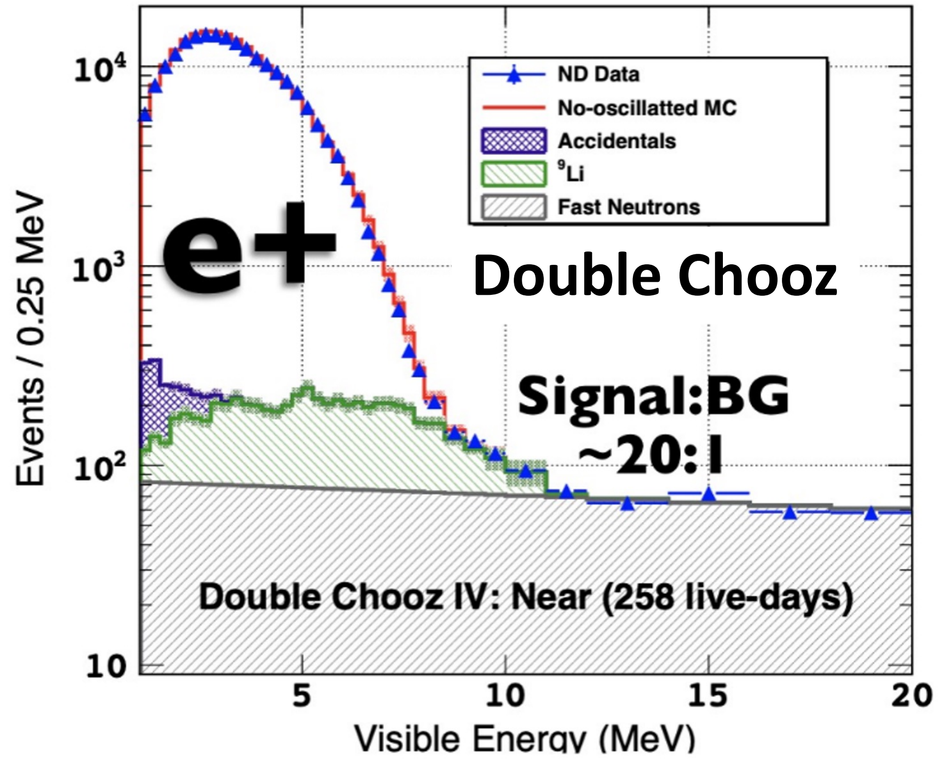
Impact on reactor neutrino detection

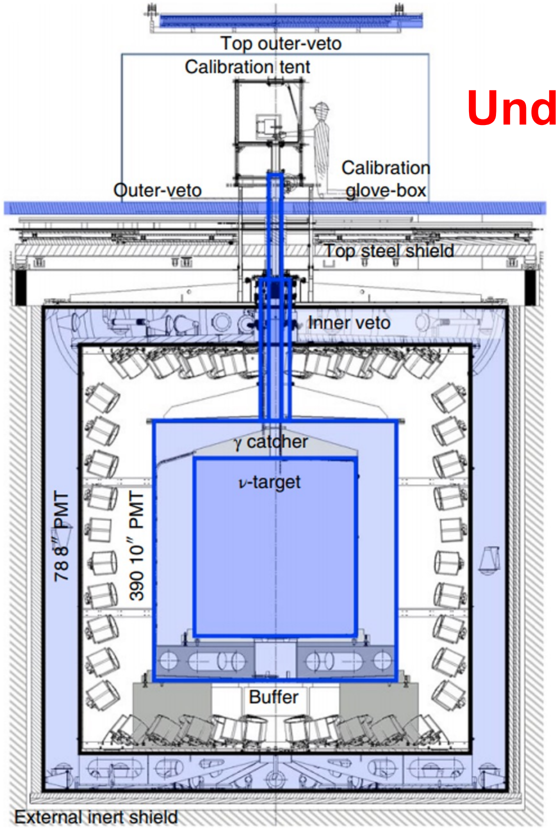


Applying expected PID for BG rejection (100:1)

Expensive way to veto backgrounds

Inverse beta decay signal → positron

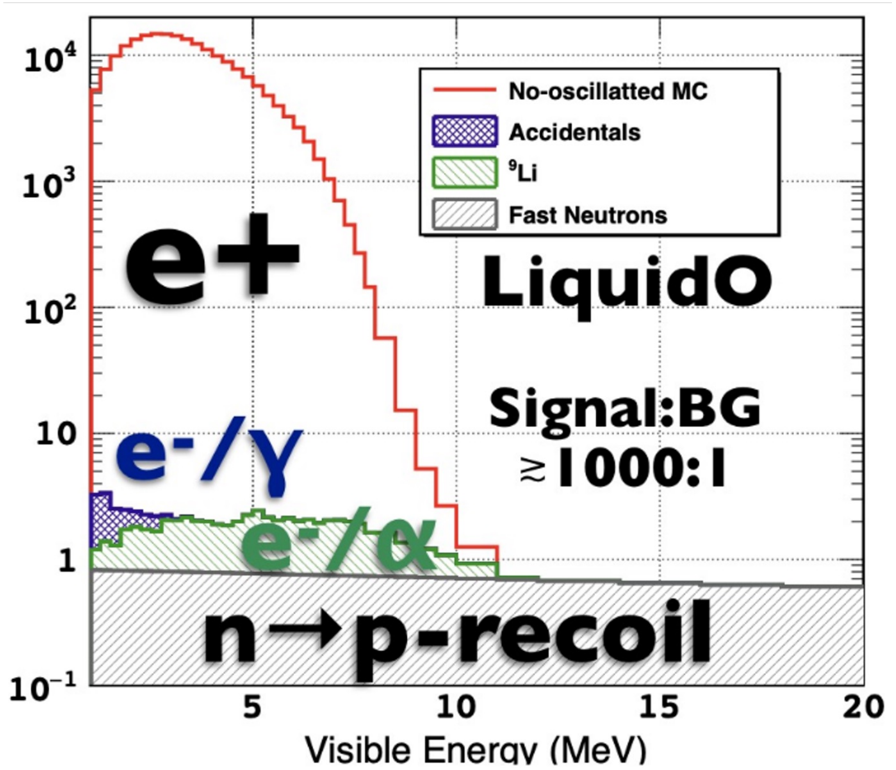


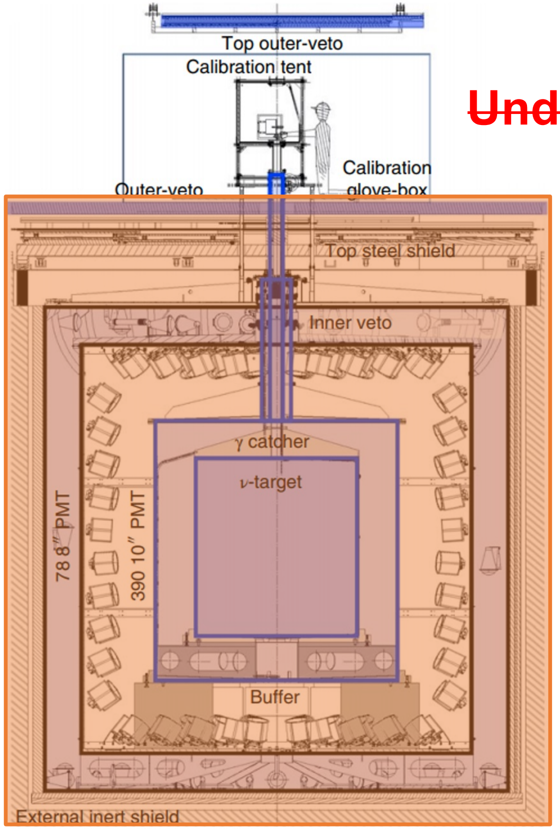


Underground

Simpler way to veto backgrounds

CLOUD

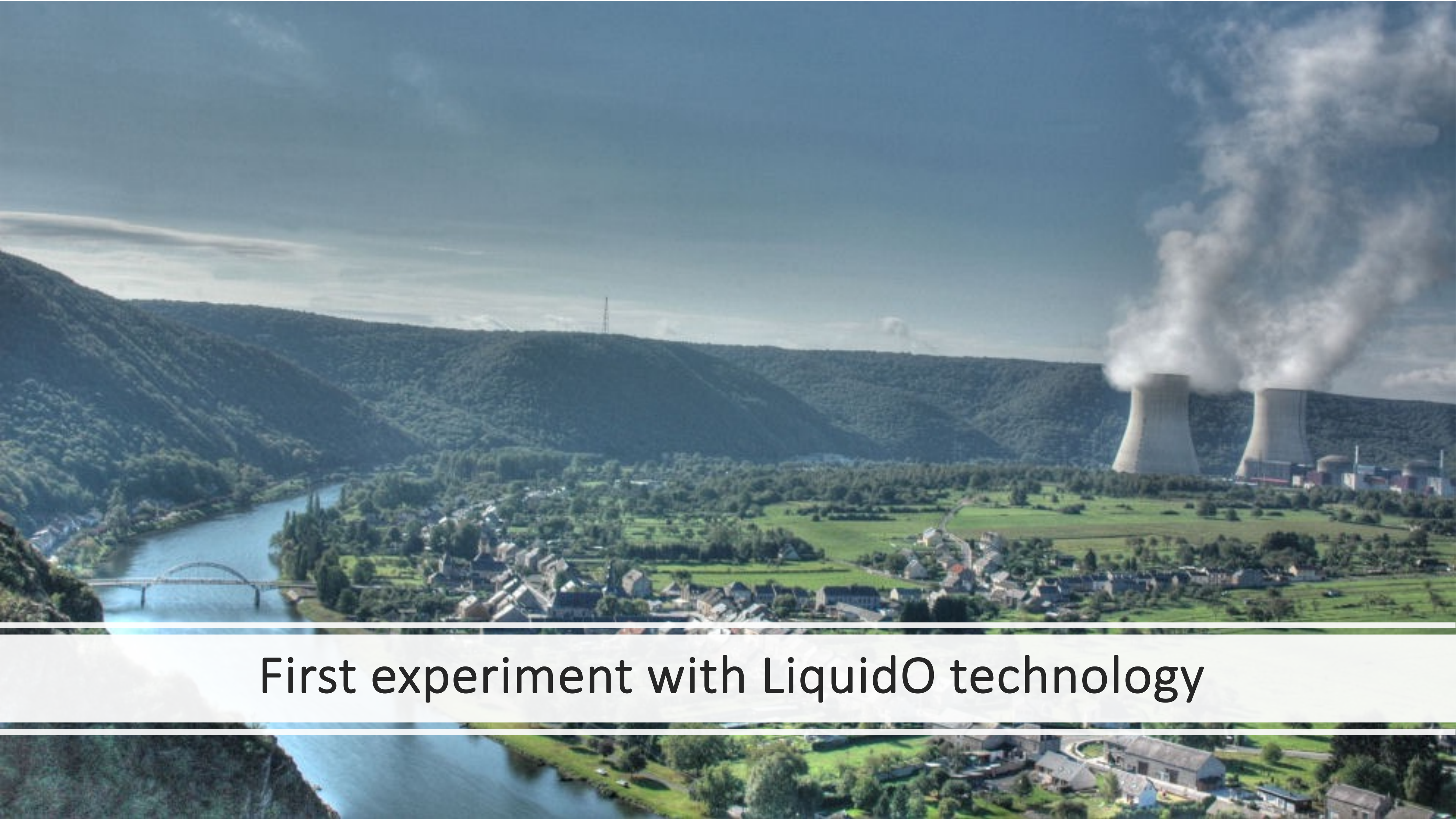




~~Underground~~

All available space as target

10 fold increase!



First experiment with LiquidO technology

European Innovation Council

UK Research and Innovation

CLOUD

International Collaboration:

- **Électricité de France, EDF** (France) — first time in neutrino science
- **LP2I Bordeaux** (France)
- **Brookhaven National Laboratory** (USA)
- **Charles University** (Czechia)
- **CIEMAT** (Spain)
- **IJCLab / Université Paris-Saclay** (France)
- **Imperial College London** (UK)
- **INFN-Padova** (Italy)
- **Instituto Superior Técnico** (Portugal)
- **Johannes Gutenberg-Universität Mainz** (Germany)
- **Pennsylvania State University** (USA)
- **Pontifícia Universidade Católica do Rio de Janeiro** (Brazil)
- **Queen’s University** (Canada)
- **Subatech / Nantes Université** (France)
- **Tohoku University / RCNS** (Japan)
- **Universidad de Zaragoza** (Spain)
- **Universidade Estadual de Londrina** (Brazil)
- **University of California Irvine** (USA)
- **University of Michigan** (USA)
- **University of Sussex** (UK)

⟹ **20 institutions in 11 countries**

Spokespersons:

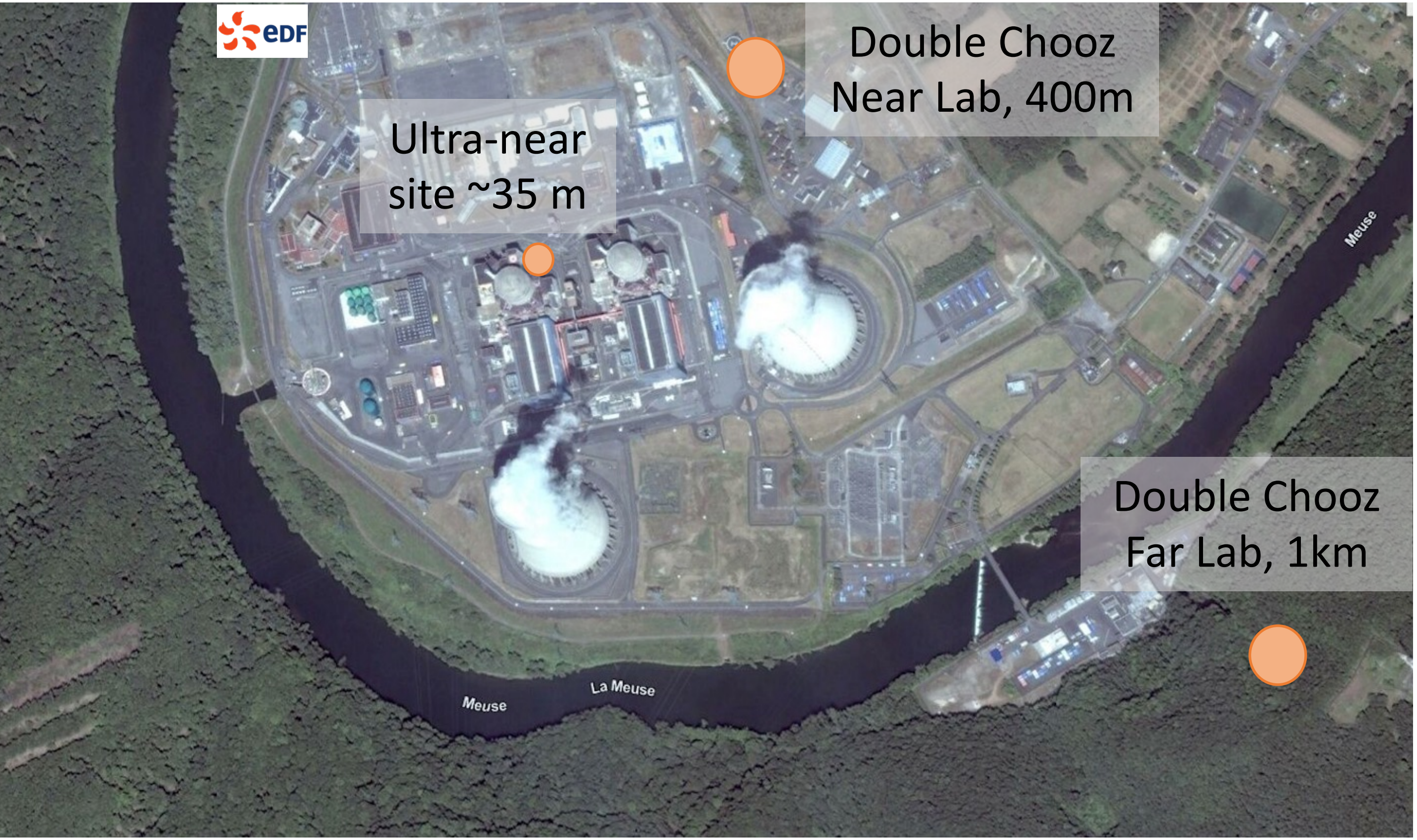
- A. Cabrera — IJCLab / Université Paris-Saclay (France)
- J. Hartnell — Sussex University (UK)

IB Chair:

- M. Chen — Queen’s University (Canada)

https://antimatter-otech.ijclab.in2p3.fr/ [AMOTech]
https://liquido.ijclab.in2p3.fr/nucloud [via LiquidO]

Chooz LiquidO Ultra-near Detector



5~10-ton LiquidO detector
@ Chooz reactors site

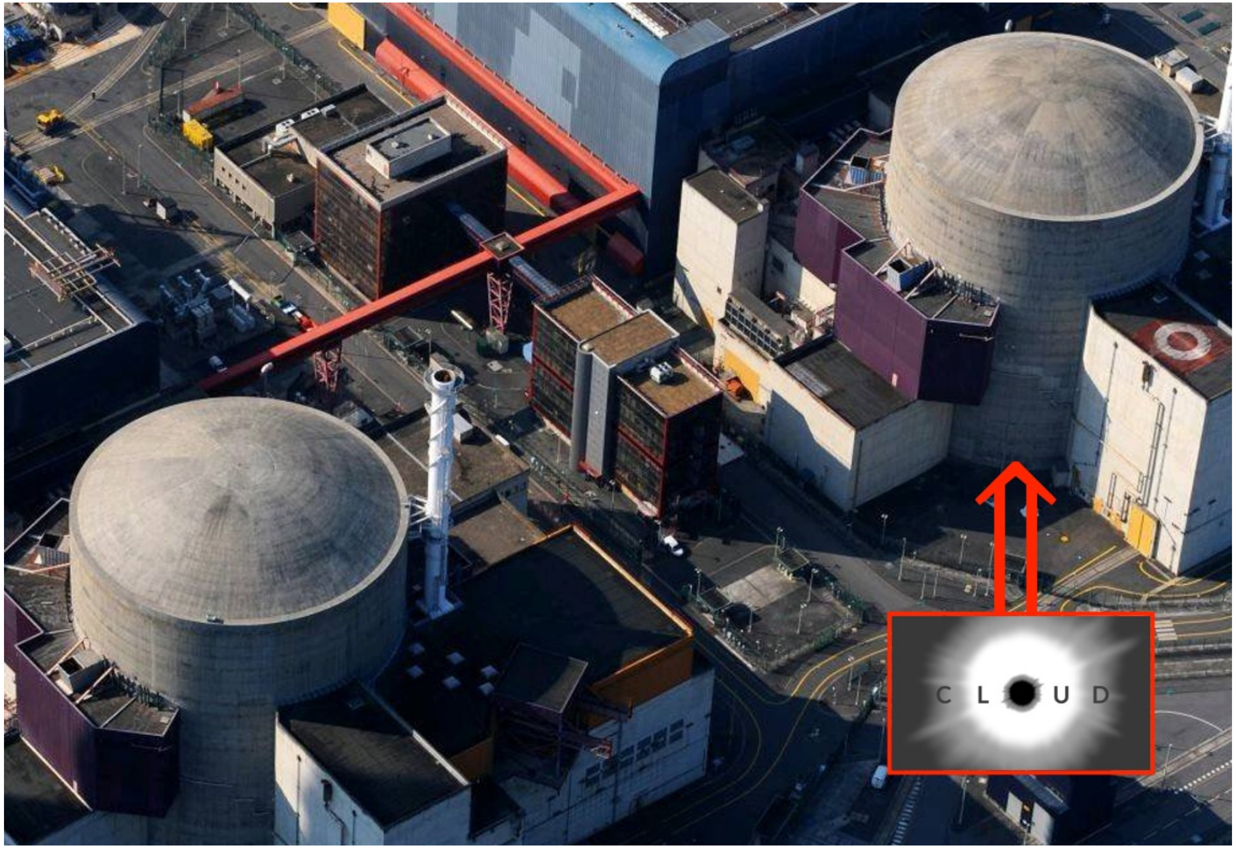
Innovation (2023-26)
- Reactor Monitoring

Fundamental Science (>2024)
- LiquidO capability for Low-E physics

> 10,000 IBDs / day

High-resolution imaging to greatly diminish backgrounds

Chooz LiquidO Ultra-near Detector



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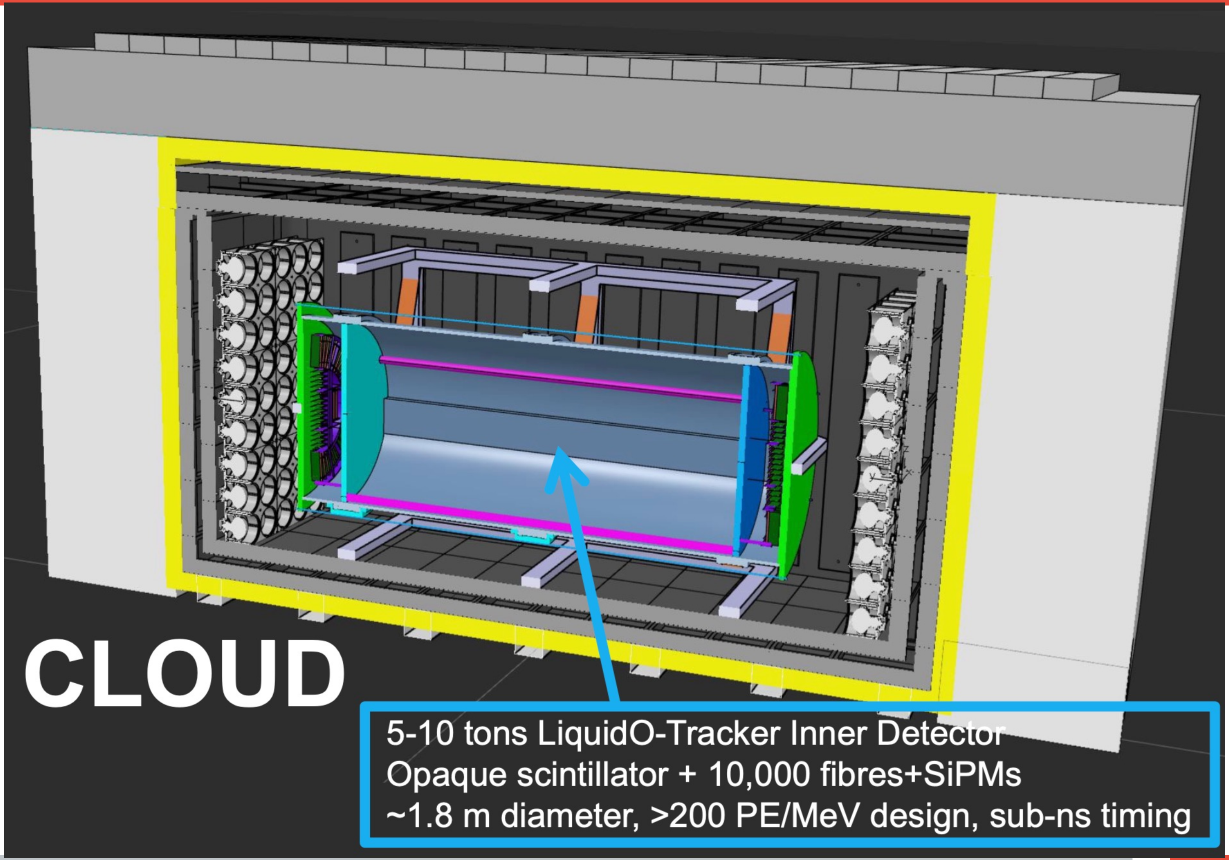
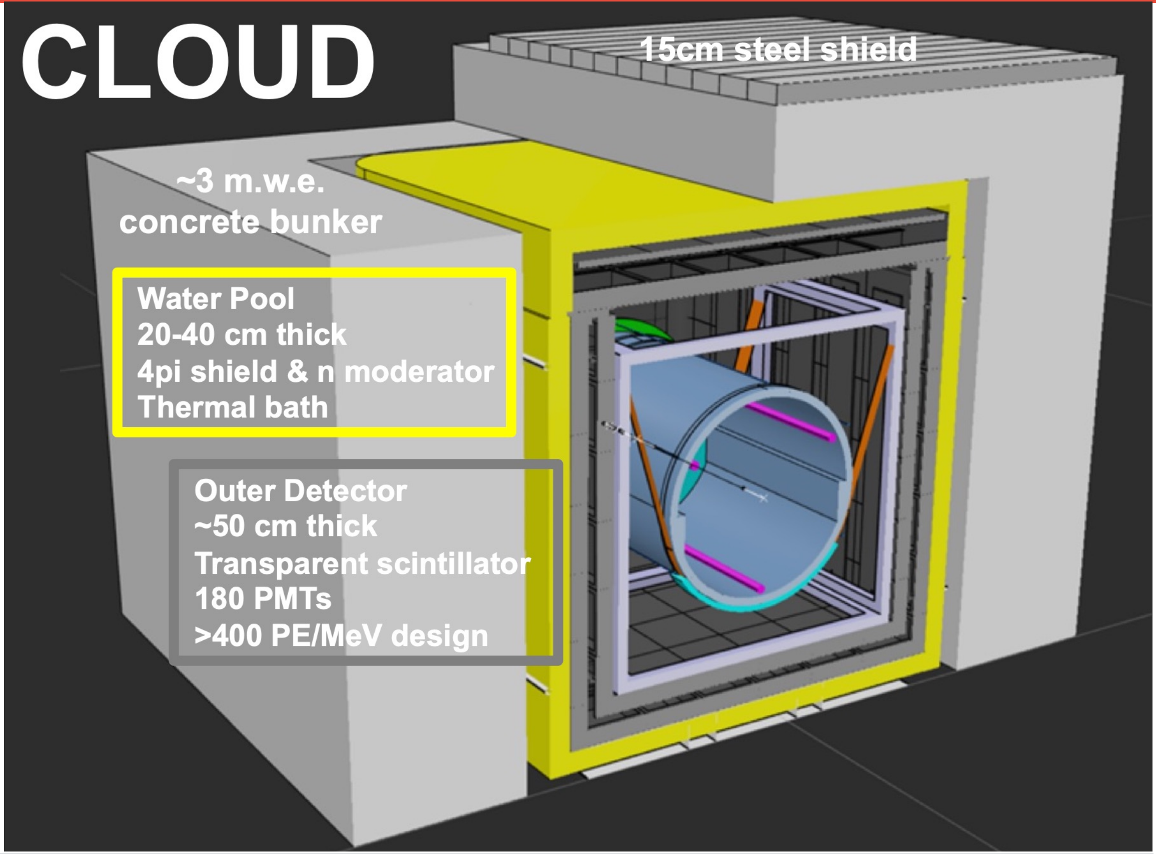
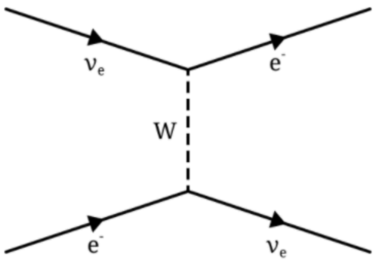
CLOUD's Inner Detector

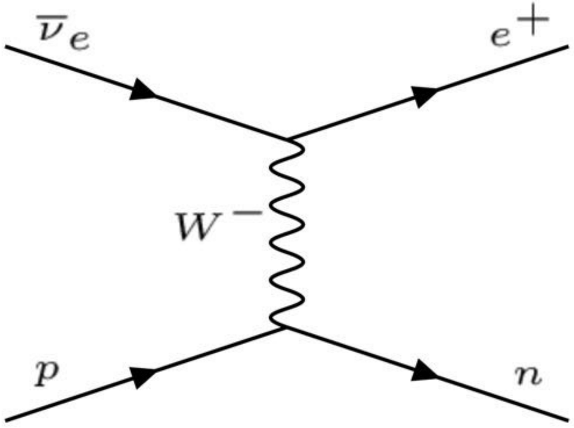


CLOUD's Outer Detector and Shielding



Physics of CLOUD





Interactions with Protons or Electrons

CLOUD

- Inverse Beta Decay (IBD)

$$\bar{\nu}_e \quad + \quad p^+ \rightarrow e^+ \quad + \quad n$$
$$\qquad\qquad\qquad\qquad \hookrightarrow \gamma + \gamma \qquad \hookrightarrow \gamma$$

- 1.8 MeV threshold
- Signature:

  e^+ promptly loses kinetic energy and annihilates

  n-capture on a p^+ gives 2.2 MeV γ in delayed coincidence ($\tau = 215\ \mu s$)

- Elastic Scattering on electrons (NC+CC channel)

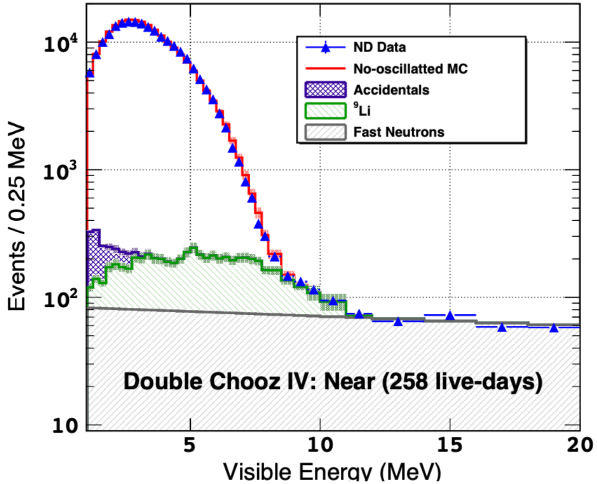
$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$

- Signature:

  Single energetic e^-

CLOUD Phase I: Pure Opaque Scintillator

- >10,000 IBD per day
- S/BG >100 (unprecedented)
  - Precision reactor characterisation
  - <1% flux measurement, U/Pu composition
- Reactor OFF measurements
  - Quantify backgrounds
  - Reactor fuel monitoring
  - ON-OFF-ON transitions



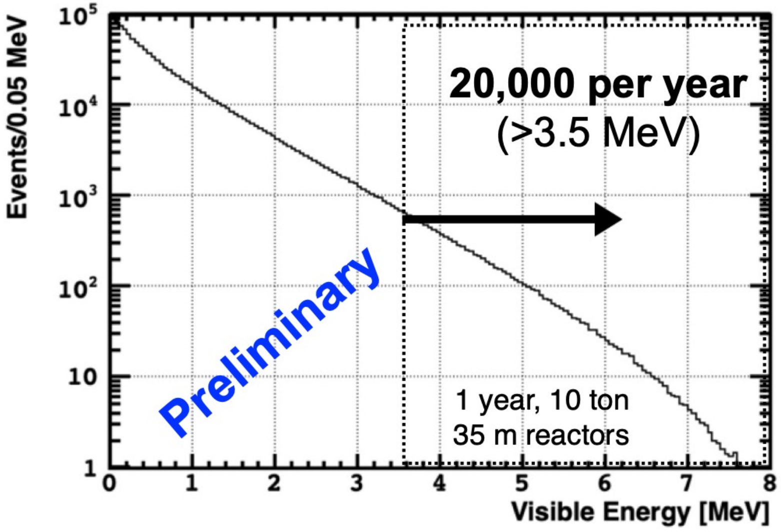
Improvements with LiquidO event classification

- Reject accidentals involving betas, p-recoils and alphas
  - Prompt: Not positrons
  - Delayed: Not a gamma
- Reject cosmogenic ^{9}Li beta
  - Not a positron
  - Precise muon tracking
- Reject fast neutron p-recoil
  - Not a positron

CLOUD Phase I: Pure Opaque Scintillator

CLOUD

- Electron elastic scattering
  - 5,000 per day
- Challenge:
  - Isolate electrons
  - Require
    - Electron classification
    - Fiducial volume
    - Higher energies
- Probe of $\sin^2(\theta_w)$ at very low energy using antineutrinos



CLOUD Phase II: *Indium* Loading in Scintillator

CLOUD

- Electron neutrino CC with indium nucleus

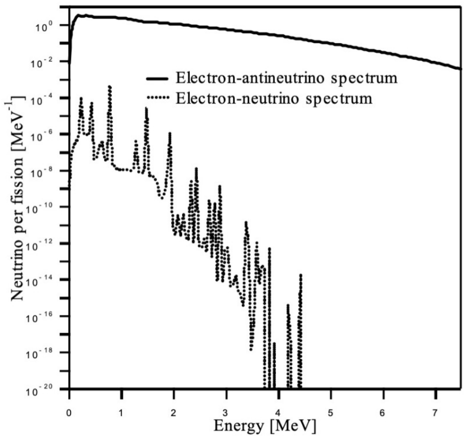
$$\nu_e + {}^{115}In \rightarrow e^- + {}^{115}Sn^*$$
$$\hookrightarrow \gamma/e^-\ (116\ keV) + \gamma\ (497\ keV)$$

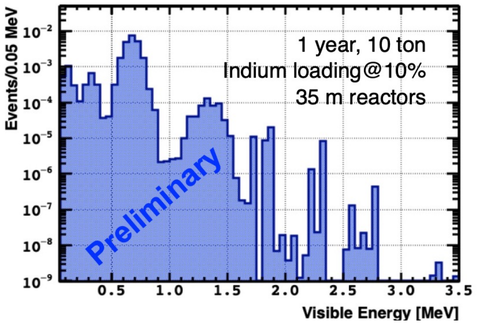
- Very low threshold (114 keV)
- High natural abundance (96%)
- Fast delayed coincidence ($\tau = 4.8\ \mu s$)
- Signature: multi-fold coincidence
  - Require right particles in right places at right times with right energies…
  - LiquidO precision imaging means
    - can require 1st e^- to be in same cubic cm of the detector as the 2nd e^-
    - can require a nearby gamma-like event has 497 keV in time with 2nd e^-

CLOUD Phase II: *Indium* Loading in Scintillator

- Fission also produces electron neutrinos
    - Albeit at a vastly reduced rate
- Never been measured!
- 10-ton detector is too small..
- Unless prediction is wrong?
- What could we measure?

T. Nishimura et al., AIP Conference Proceedings 769, 1702 (2005)
https://doi.org/10.1063/1.1945337

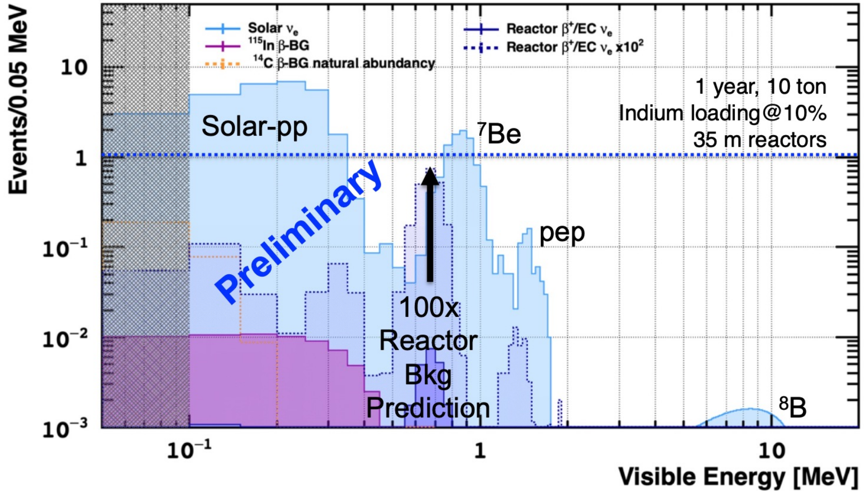




CLOUD Phase II: *Indium* Loading in Scintillator

CLOUD

What's the Solar Neutrino Spectrum?



Solar-pp ~25/year

Solar-^{7}Be ~9/year

^{115}In intrinsic bkg ~negligible (w/ LiquidO)

^{14}C ~negligible

- Plot uses LENS background model
  - Under feasibility study for CLOUD
- Demonstrator for future SuperChooz expt.

CLOUD Phase III: *Copper* Loading in Scintillator

CLOUD

- Electron antineutrino CC with copper nucleus

$$\bar{\nu}_e + {}^{63}Cu \rightarrow e^+ + {}^{63}Ni^{(*)}$$
$$\hookrightarrow \gamma\ (87\ keV) \quad \text{[if Ni was excited]}$$

- Lower threshold (1.2 MeV, below usual 1.8 MeV)
- High abundance (69%)
- Fast delayed coincidence ($\tau = 1.7\ \mu s$)
- Signature:
  - Prompt positron
  - Delayed gamma, close-by spatially

- Make first observation of IBD@Cu
- Lower threshold – see unmeasured part of reactor spectrum
- Measure BR for final state of excited nickel
- IBD@p provide >10,000 positrons a day (with n-capture tag) as a calibration source for classification
  - Will know efficiency of cuts precisely
- Proof of principle for ^{40}K geo-neutrinos (extremely challenging topic)

Probing Earth's Missing Potassium using the Unique Antimatter Signature of Geoneutrinos

A. Cabrera[*12α,2,a], M. Chen[†6], F. Mantovani[‡3α,3β], A. Serafini[§3α,3β,13α,13β], V. Strati[¶3α,3β], J. Apilluelo[18], L. Asquith[1], J.L. Beney[11], T.J.C. Bezerra[1], M. Bongrand[11], C. Bourgeois[12α], D. Breton[12α], M. Briere[12α], J. Busto[10], A. Cadiou[11], E. Calvo[8], V. Chaumat[12α], E. Chauveau[4], B.J. Cattermole[1], P. Chimenti[7], C. Delafosse[12α], H. de Kerret[‖a], S. Dusini[13α], A. Earle[1], C. Frigerio-Martins[7], J. Galán[18], J. A. García[18], R. Gazzini[12α], A. Gibson-Foster[1], A. Gallas[12α], C. Girard-Carillo[9α], W.C. Griffith[1], F. Haddad[11], J. Hartnell[1], A. Hourlier[17], G. Hull[12α], I. G. Irastorza[18], L. Koch[9α], P. Laniéce[12α,12β], J.F. Le Du[12α,2], C. Lefebvre[6], F. Lefevre[11], F. Legrand[12α], P. Loaiza[12α], J. A. Lock[1], G. Luzón[18], J. Maalmi[12α], C. Marquet[4], M. Martínez[18], B. Mathon[12α], L. Ménard[12α,12β], D. Navas-Nicolás[12α], H. Nunokawa[15], J.P. Ochoa-Ricoux[5], M. Obolensky[a], C. Palomares[8], P. Pillot[11], J.C.C. Porter[1], M.S. Pravikoff[4], H. Ramarijaona[12α], M. Roche[4], P. Rosier[12α], B. Roskovec[14], M.L. Sarsa[18], S. Schoppmann[9β], W. Shorrock[1], L. Simard[12α], H.Th.J. Steiger[9α,9β], D. Stocco[11], J.S. Stutzmann[11], F. Suekane[16,a], A. Tunc[9α], M.-A. Verdier[12α,12β], A. Verdugo[8], B. Viaud[11], S. M. Wakely[9α], A. Weber[9α], and F. Yermia[11]

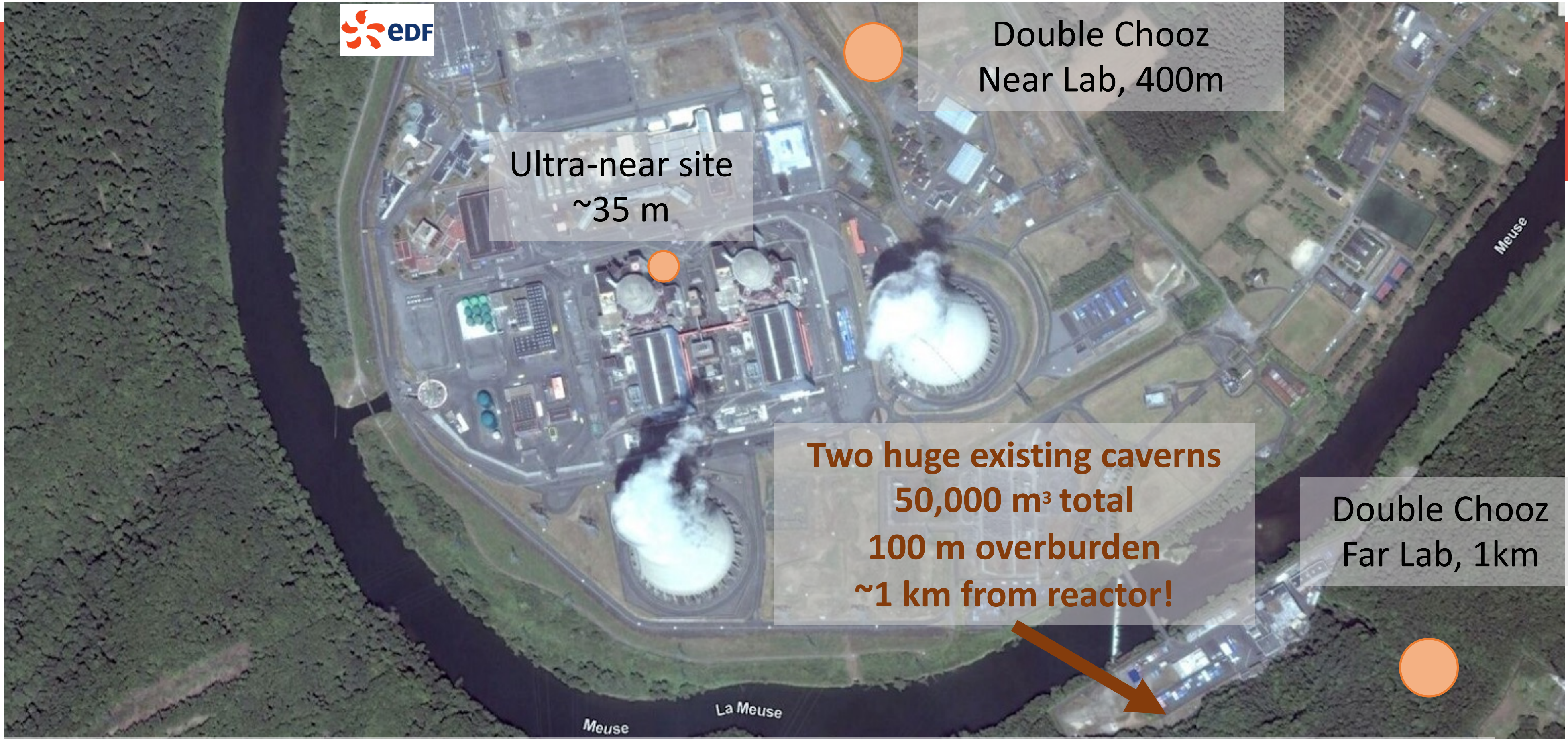
[1] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[2] LNCA Underground Laboratory, CNRS, EDF Chooz Nuclear Reactor, Chooz, France
[3α] INFN, Sezione di Ferrara, Ferrara, Italy
[3β] Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Ferrara, Italy
[4] Université de Bordeaux, CNRS, LP2I Bordeaux, Gradignan, France
[5] Department of Physics and Astronomy, University of California at Irvine, Irvine, CA, USA
[6] Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Canada
[7] Departamento de Física, Universidade Estadual de Londrina, Londrina, Brazil
[8] CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, Spain
[9α] Johannes Gutenberg-Universität Mainz, Institut für Physik, Mainz, Germany
[9β] Johannes Gutenberg-Universität Mainz, Detektorlabor, Exzellenzcluster PRISMA+, Mainz, Germany
[10] Université de Aix Marseille, CNRS, CPPM, Marseille, France
[11] Nantes Université, IMT-Atlantique, CNRS, Subatech, Nantes, France
[12α] Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
[12β] Université Paris Cité, IJCLab, Orsay, France
[13α] INFN, Sezione di Padova, Padova, Italy
[13β] Dipartimento di Fisica e Astronomia, Università di Padova, Padova, Italy
[14] Institute of Particle and Nuclear Physics, Charles University, Prague, Czech Republic
[15] Department of Physics, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, Brazil
[16] RCNS, Tohoku University, Sendai, Japan
[17] Université de Strasbourg, CNRS, IPHC, Strasbourg, France
[18] Centro de Astropartículas y Física de Altas Energías (CAPA), Universidad de Zaragoza, Zaragoza, Spain
[a] Université de Paris Cité, CNRS, APC, Paris, France

(LiquidO Consortium)

CLOUD

arXiv:2308.04154

SuperChooz



CERN Seminar: ***"The SuperChooz Experiment: Unveiling the Opportunity"***

https://indico.cern.ch/event/1215214/

https://zenodo.org/doi/10.5281/zenodo.7504161

Conclusions

→ Groundbreaking detector development project

→ 5-10 ton LiquidO precision imaging calorimeter

→ Demonstrator for a wide range of future projects

→ Pure opaque scintillator for phase I (approved and funded)

→ >10,000 IBD/day from 2025, <1% reactor ν flux measurement

→ Indium loading for phase II

→ Search for ν_es

→ Copper loading for phase III

→ First demonstration of copper's lower 1.2 MeV threshold

→ **Final thought:** LiquidO is a whole new way of thinking about the detector and neutrino experiments

→ Expect many great ideas we haven't even imagined yet!

Conclusions

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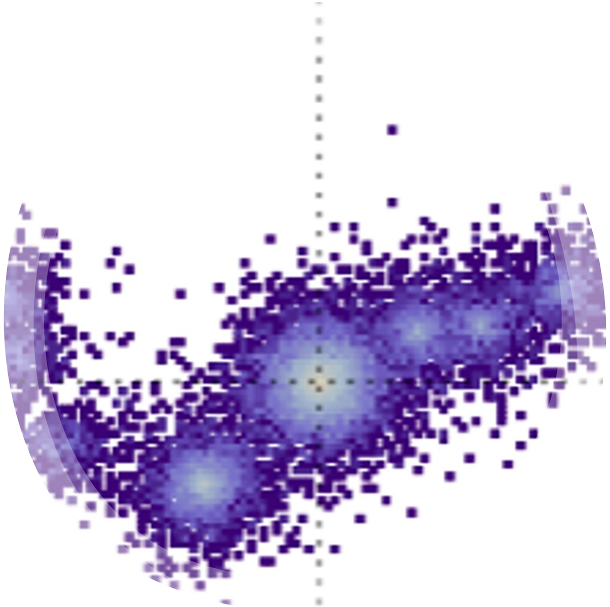
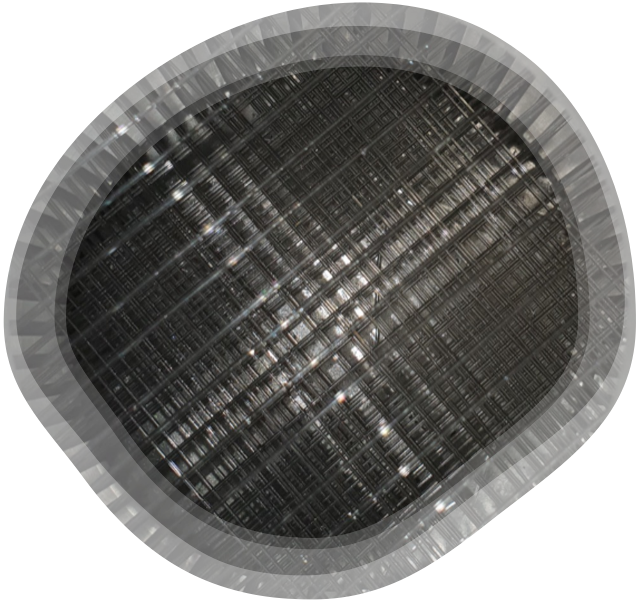
  

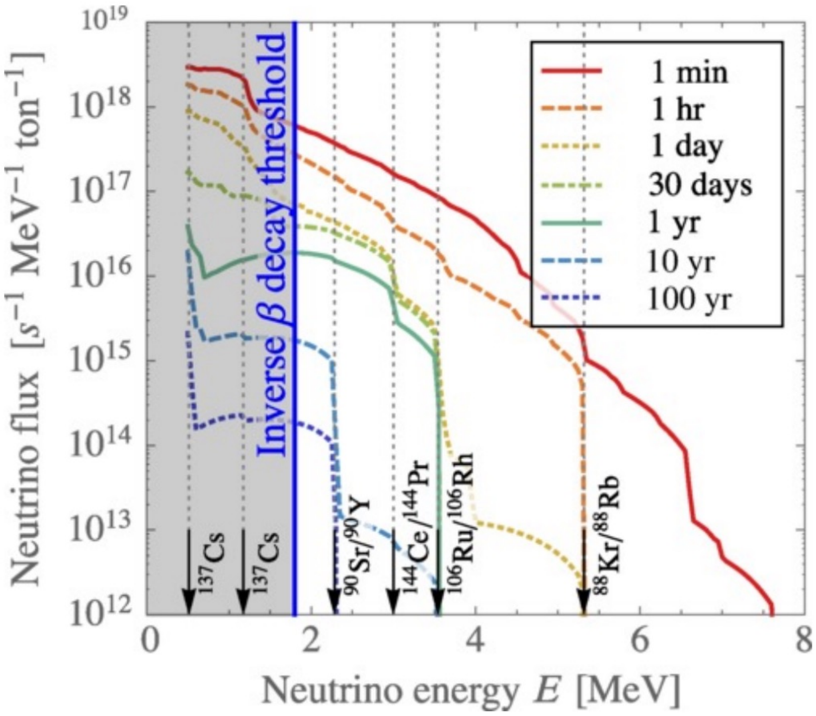
Thank you!

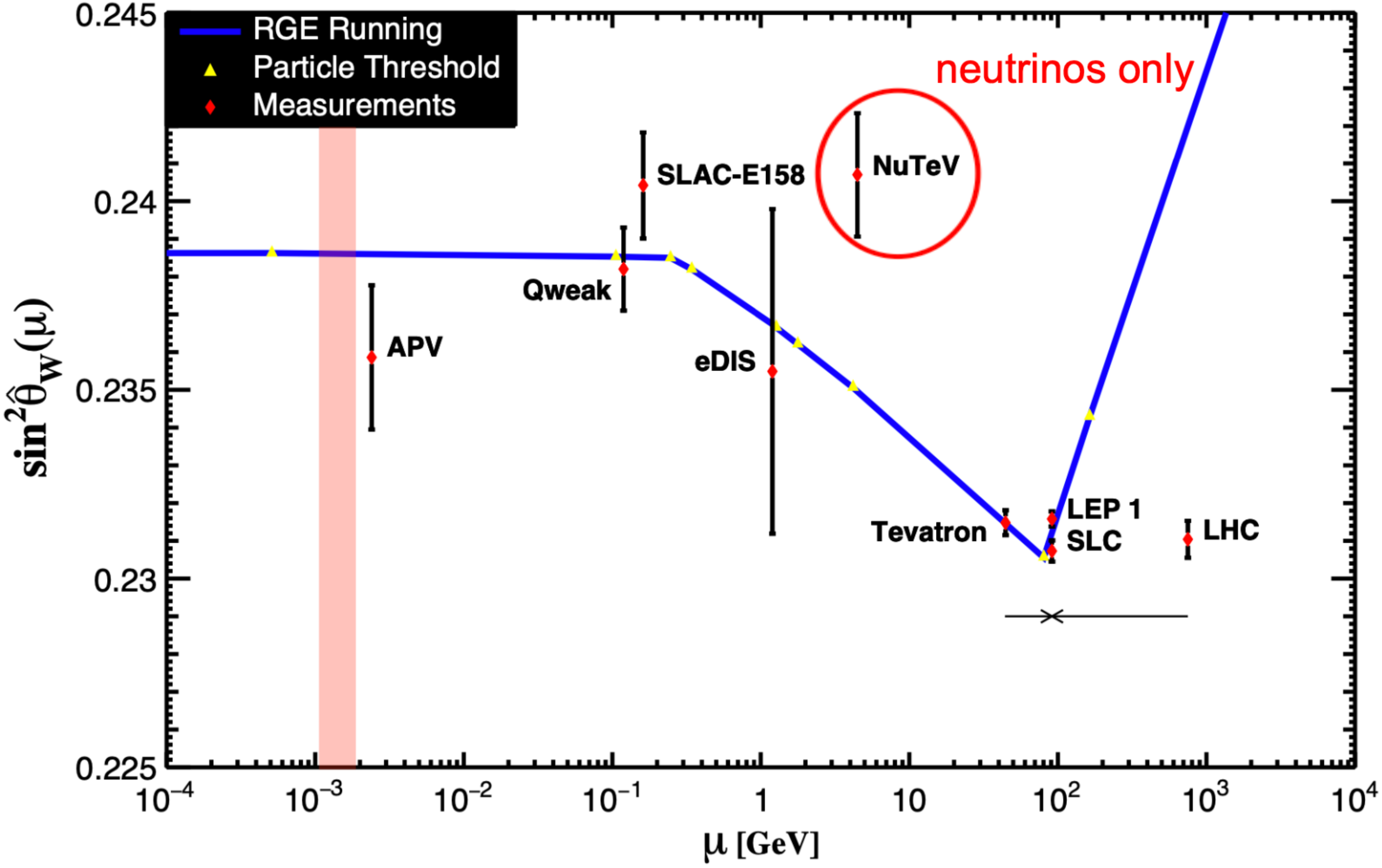
Backup

Reactor nuclear fuel characterization

CLOUD

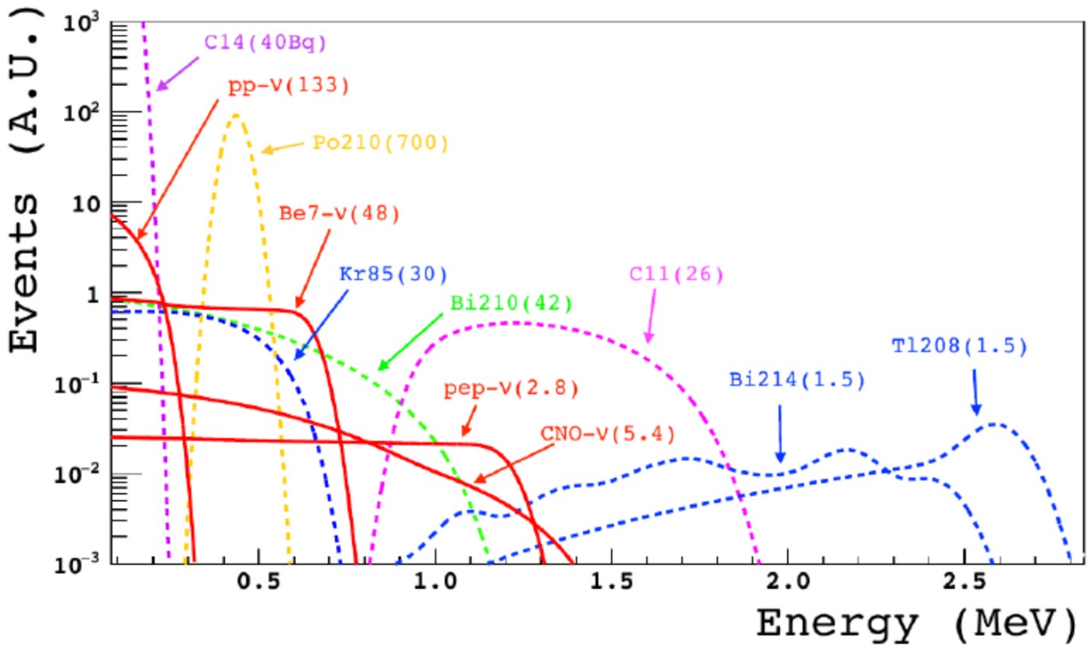
Brdar, V. and Huber, P. and Kopp, J., "Antineutrino Monitoring of Spent Nuclear Fuel",
Phys. Rev. Applied, vol. 8, issue 5, pg 054050 (2017).
DOI: https://doi.org/10.1103/PhysRevApplied.8.054050





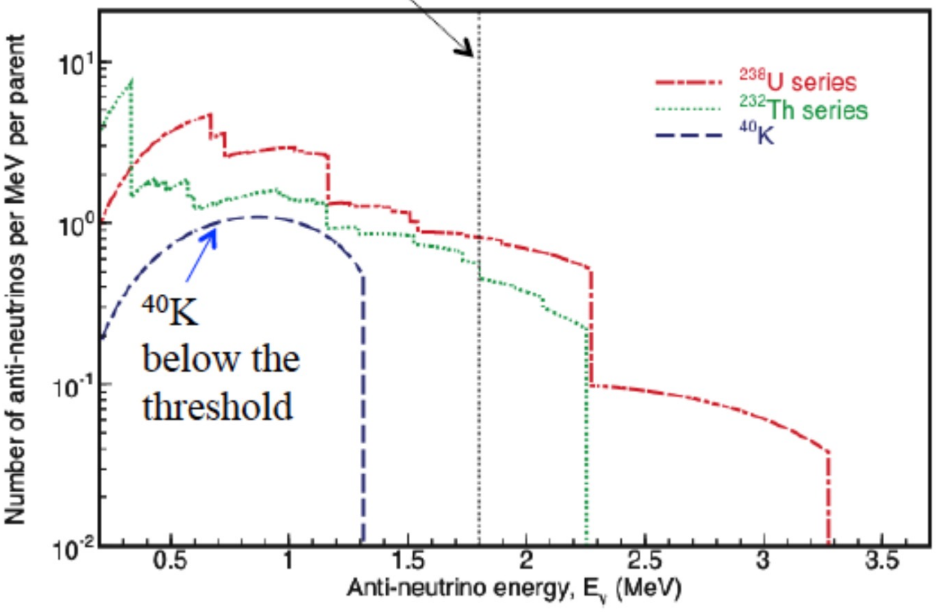
RGE Running
Particle Threshold
Measurements
neutrinos only
NuTeV
SLAC-E158
Qweak
APV
eDIS
Tevatron
LEP 1
SLC
LHC
0.245
0.24
0.235
0.23
0.225
$\sin^2\hat{\theta}_W(\mu)$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
μ [GeV]

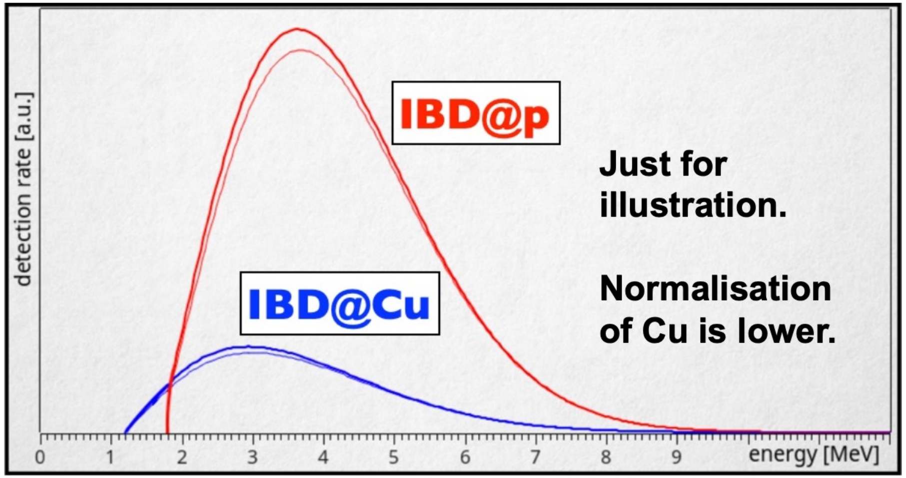
Solar neutrinos @ Borexino



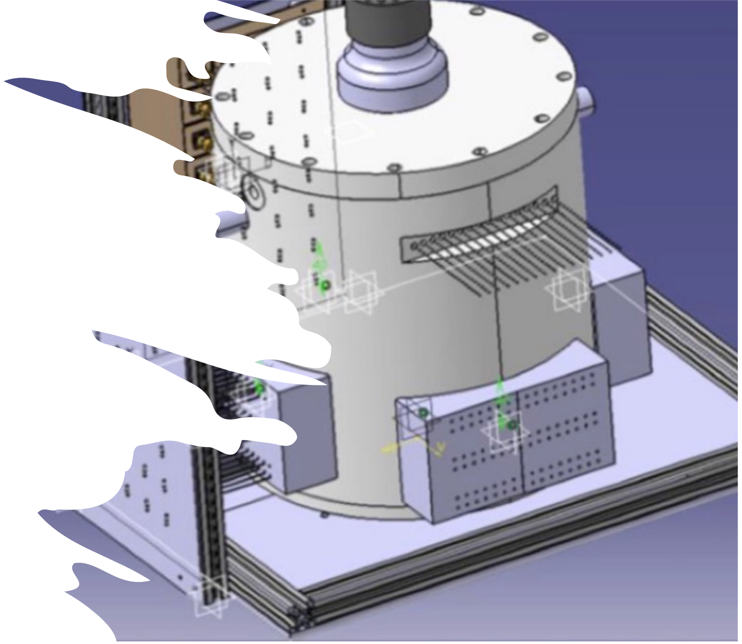
Borexino Exposure: 1291.51 days, ~ 71.3 tons $\Longrightarrow$ 134^{+6}_{-10} events [Nature 562, 505–510 (2018)]

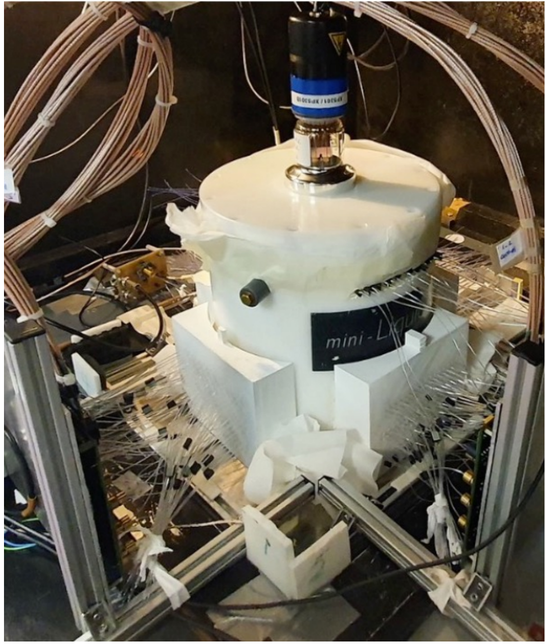
1.8 MeV kinematic threshold (IBD)

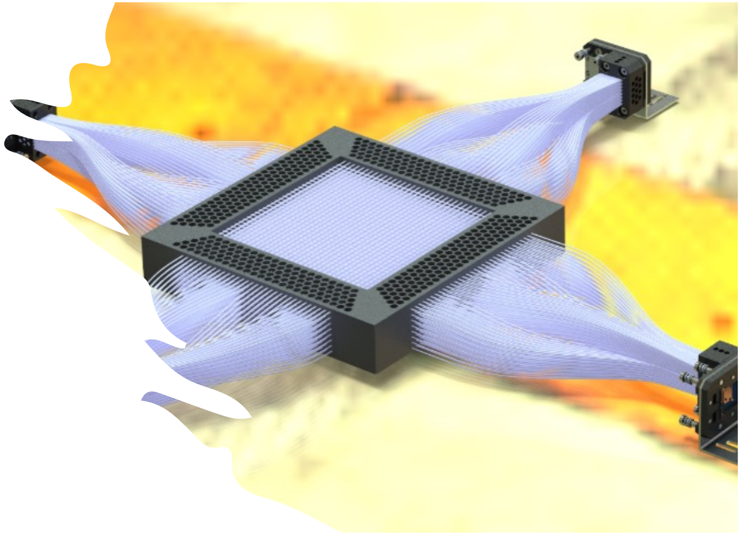


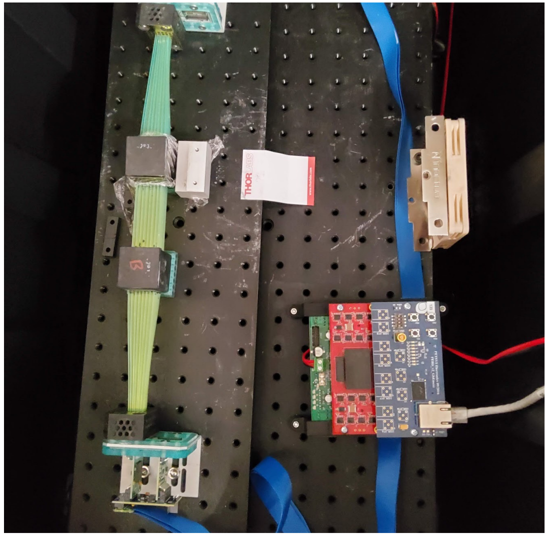


LiquidO Prototypes

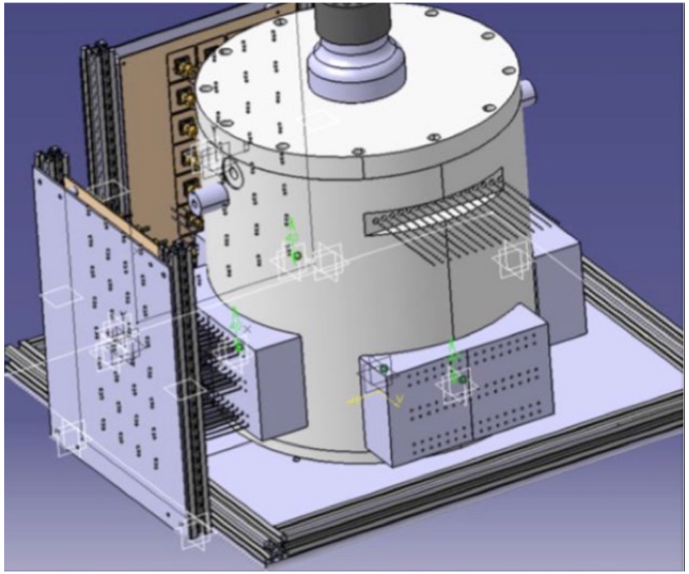








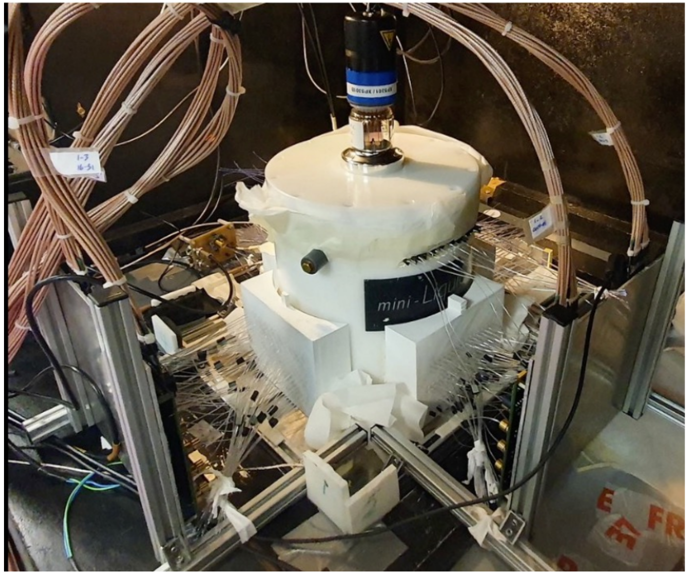
MINI-LiquidO Prototype



10 L and 64 readout fibres
3” PMT on top
Very fast electronics
Temp. control system [5, 40]°C
Runs with:

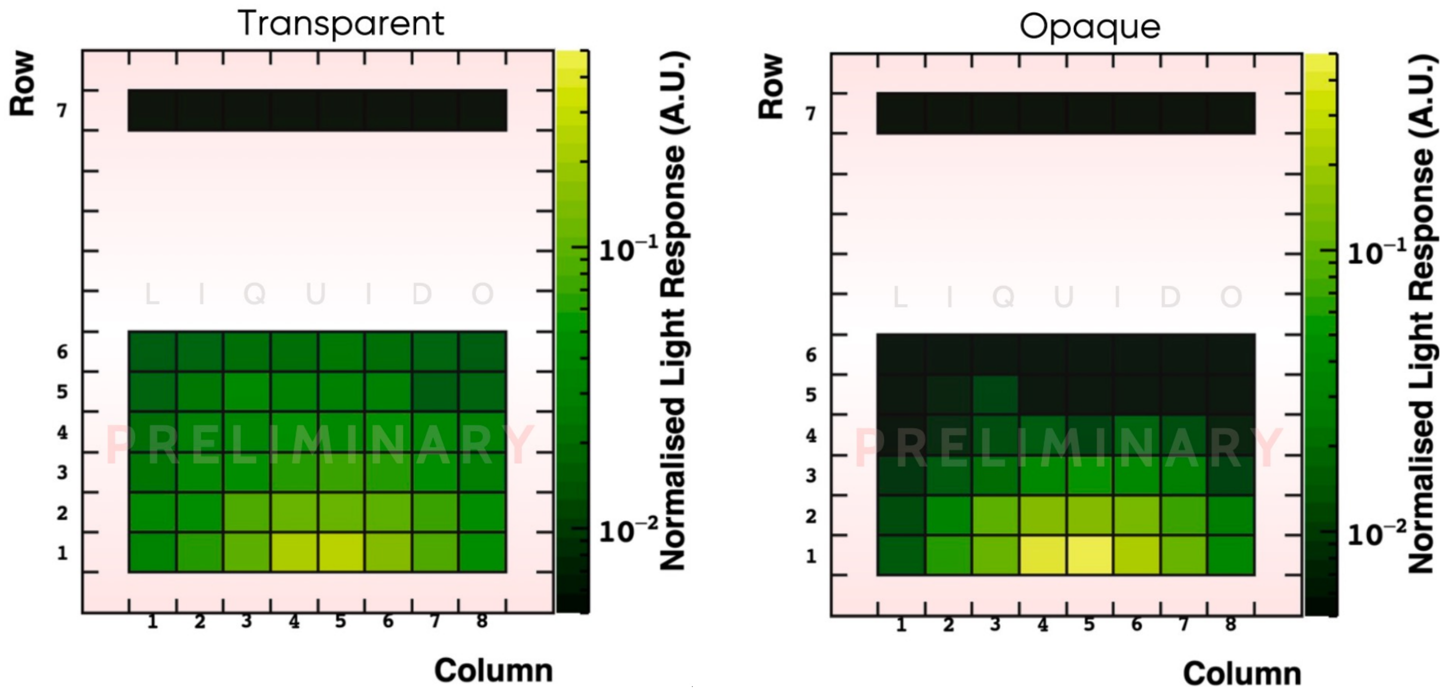
- Opaque LS (NoWash20)
- LAB (+PPO)
- Water

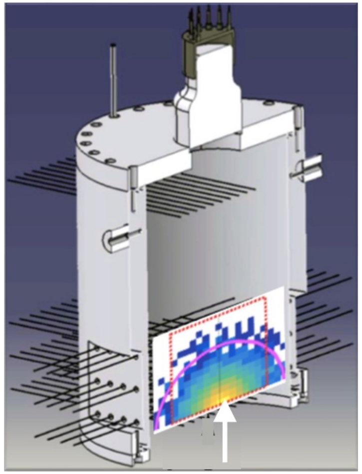
e^- beam [0.4, 1.8] MeV
Operated @ LP2i Bordeaux



Goal: demonstrate stochastic light confinement

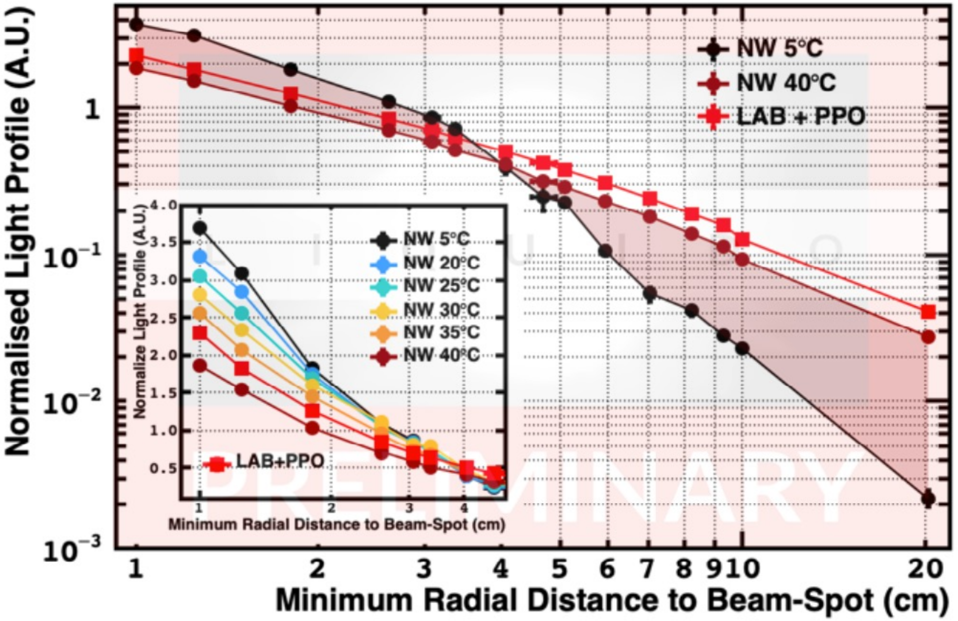
MINI-LiquidO Prototype: Results





MINI-LiquidO Prototype: Results

Transparent vs Opaque



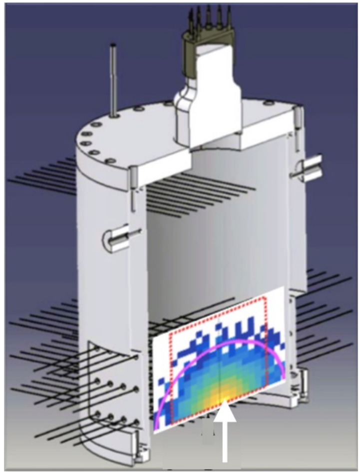
NW at 40°C ⟶ transparent
similar to LAB+PPO

NW at 5°C ⟶ Opaque

Light ball formation at ~4cm

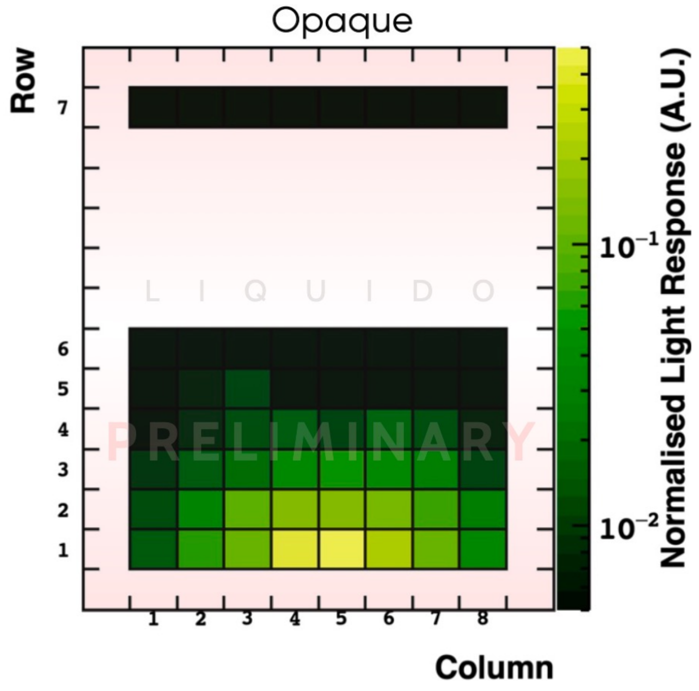
Stochastic light confinement!

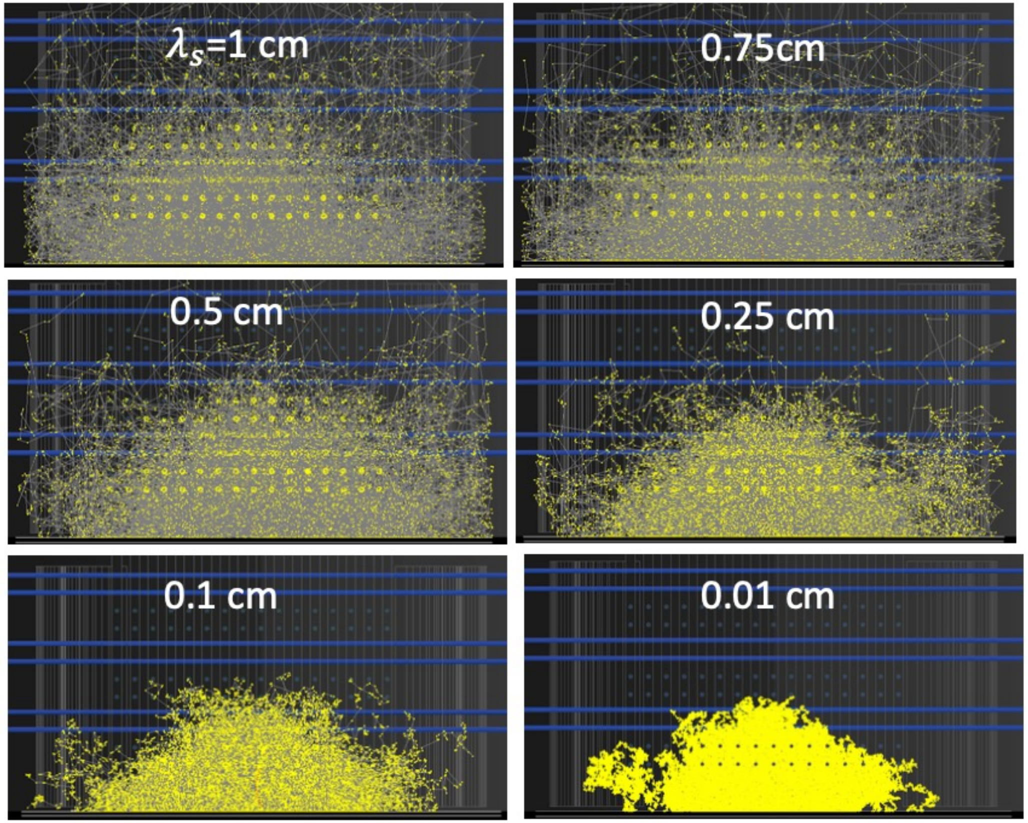
Major demonstration of the LiquidO technology



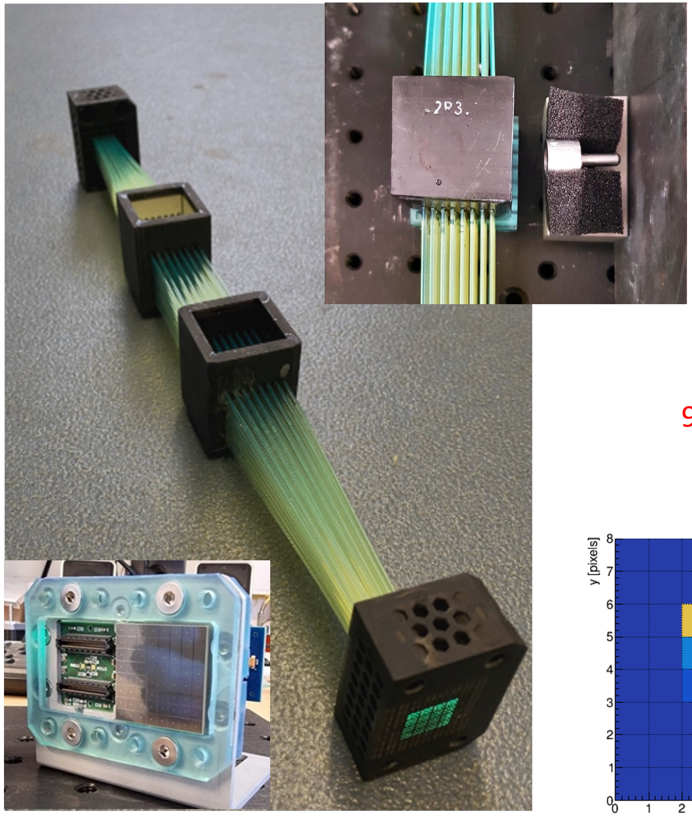
MINI-LiquidO Prototype: Results

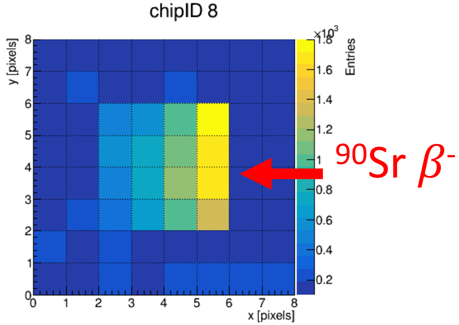
Opacity → Scattering length

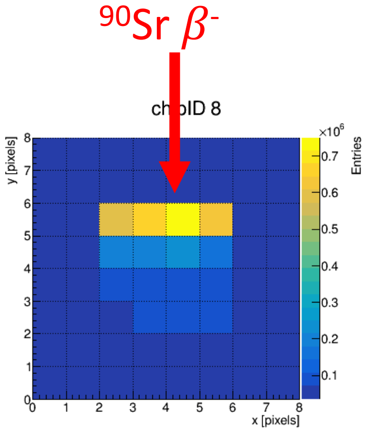




On going developments at Sussex







Goals:

→ Highest Light Yield possible

→ Muon tracking capability