LiquidO: What? Why? How? Which?

UNIVERSITY OF SUSSEX

Seminar at King's College London

Thiago Bezerra

Senior Research Fellow, University of Sussex

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Outline

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→ **What** is LiquidO?

→ **Why** LiquidO?

→ **How** are we developing LiquidO?

→ **Which** physics can we do with LiquidO?

What is LiquidO?

Radiation detection in an opaque media

Two types of opacity

Short *absorption* length
Short scattering length

Long *absorption* length
Short scattering length

Traditional detection with light

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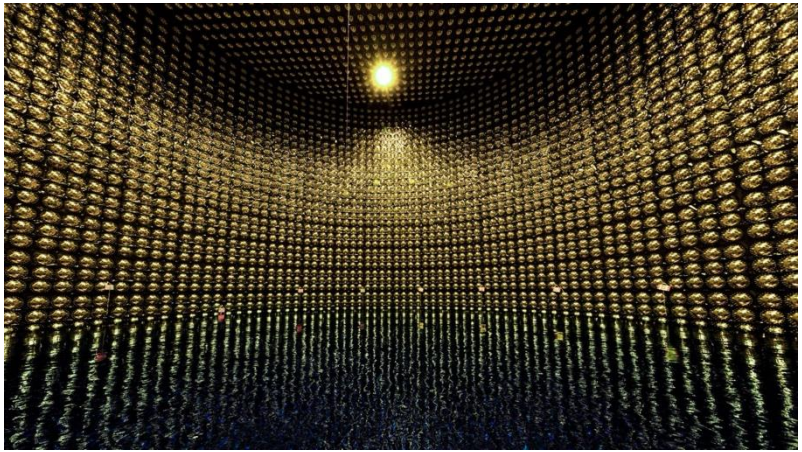
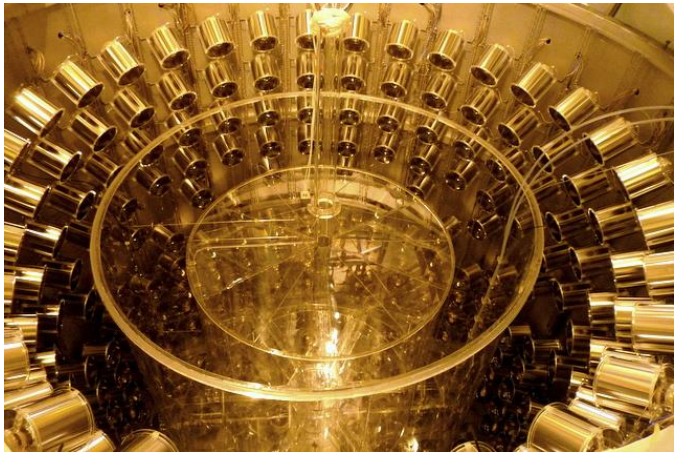
Super Kamiokande: Cherenkov



Double Chooz: Scintillation



Traditional detection with light

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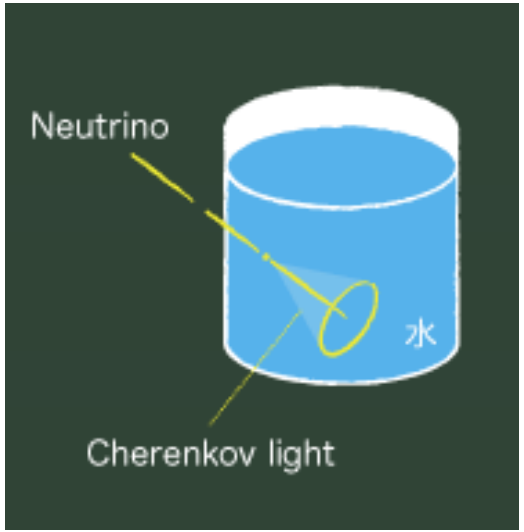
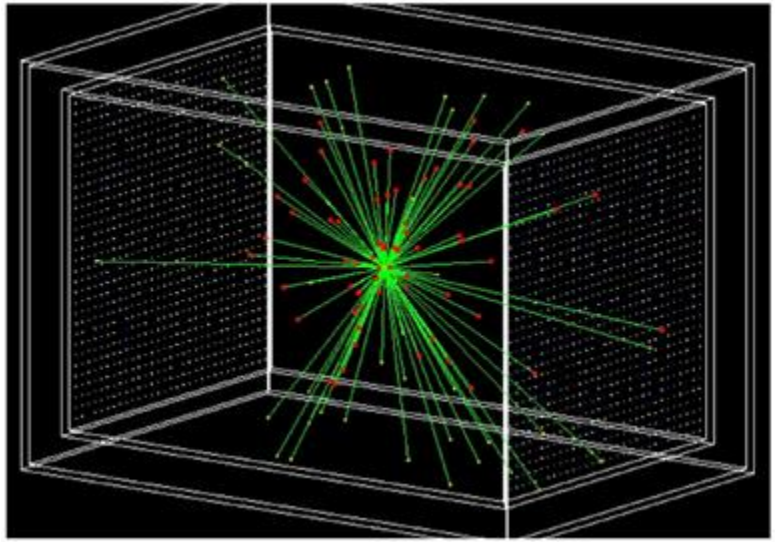
Super Kamiokande: Cherenkov



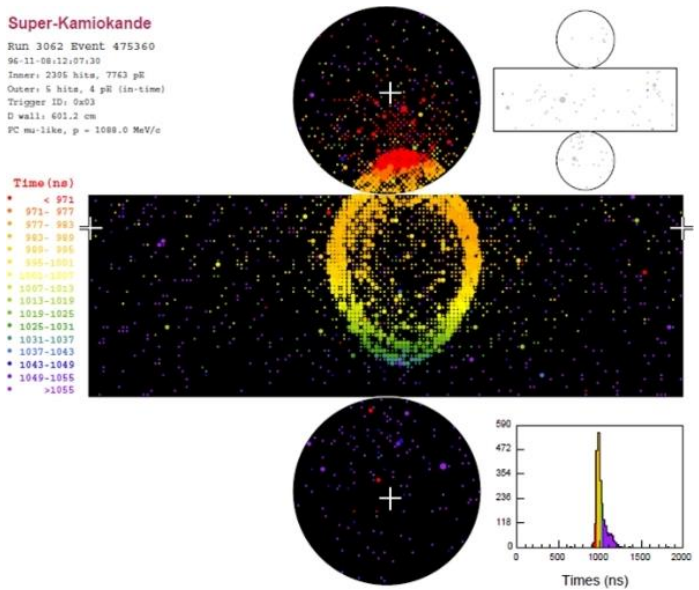
Double Chooz: Scintillation



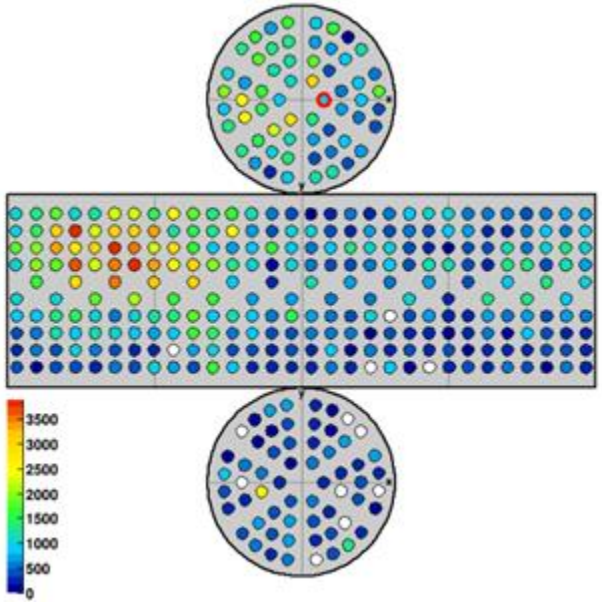
Traditional detection with light

→ **Transparent** media

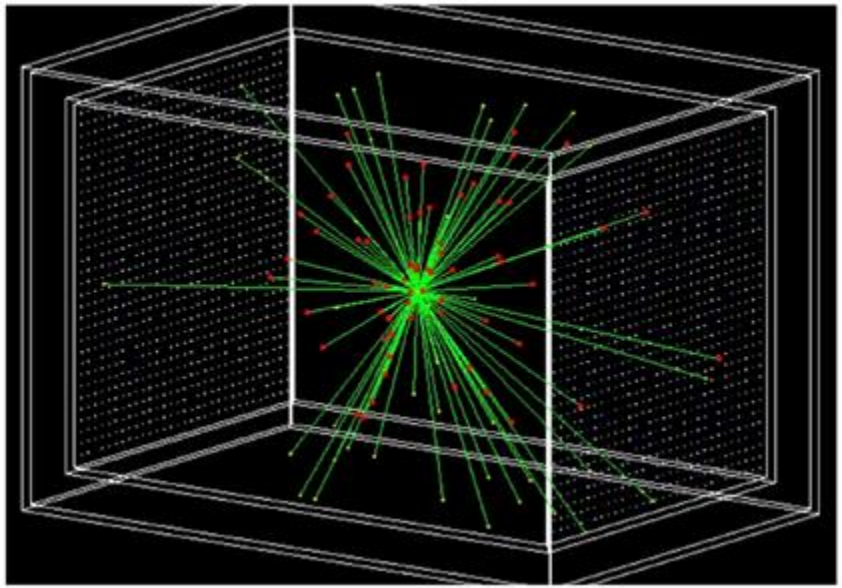
Super Kamiokande: Cherenkov



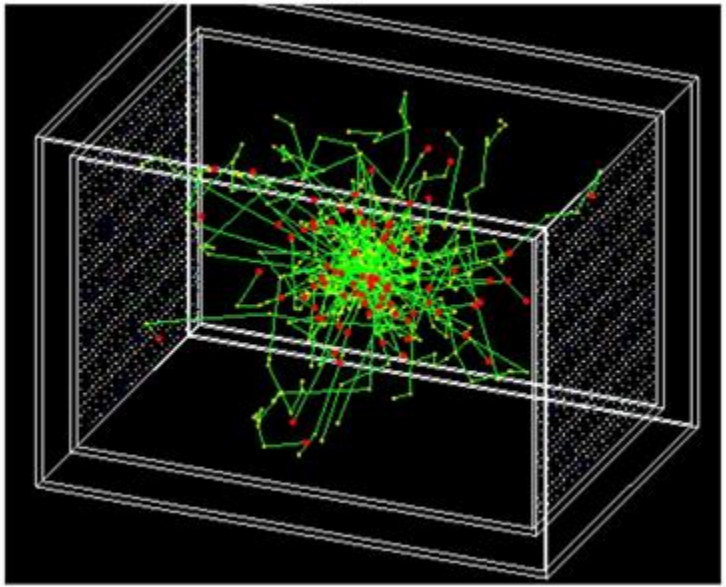
Double Chooz: Scintillation



Light paths: transparent vs opaque

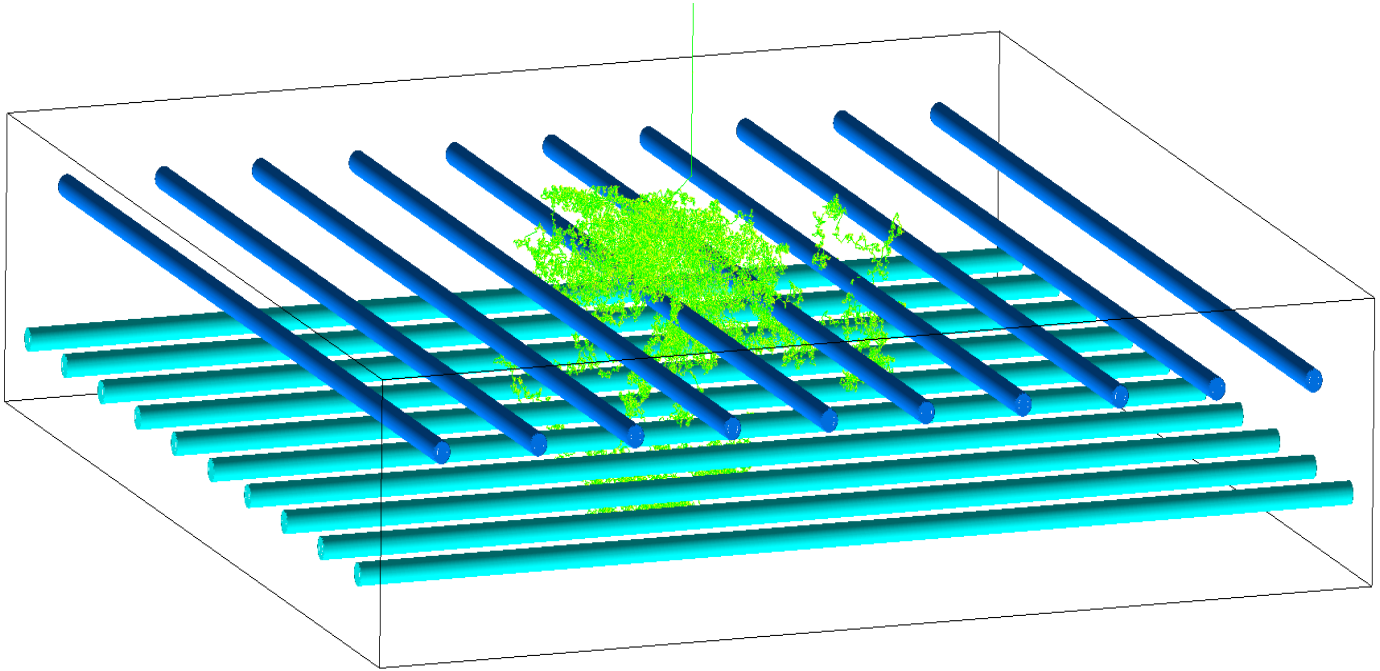


Transparent medium
Straight paths



Opaque medium
Random walk

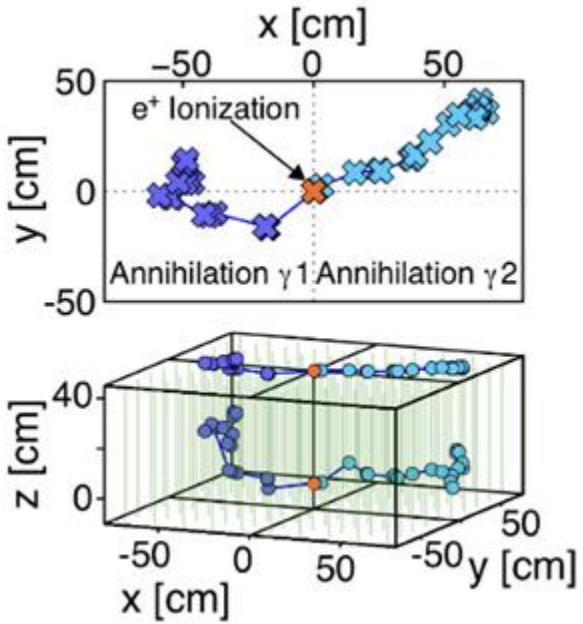
Collecting the light



Readout: wavelength shifting fibres + SiPMs

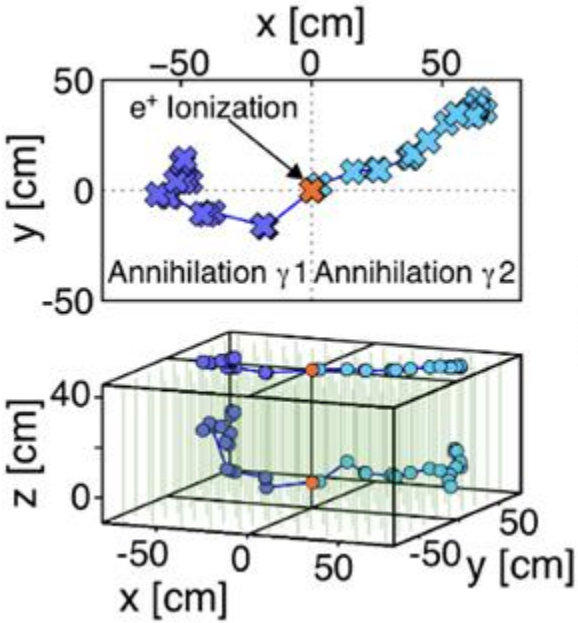
Confine energy deposition locally

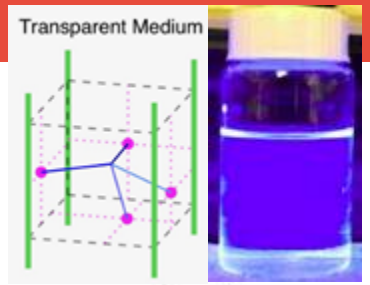
e⁺ of 1 MeV

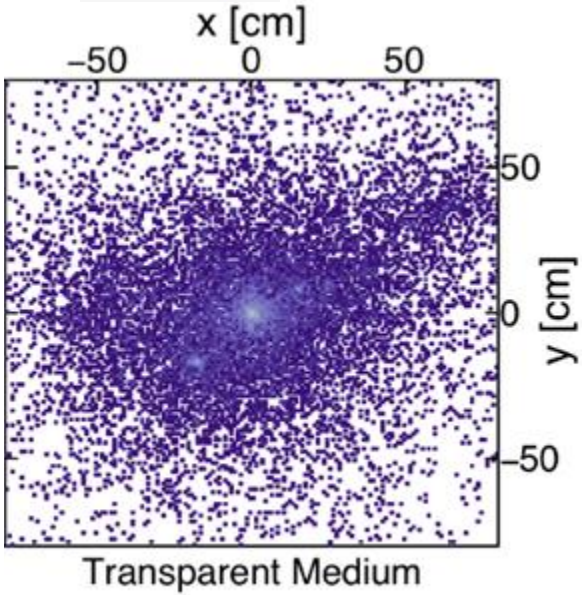


Confine energy deposition locally

e⁺ of 1 MeV

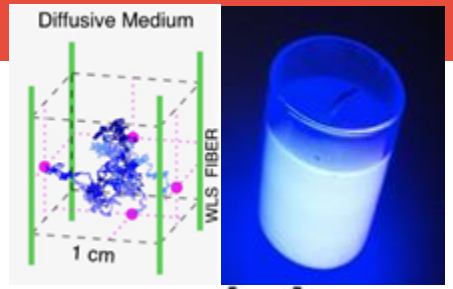


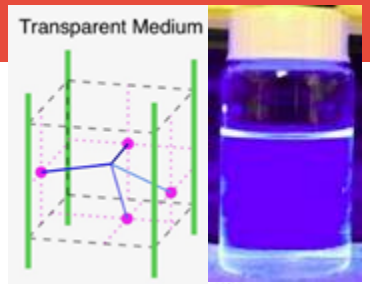


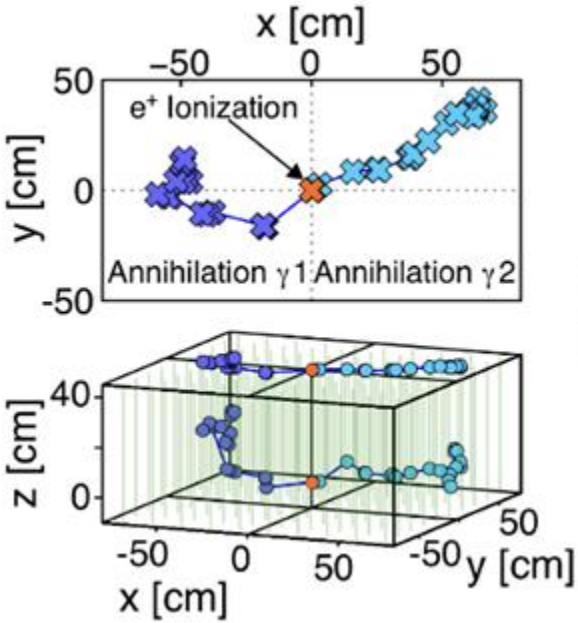


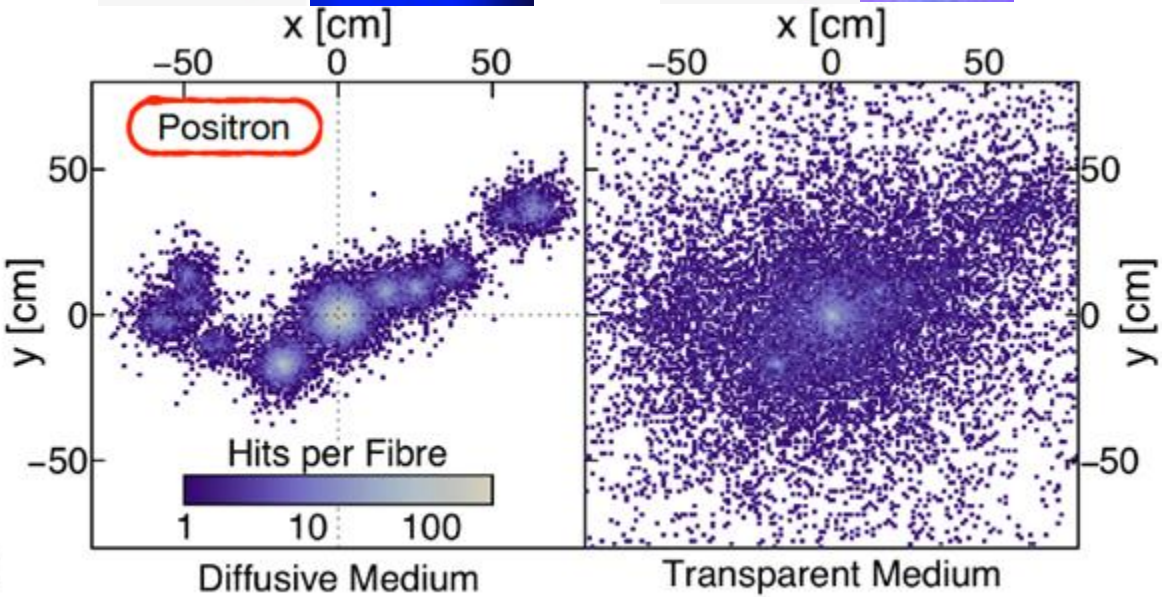
Confine energy deposition locally

e^+ of 1 MeV



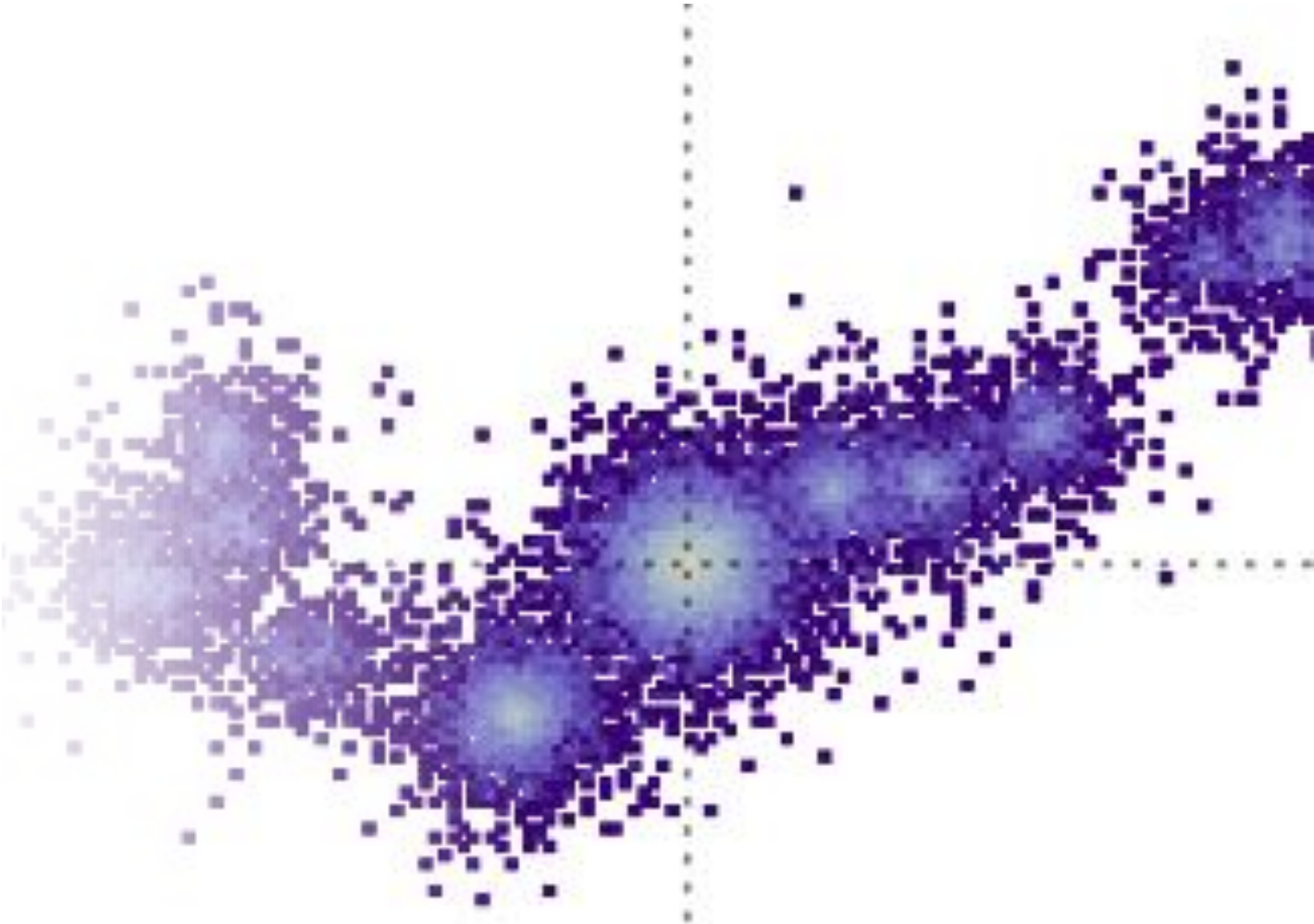




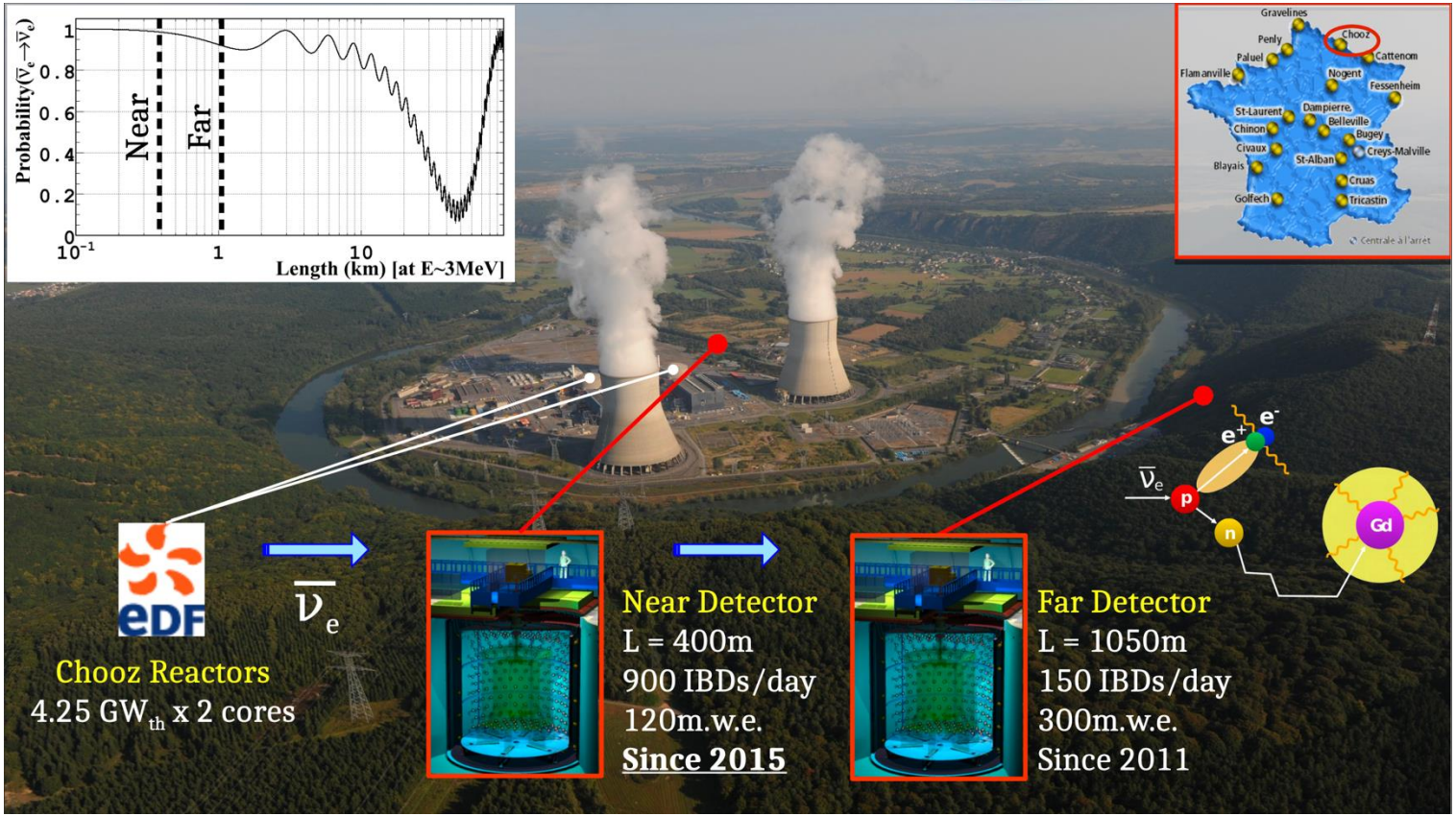


Why LiquidO?

Historical motivation

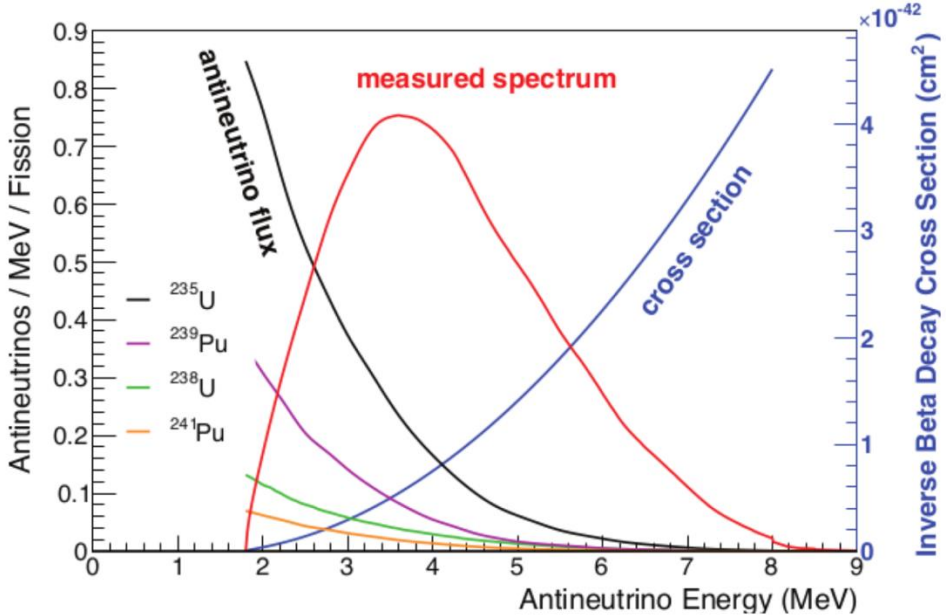


Double Chooz experiment



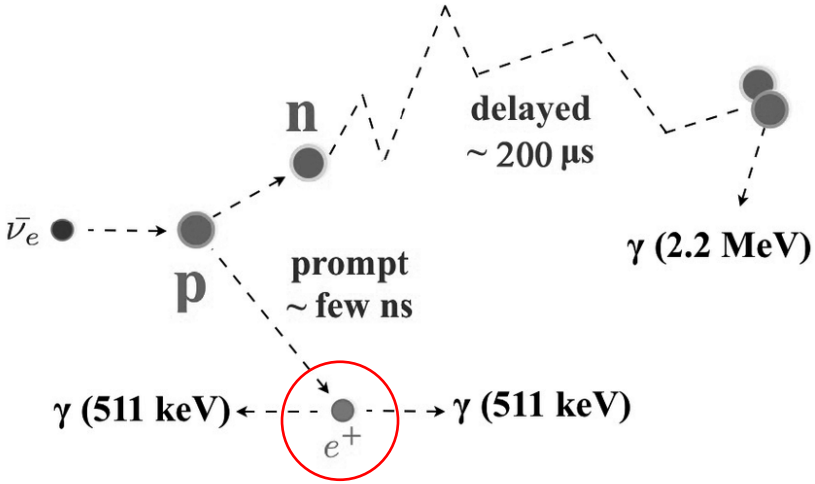
Reactor-ν detection

Nuclear reactors are a powerful anti-ν_e source!

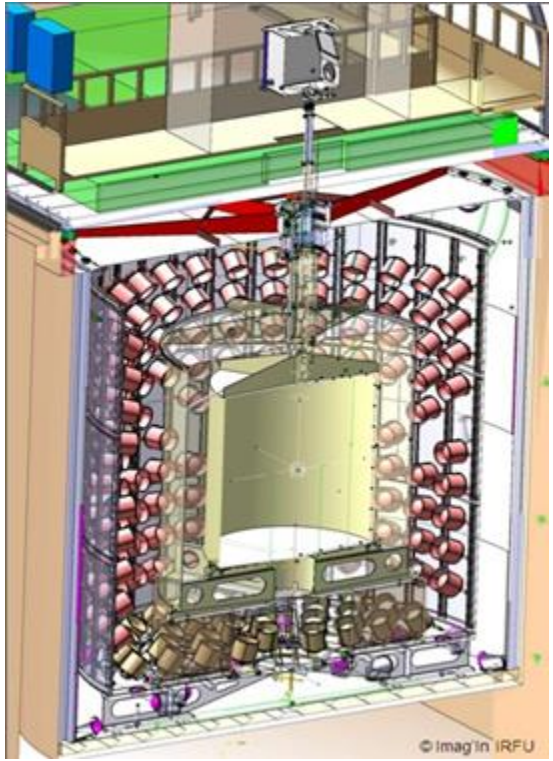


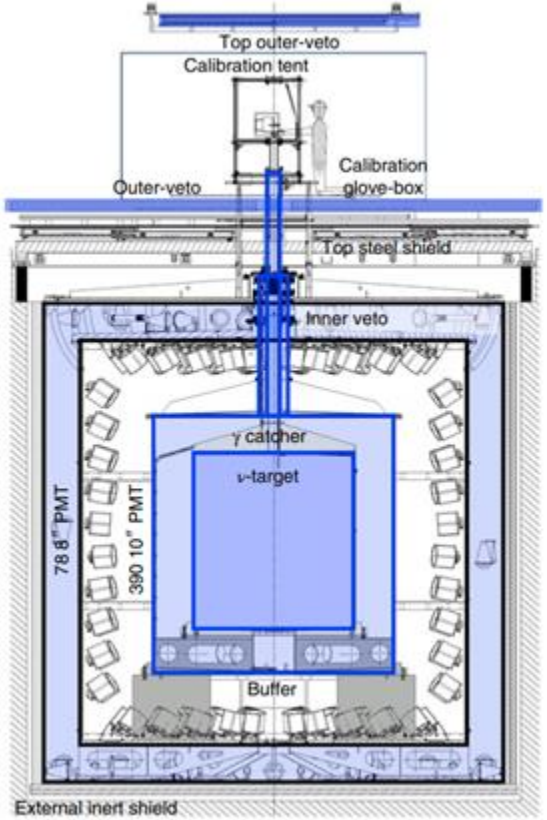
Inverse Beta Decay reaction:

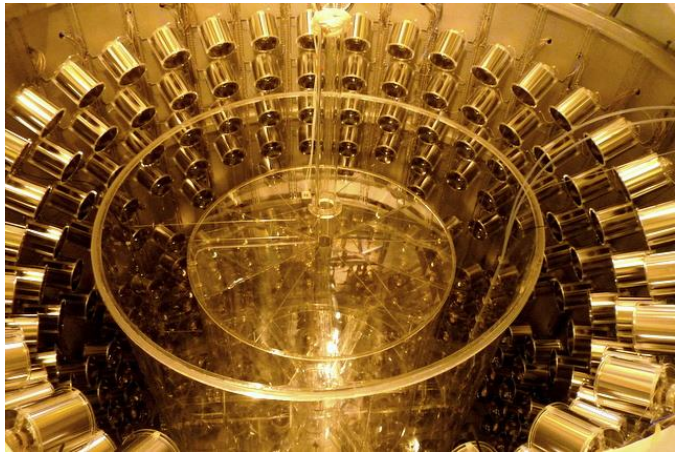
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



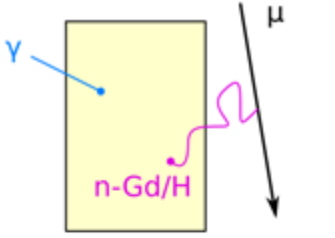
Detectors components





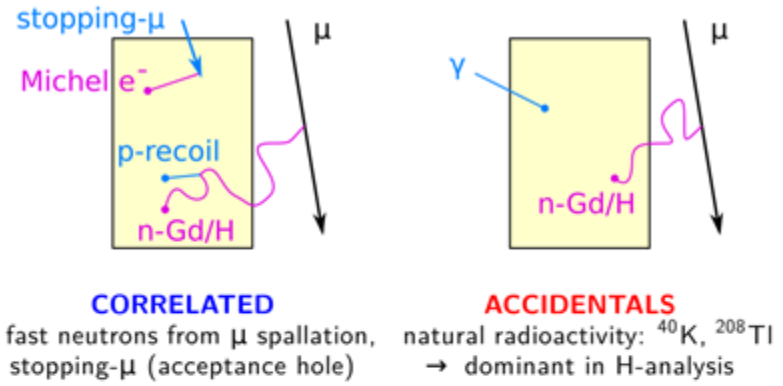


Backgrounds

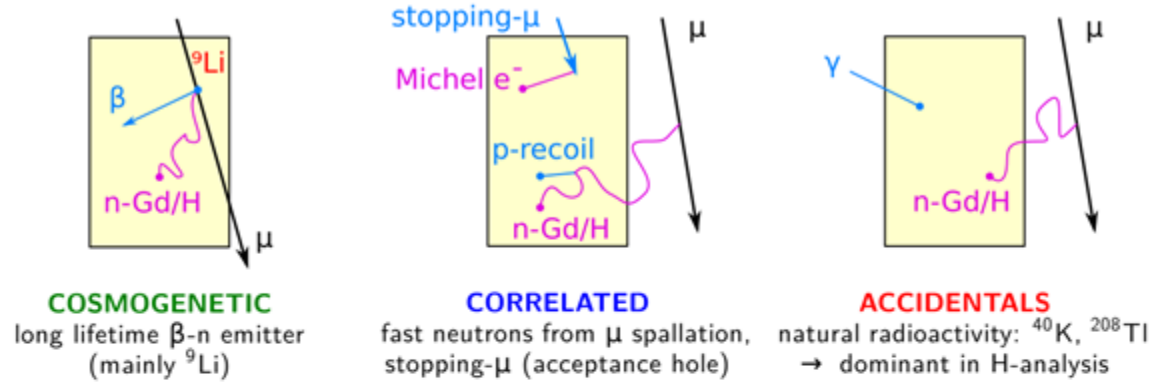


ACCIDENTALS
natural radioactivity: ^{40}K, ^{208}Tl
→ dominant in H-analysis

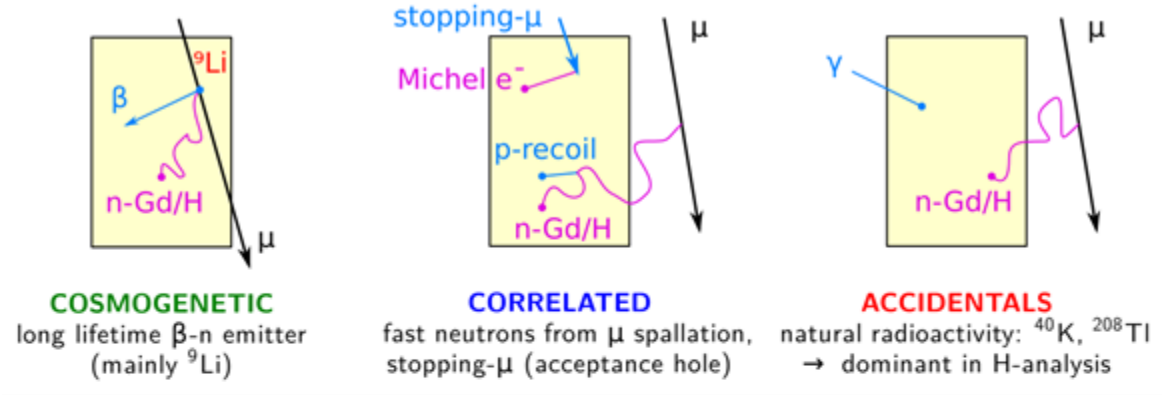
Backgrounds

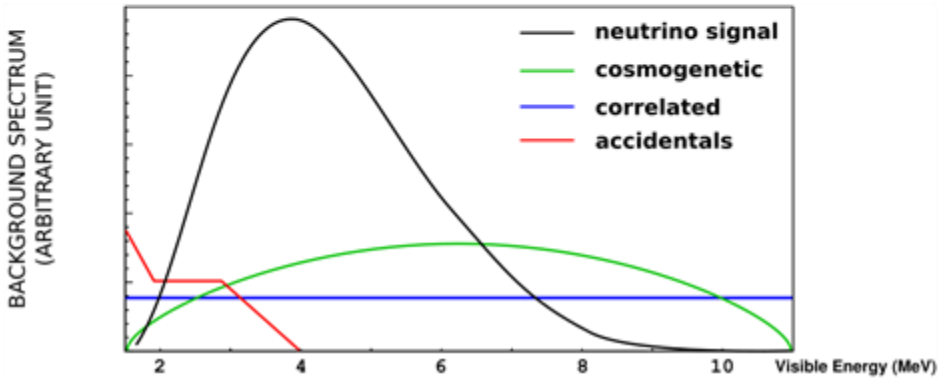


Backgrounds

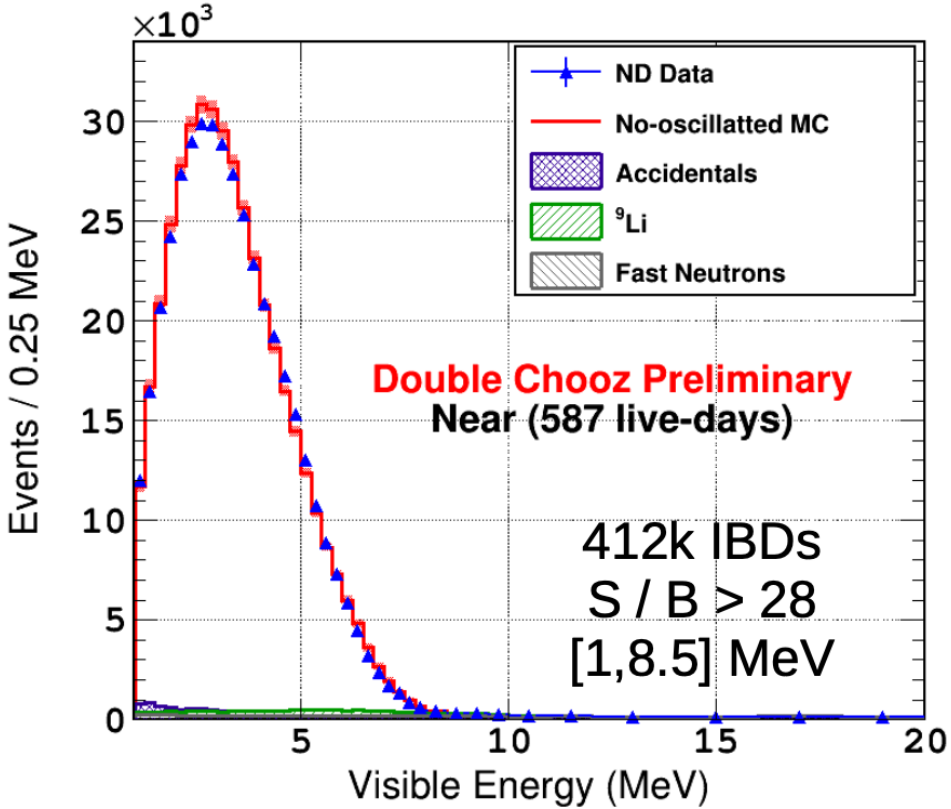


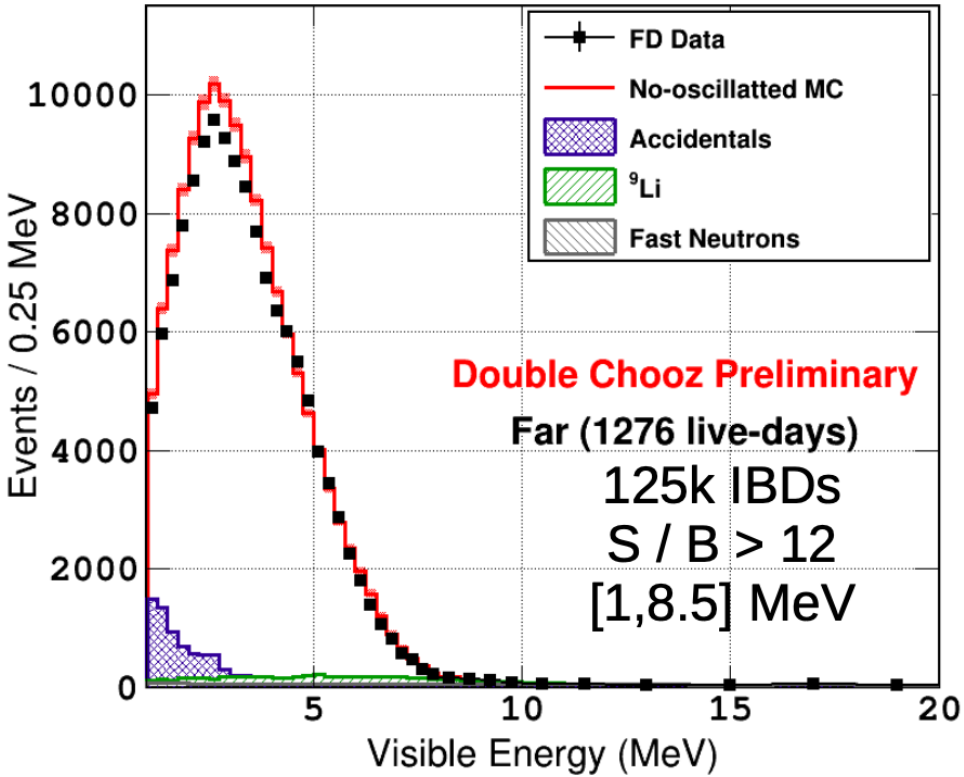
Backgrounds





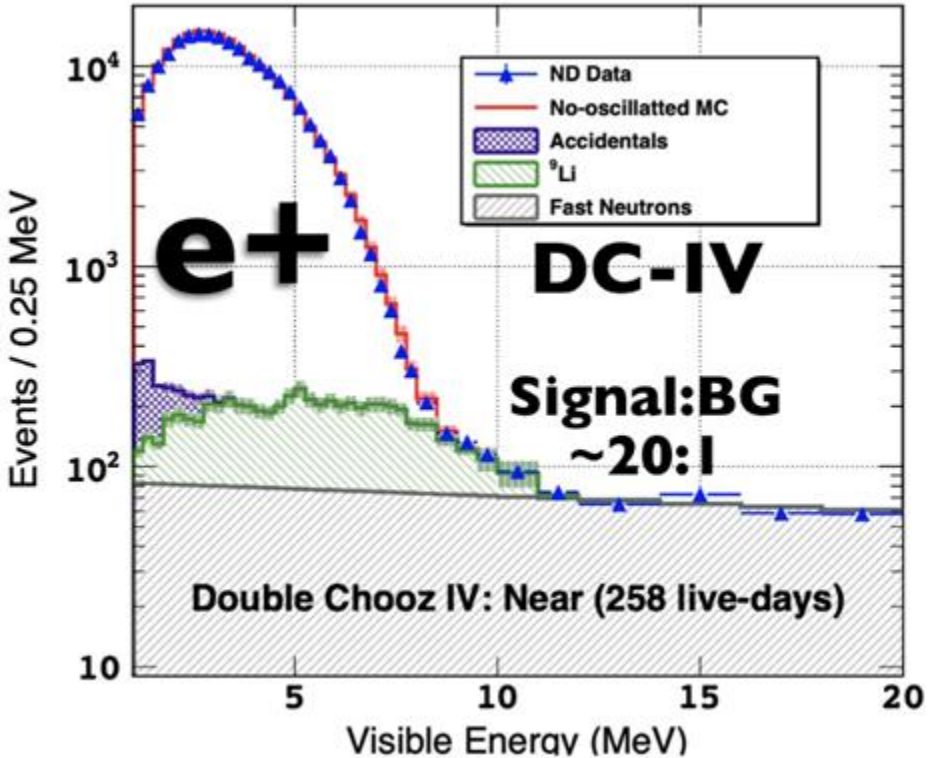
Measured spectra

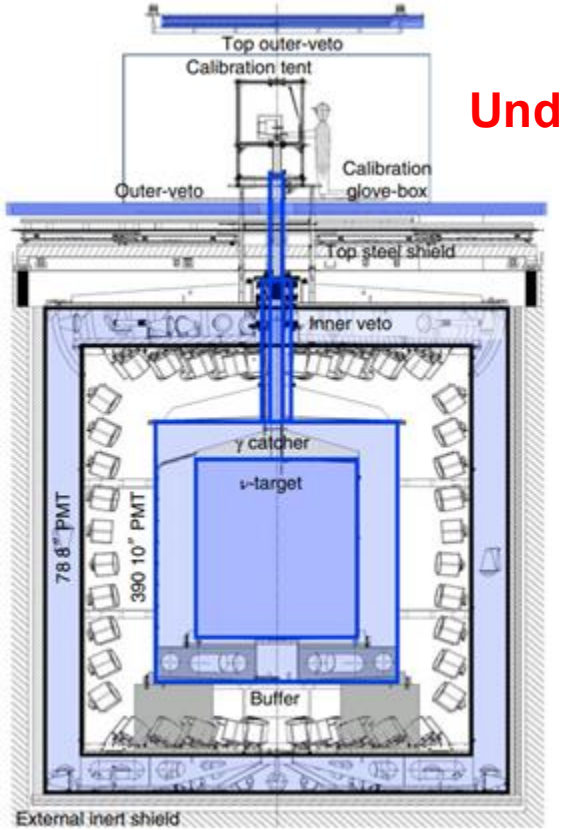




Complex machinery to veto backgrounds

Inverse beta decay signal → positron

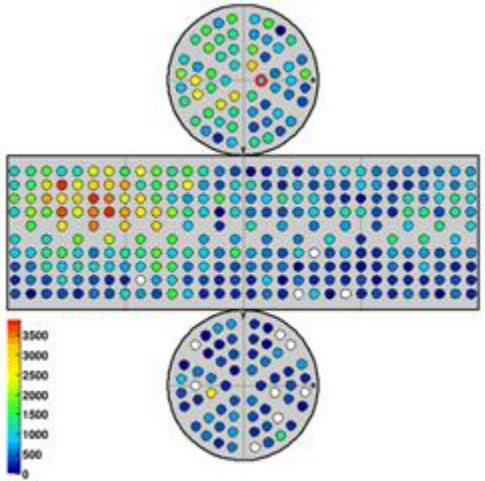


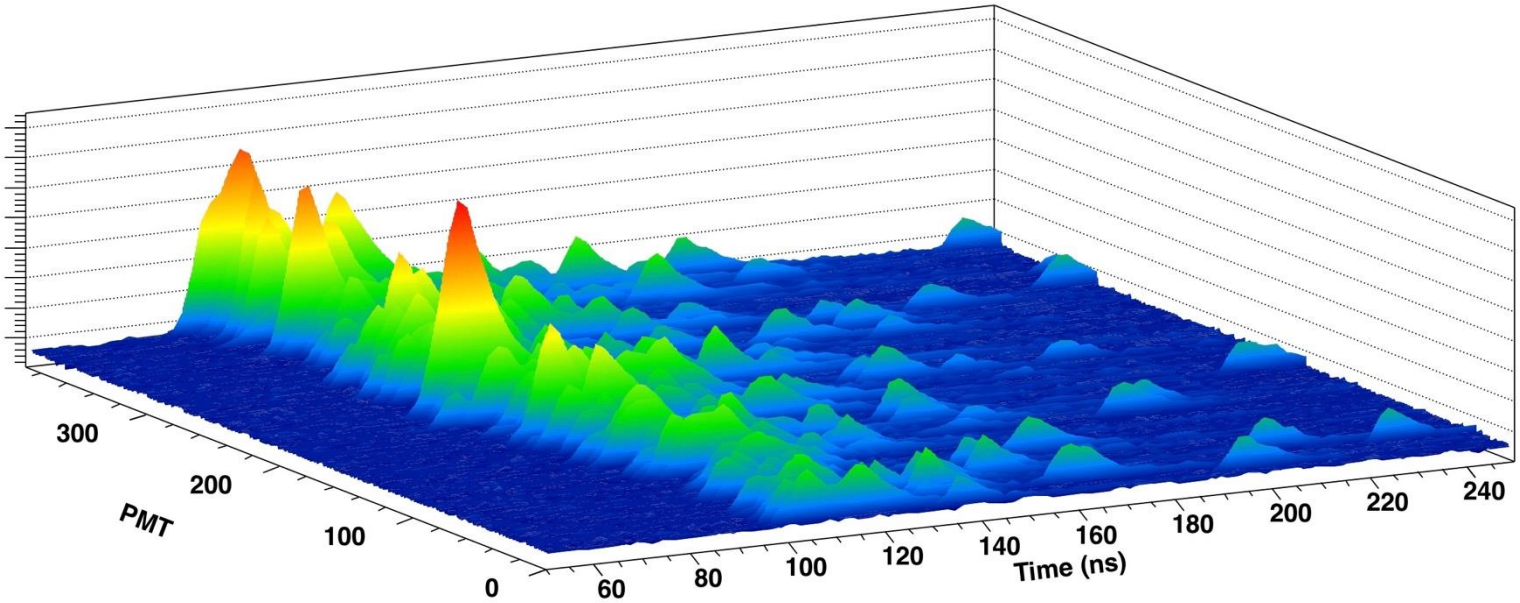


Underground

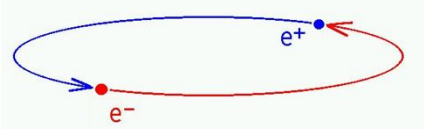
Efforts on e+ identification

FADC, a powerful tool



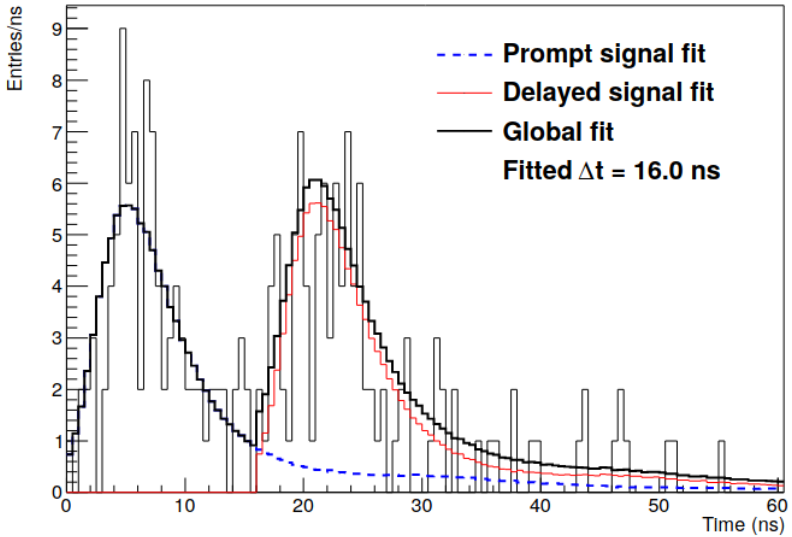


Efforts on e+ identification



$\varepsilon < 50\%$

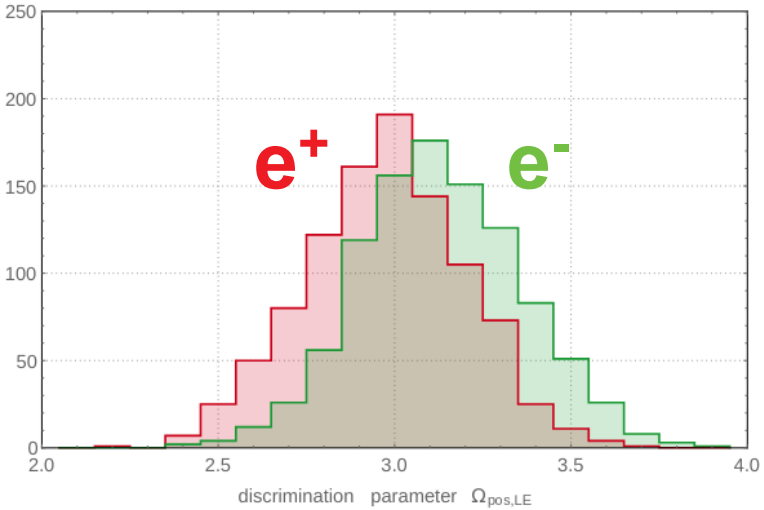
Ortho-positronium observation



arXiv:1407.6913

Pulse shape discrimination

Fourier power spectra of scintillator pulses



arXiv:1710.04315

Efforts on e+ identification

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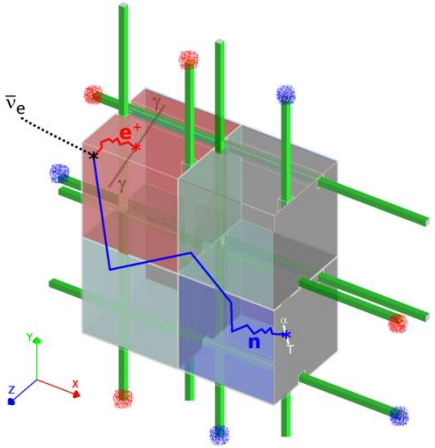
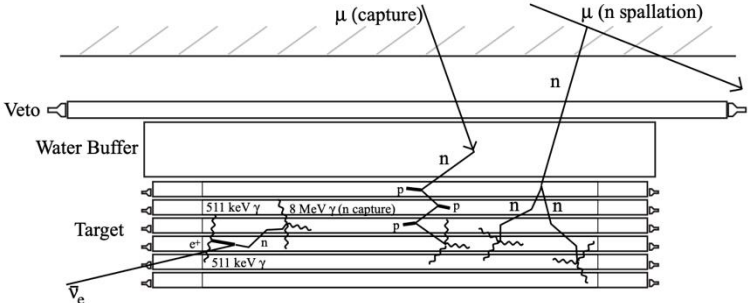
-> Segmentation

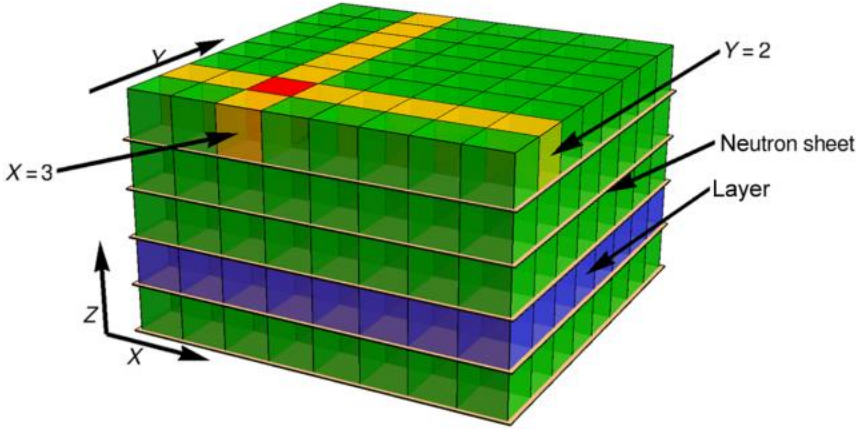
SoLid
arXiv:2407.14382



Palo Verde
arXiv:hep-ex/0003022

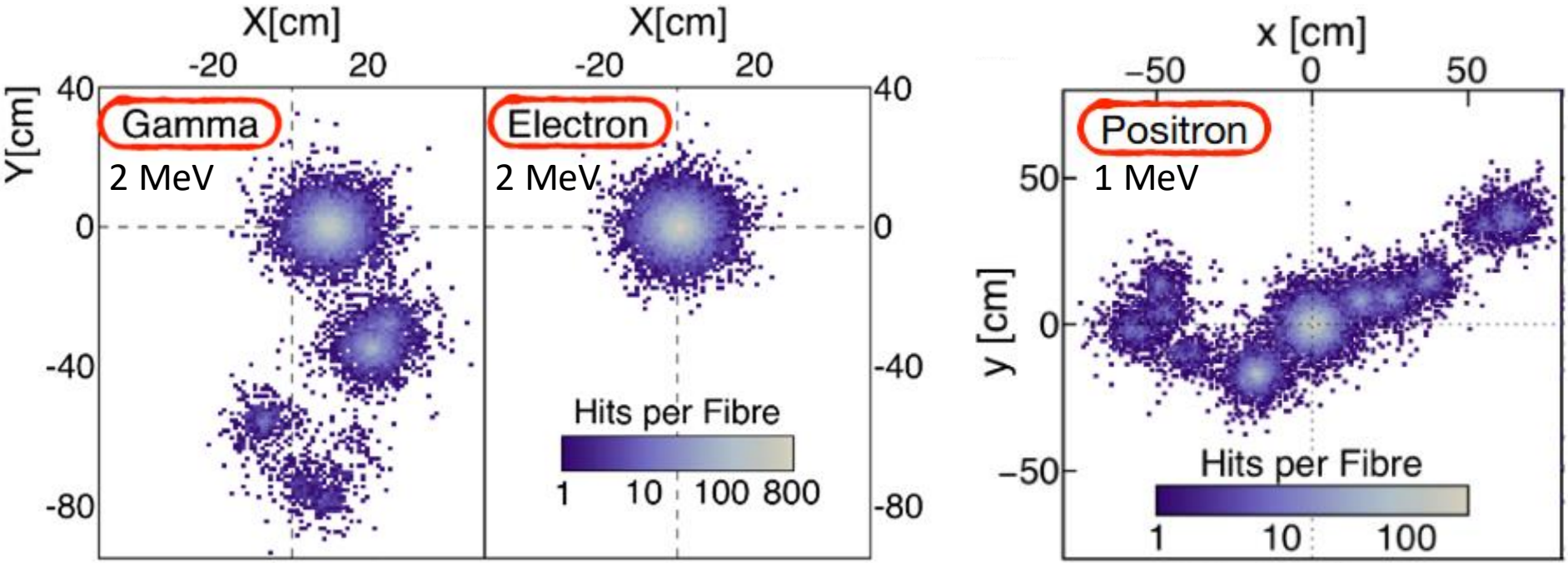


CHANDLER
arXiv:1812.02163



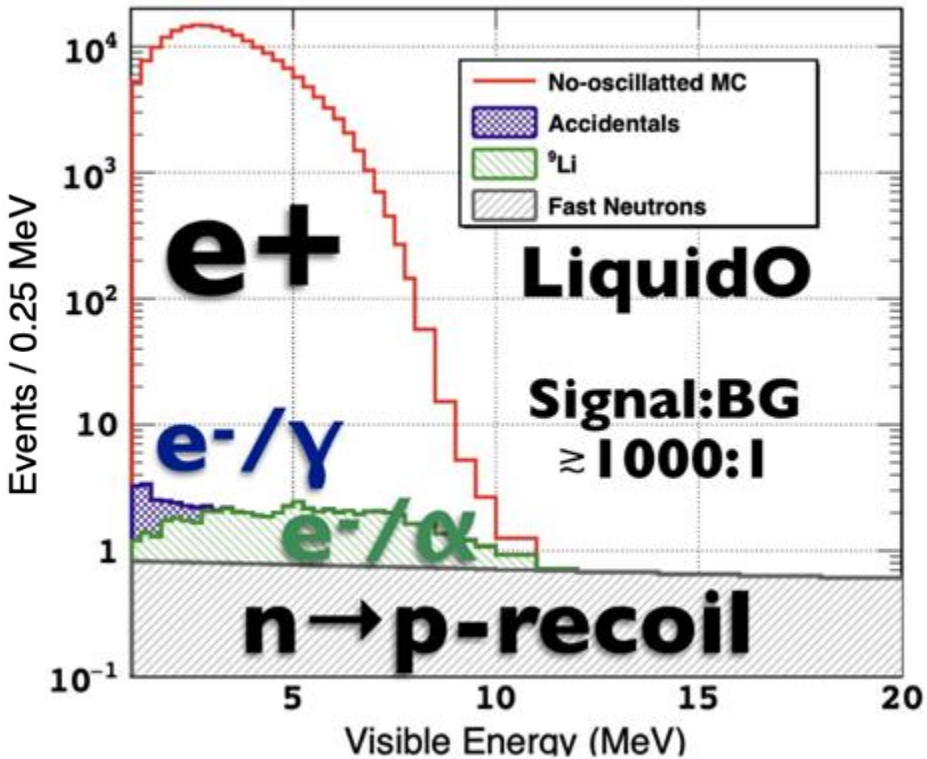
PANDA
arXiv:1404.7309

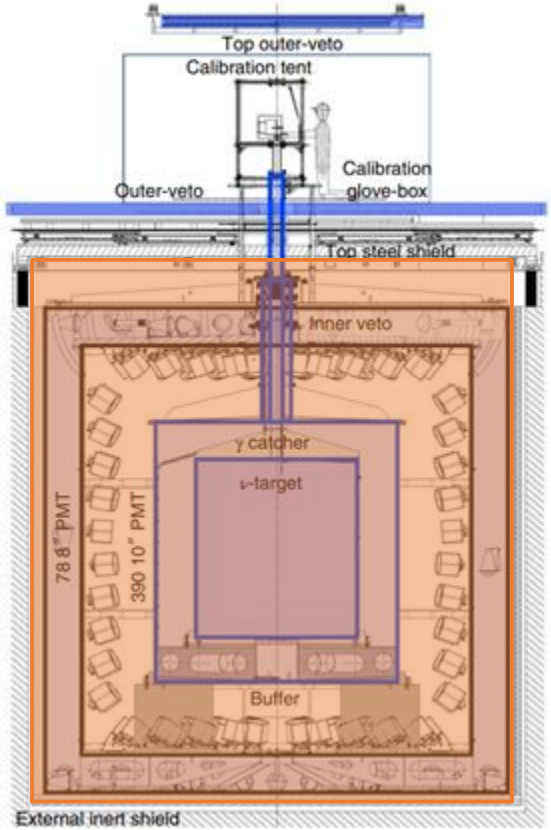
LiquidO: Powerful particle identification



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

Simpler machinery to veto backgrounds

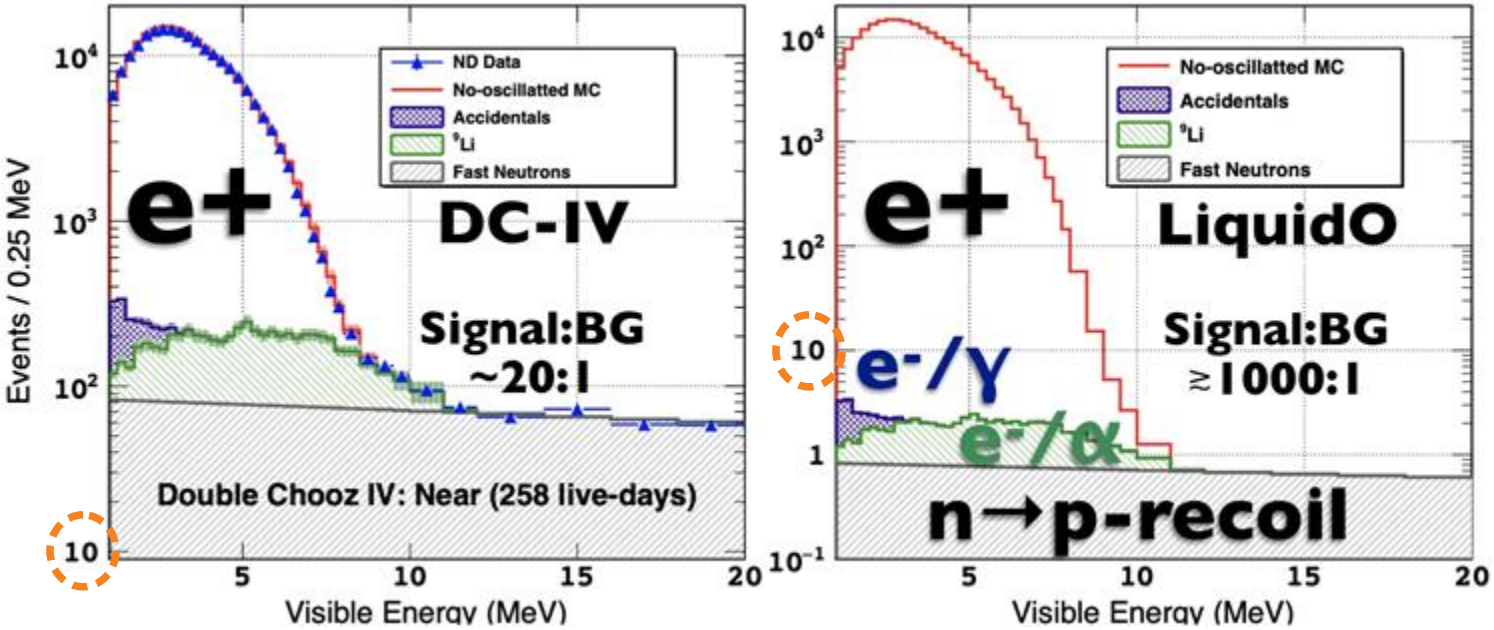




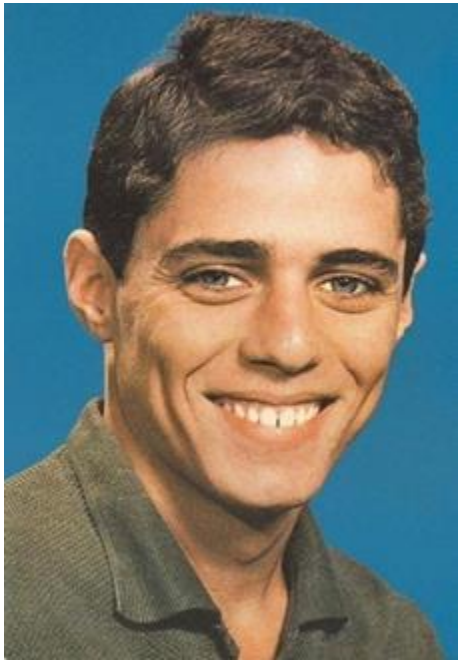
All available space as target

10 fold increase!

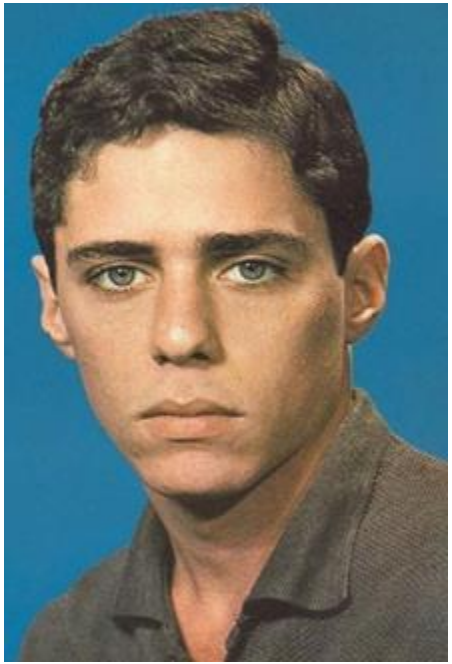
Impact on IBD (e^+) detection



Applying expected PID for BG rejection (100:1)

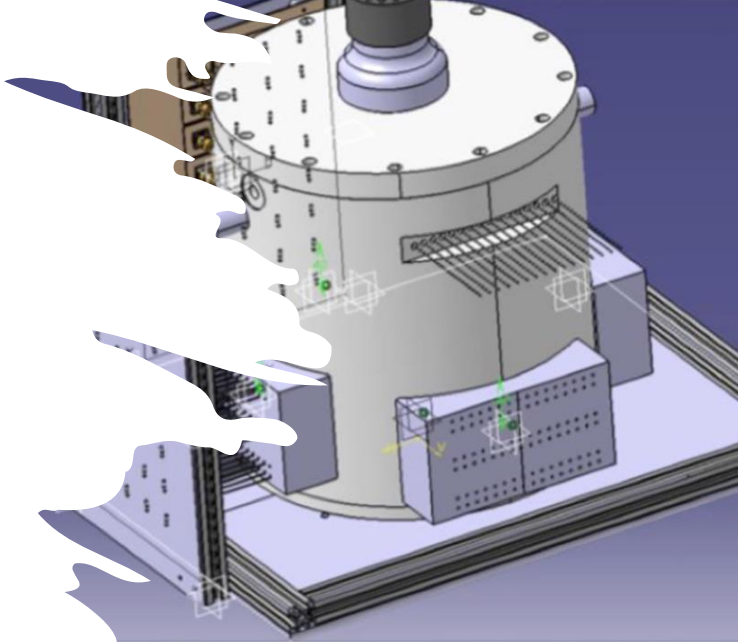


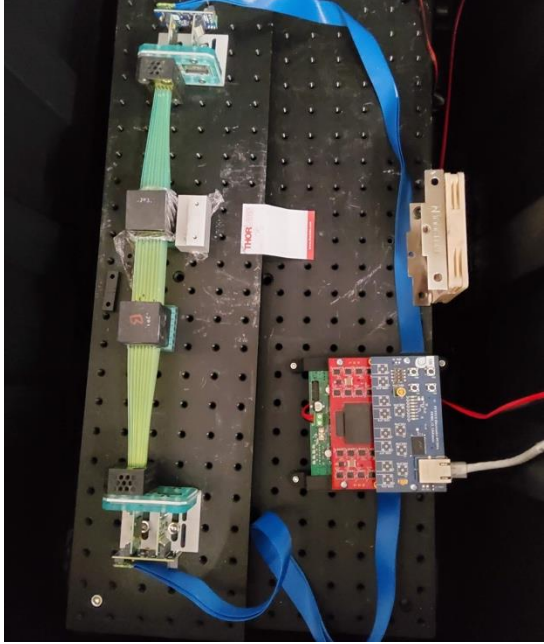
Nice MC plots!



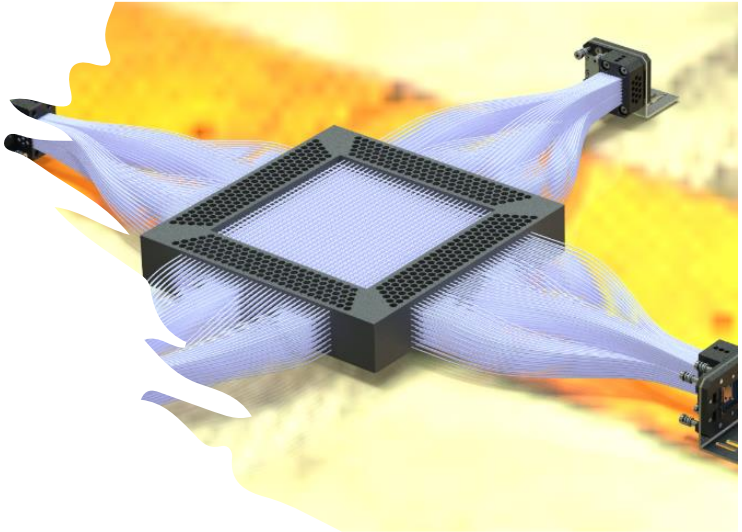
Nice **MC** plots.

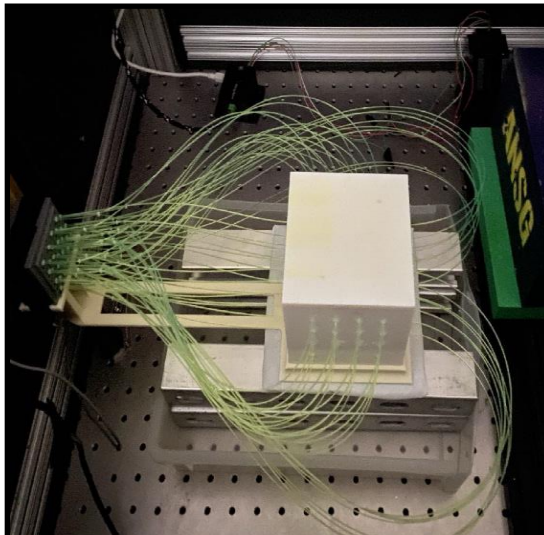
How are we developing LiquidO?





Prototypes





First proof of principle demonstrator

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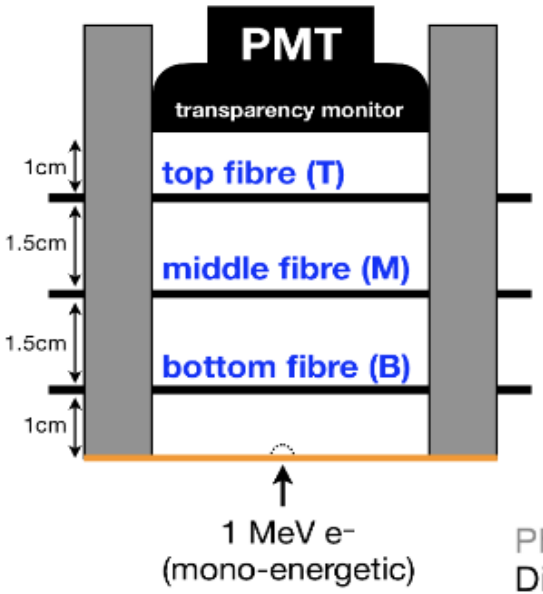
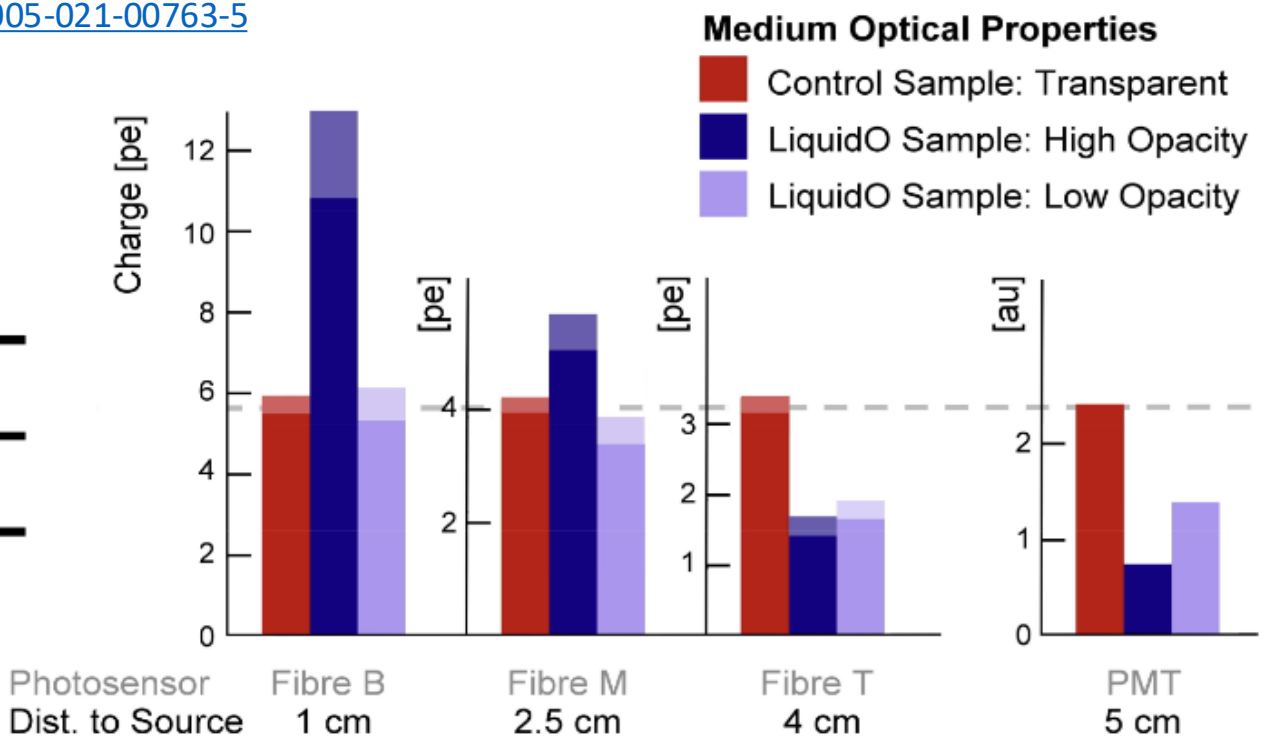
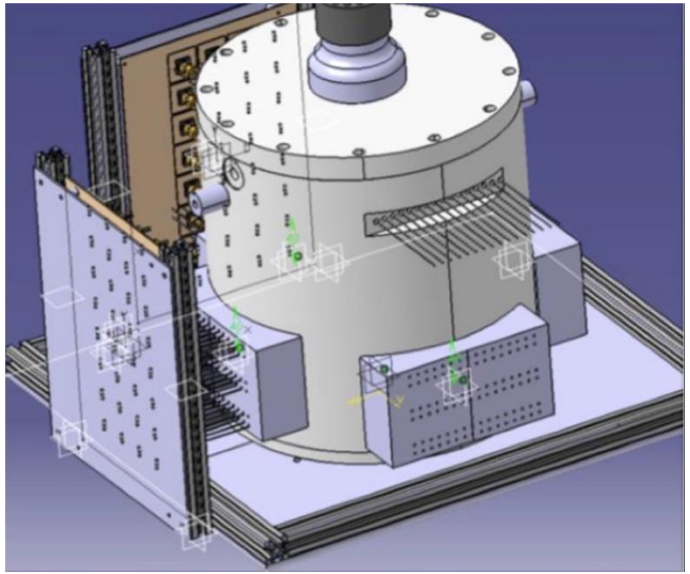
https://www.nature.com/articles/s42005-021-00763-5
arXiv:1908.03334

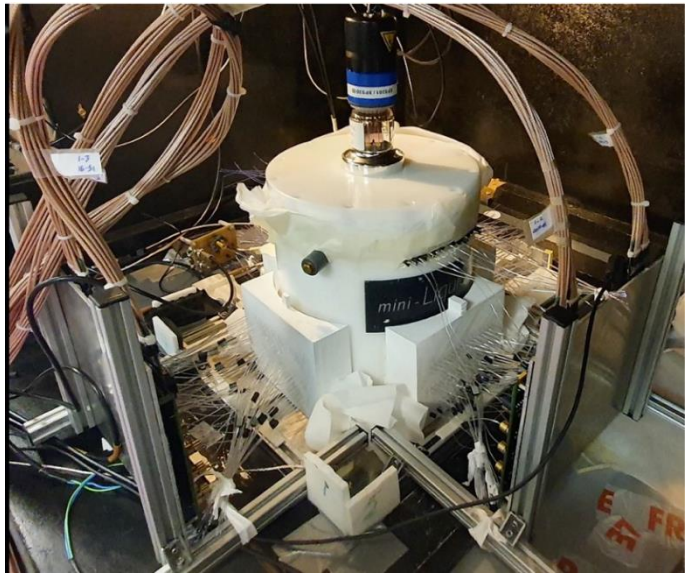




MINI-LiquidO Prototype



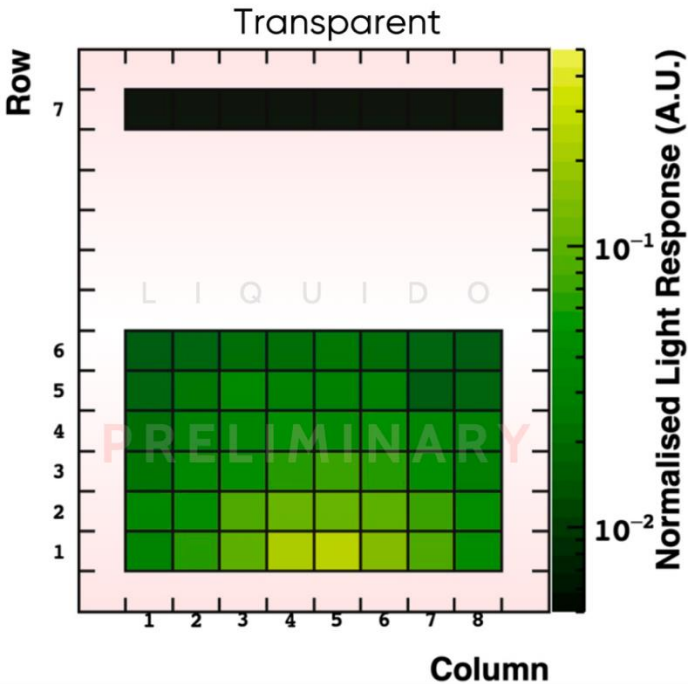
- 10 L and 64 readout fibres
- Very fast electronics
- Temp. control system [5, 40]^{o}C
- Runs with:
  - Opaque LS (NoWash20, NW)
  - LAB (+PPO)
  - Water
- e^- beam [0.4, 1.8] MeV
- Operated @ LP2i Bordeaux

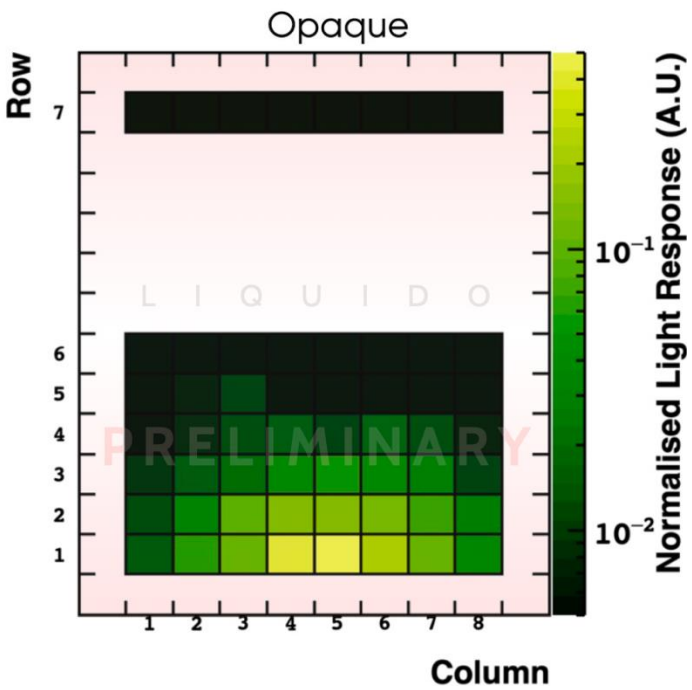


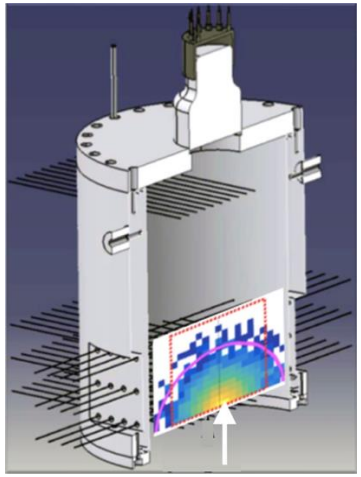
Goal: demonstrate stochastic light confinement

arXiv:2503.02541

MINI-LiquidO Prototype: Results



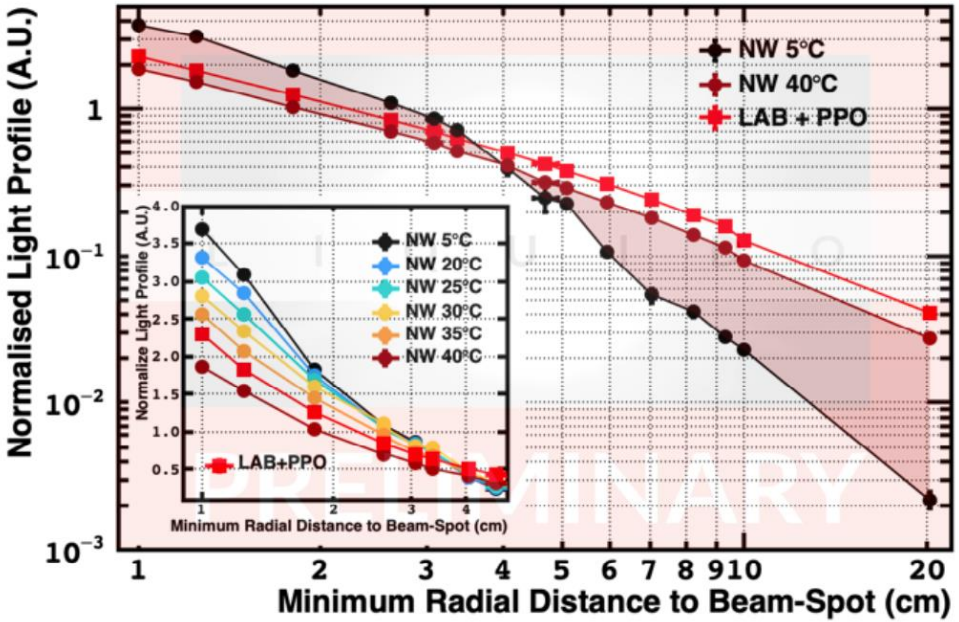




arXiv:2503.02541

MINI-LiquidO Prototype: Results

Transparent vs Opaque

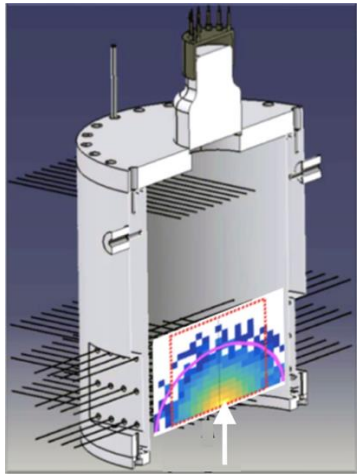


NW at 40°C → transparent
similar to LAB+PPO
NW at 5°C → Opaque

Light ball formation at ~4cm

Stochastic light confinement!

Major demonstration of the LiquidO technology



arXiv:2503.02541

MINI-LiquidO Prototype: Results

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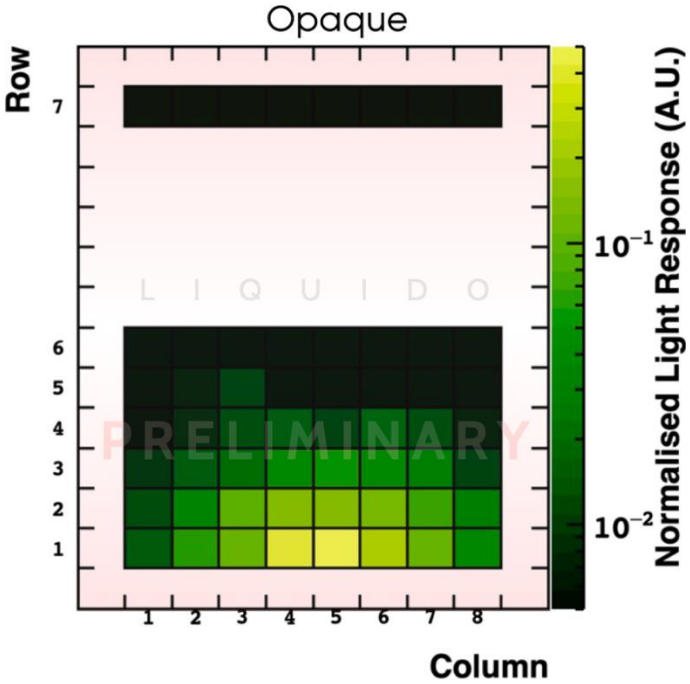
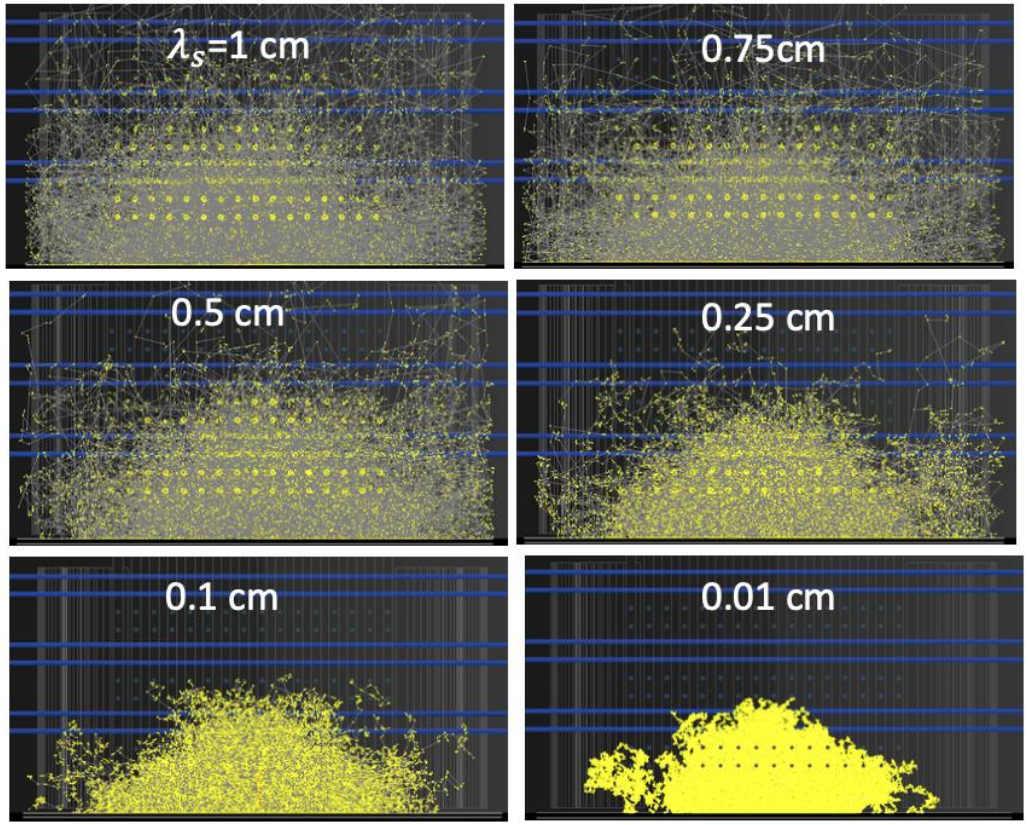
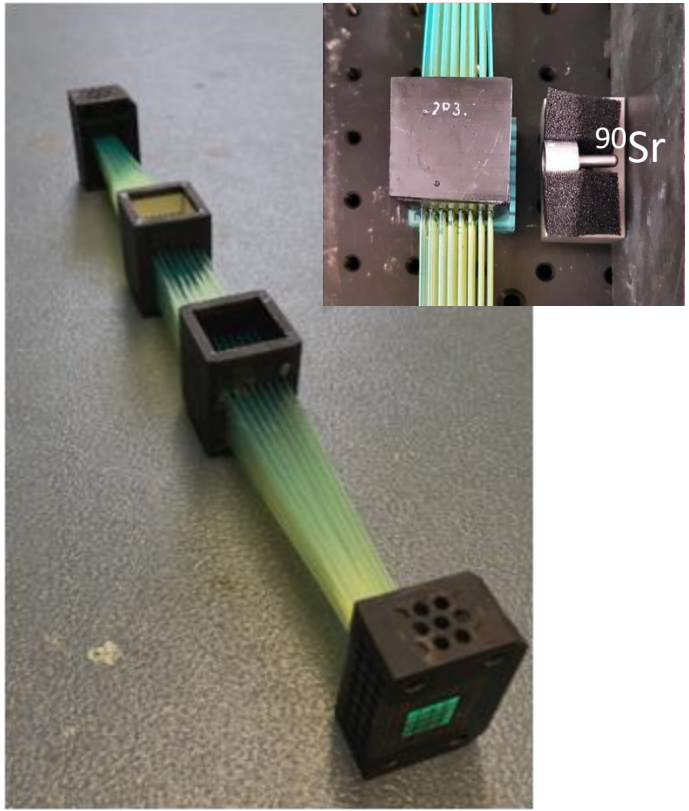
Opacity → Scattering length

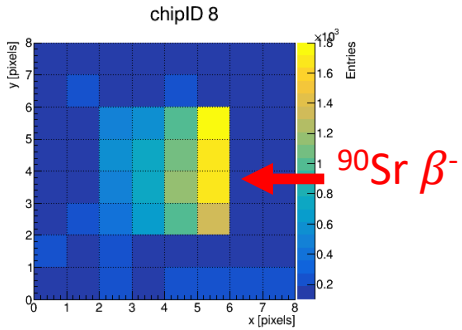


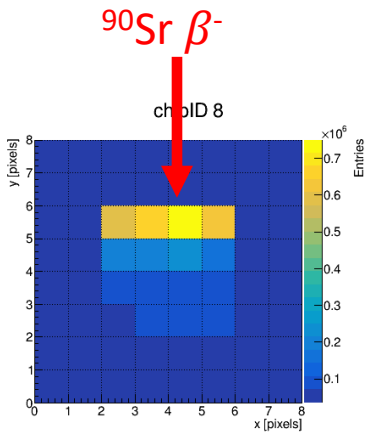


arXiv:2503.02541

On going developments at Sussex: Cubes



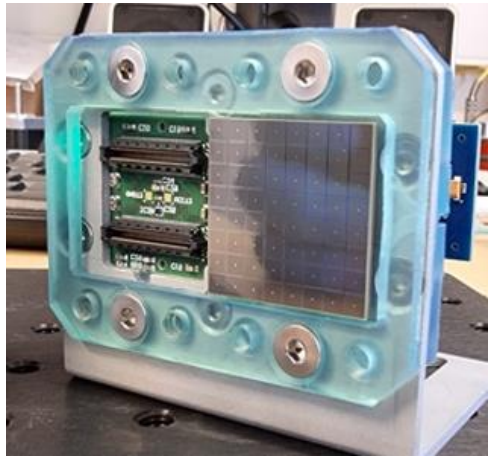




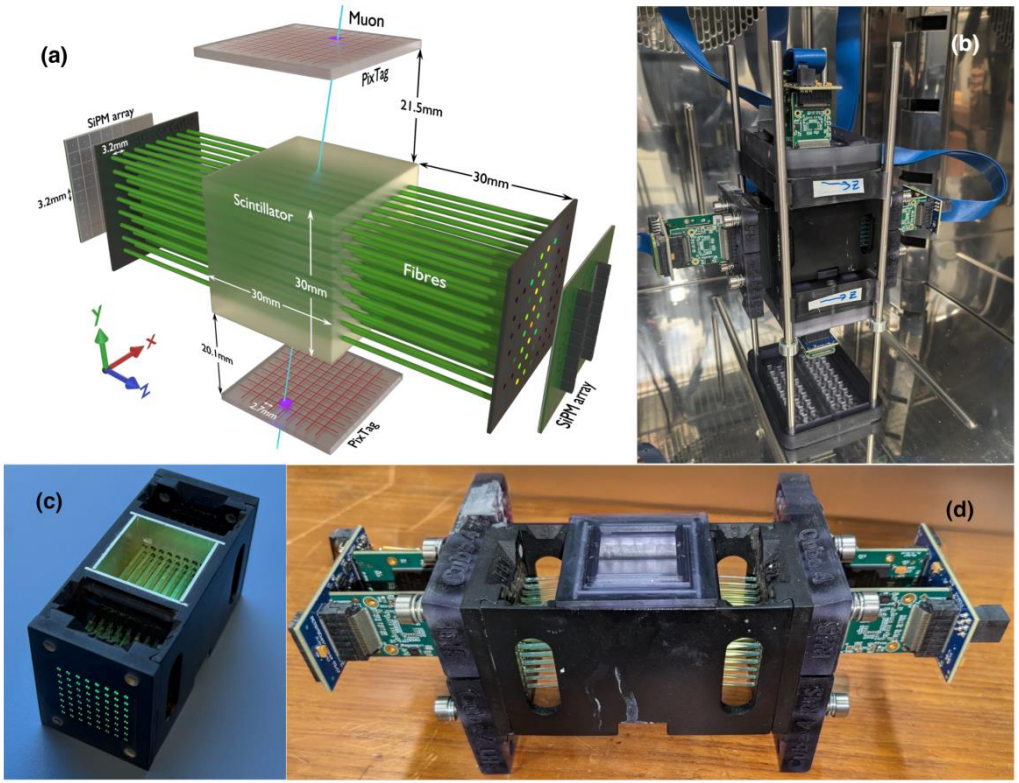
Goals:

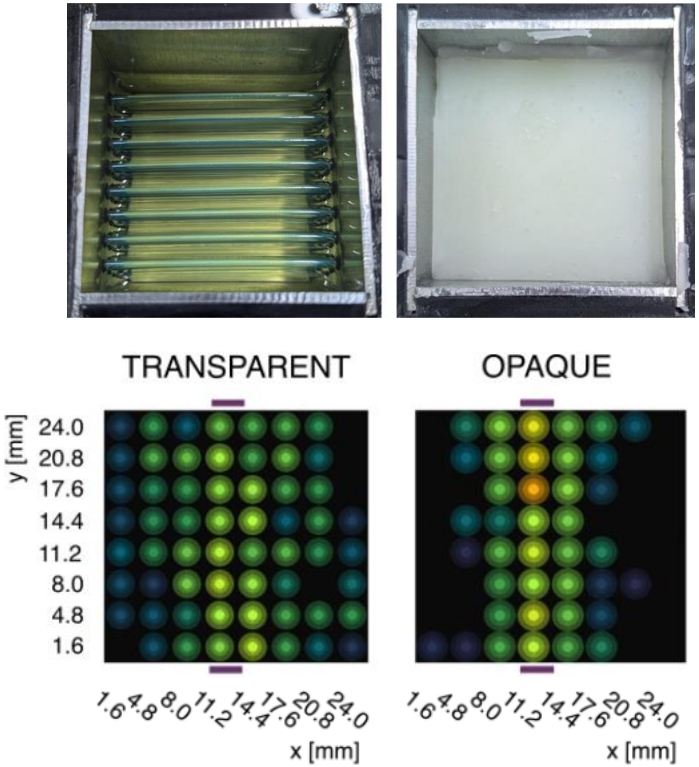
→ Boosted light collection

→ Muon tracking



On going developments at Sussex: Cubes





Publication under internal review

On going developments at Sussex: Tile

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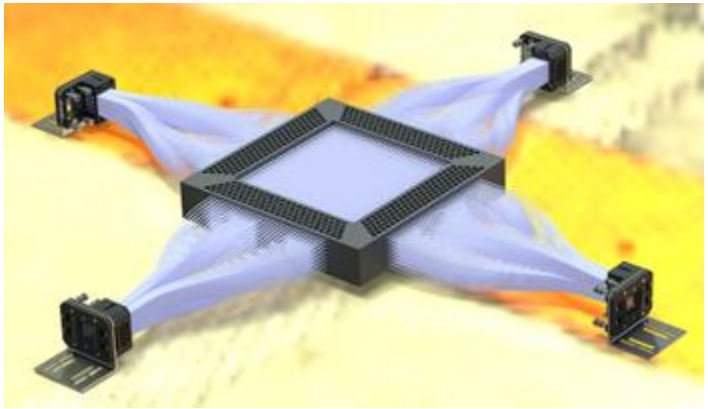

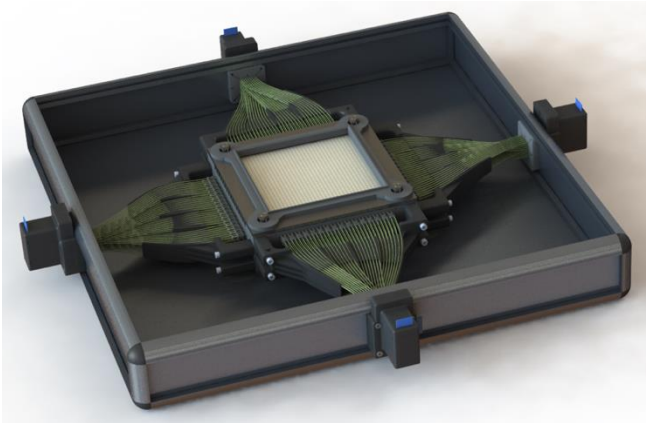

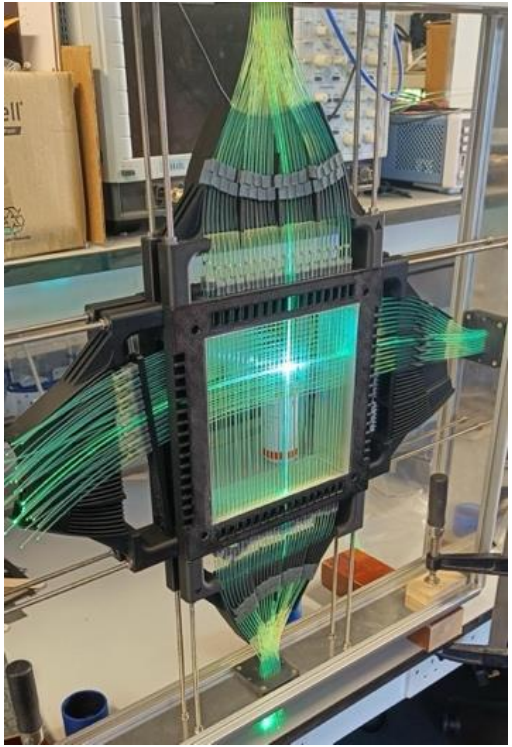

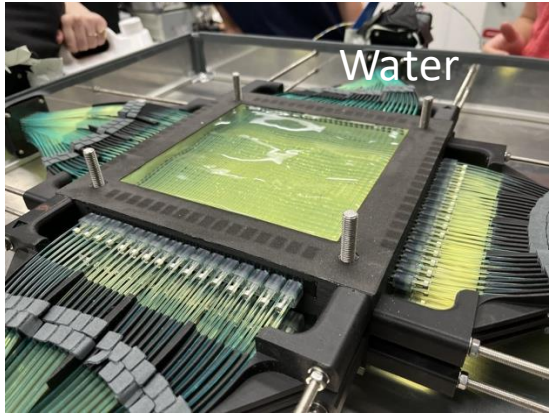

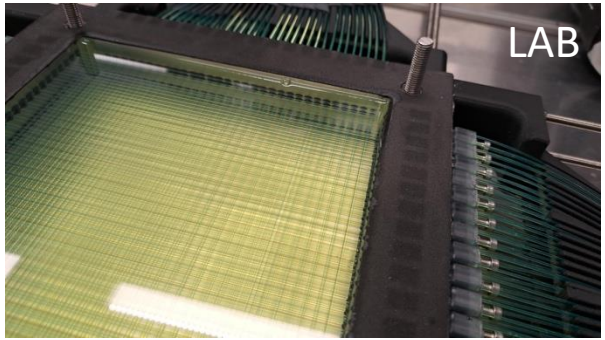

Water-based opaque scintillators

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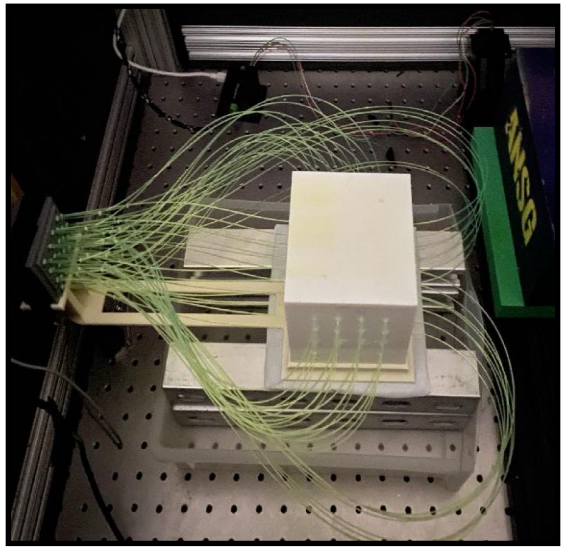
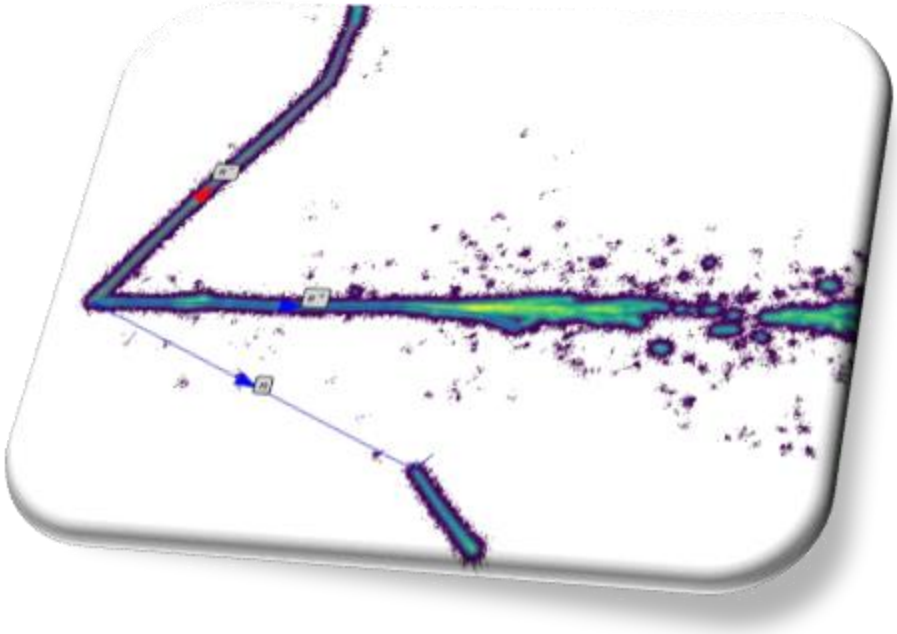
arXiv:2406.13054



1L, 32 ch

"A mean position reconstruction error of **4.4 mm** for 1.6 MeV equivalent events and 7.4 mm for 0.8 MeV equivalent events”

Which physics can we do with LiquidO?



First experiment with LiquidO technology

European Innovation Council

UK Research and Innovation

C L O U D

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)

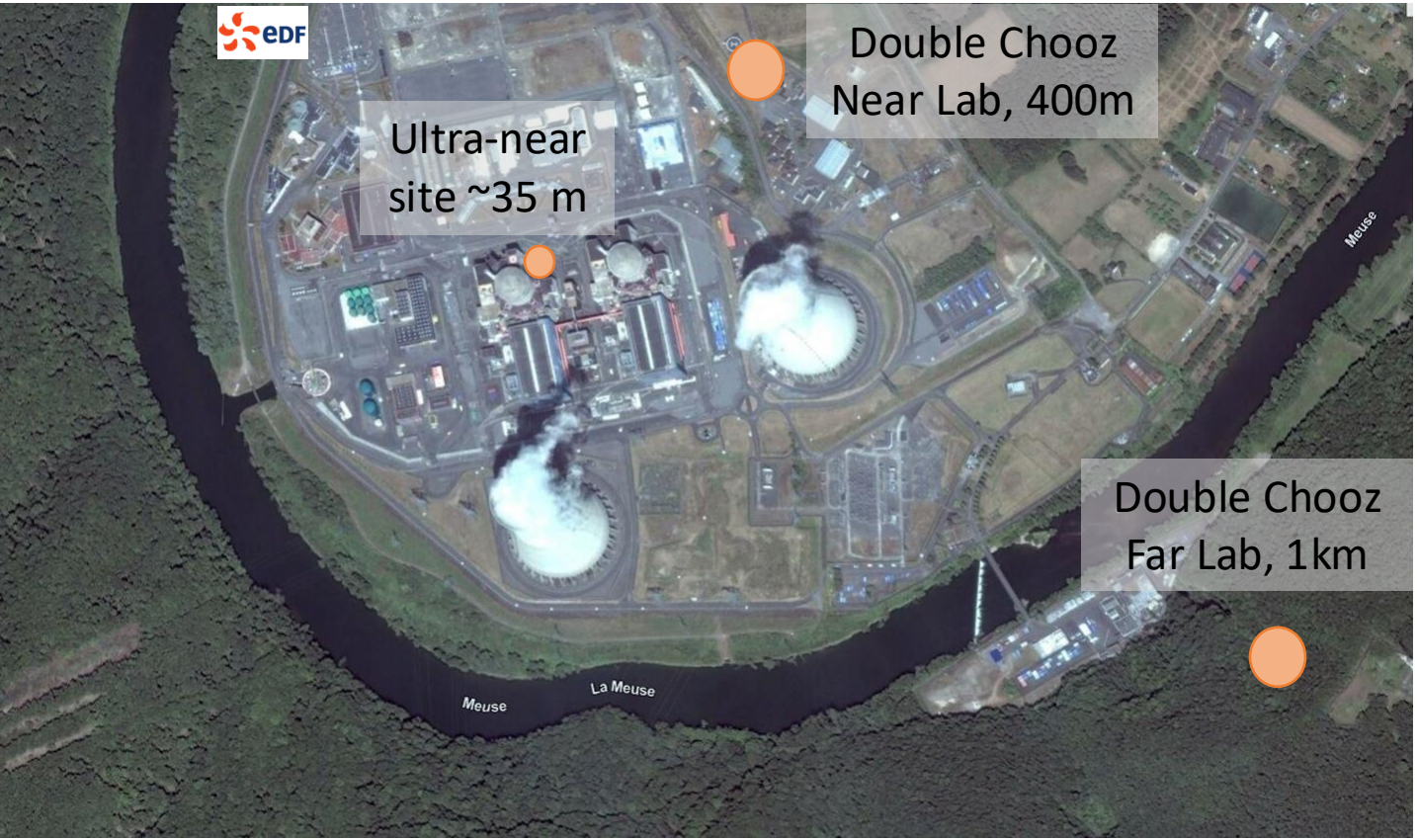
⟹ **20 institutions in 11 countries**

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

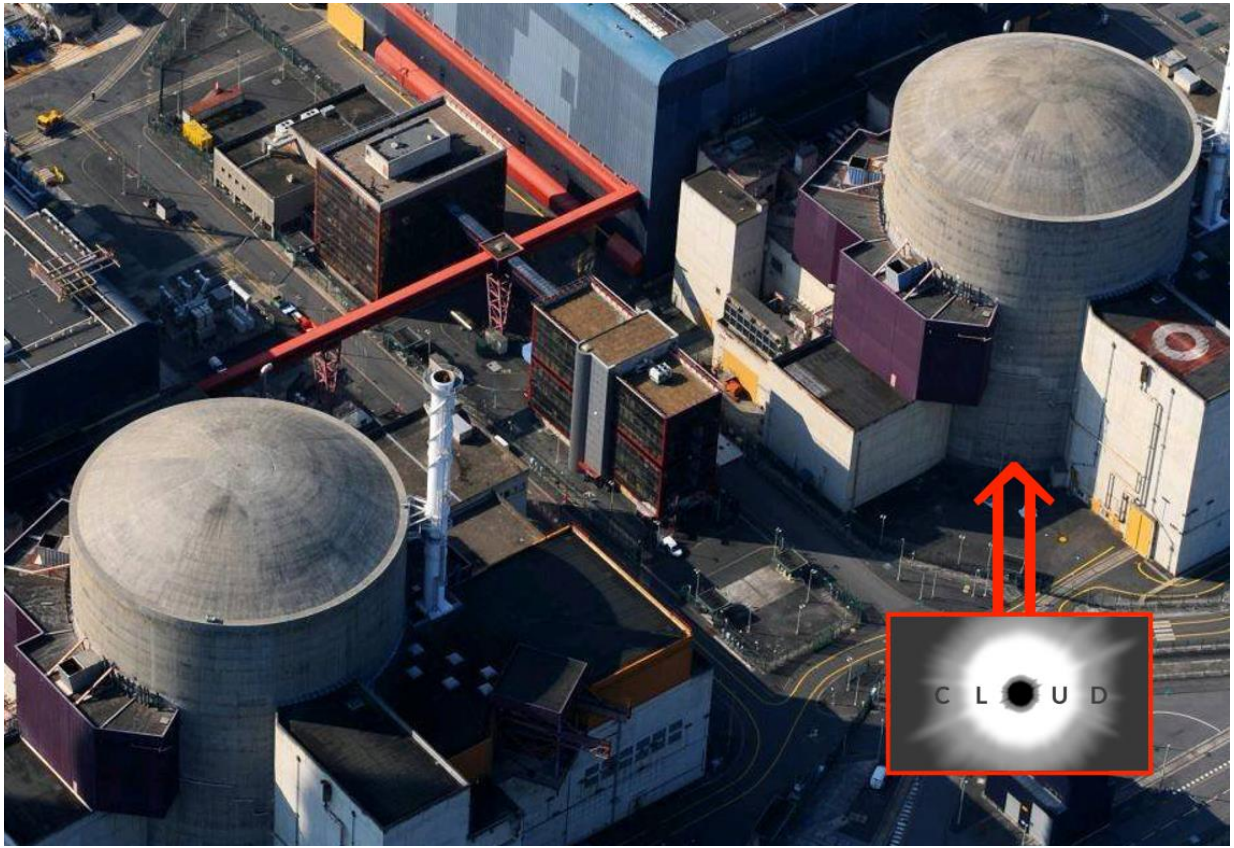
Innovation (2025-28)
- Reactor Monitoring

Fundamental Science (>2026)
- 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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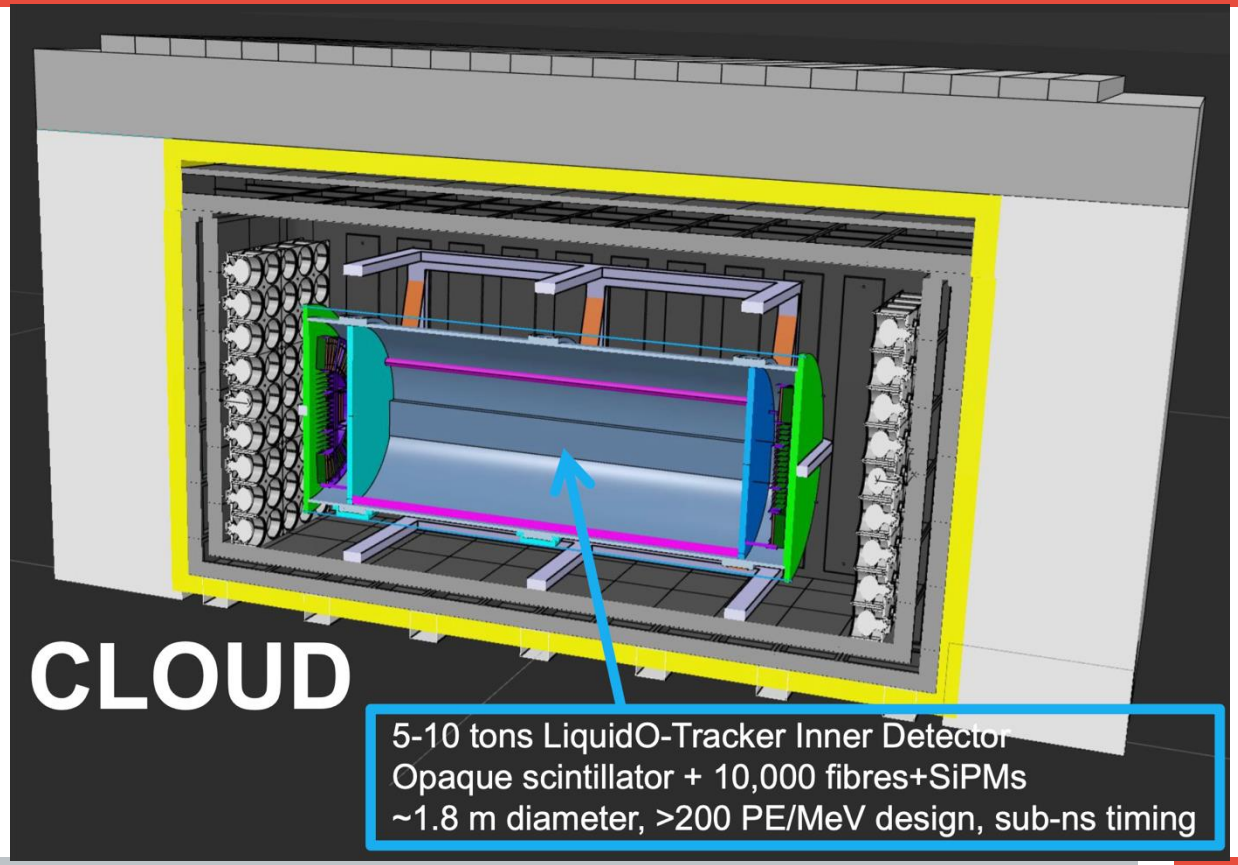
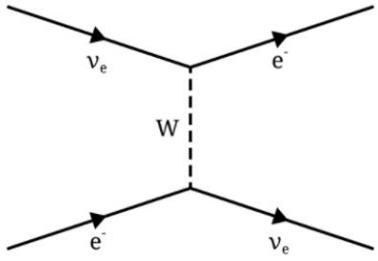
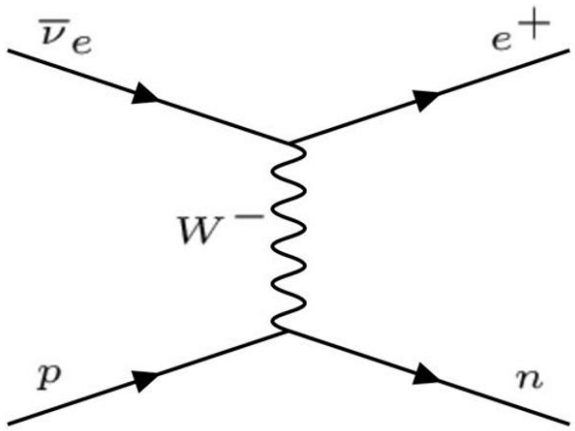


Physics of CLOUD





Interactions with Protons or Electrons

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- Inverse Beta Decay (IBD)

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

- 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)

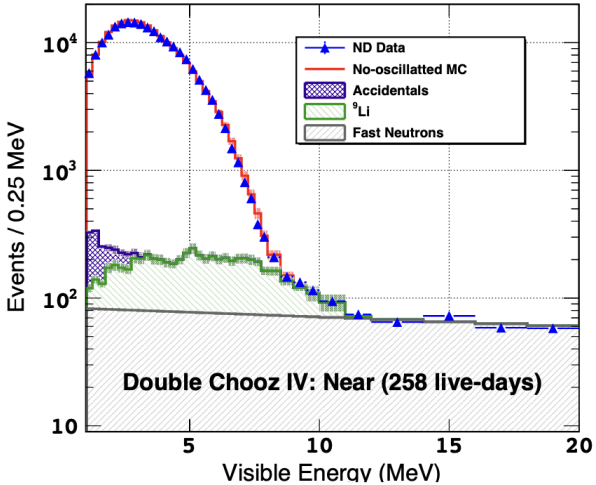
$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$

- Signature:

  Single energetic e^-

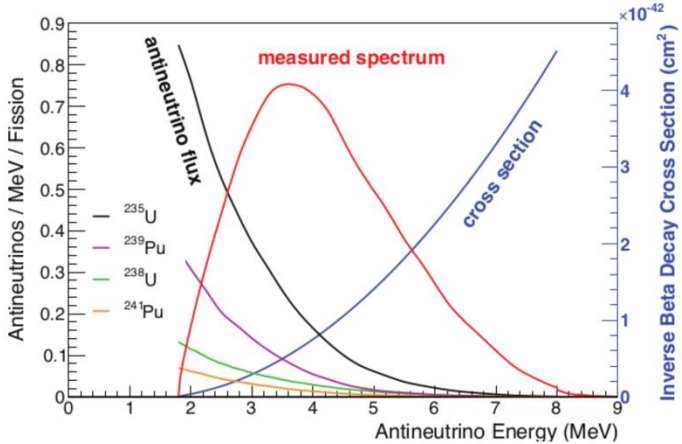
CLOUD Phase I: Pure Opaque Scintillator

- >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

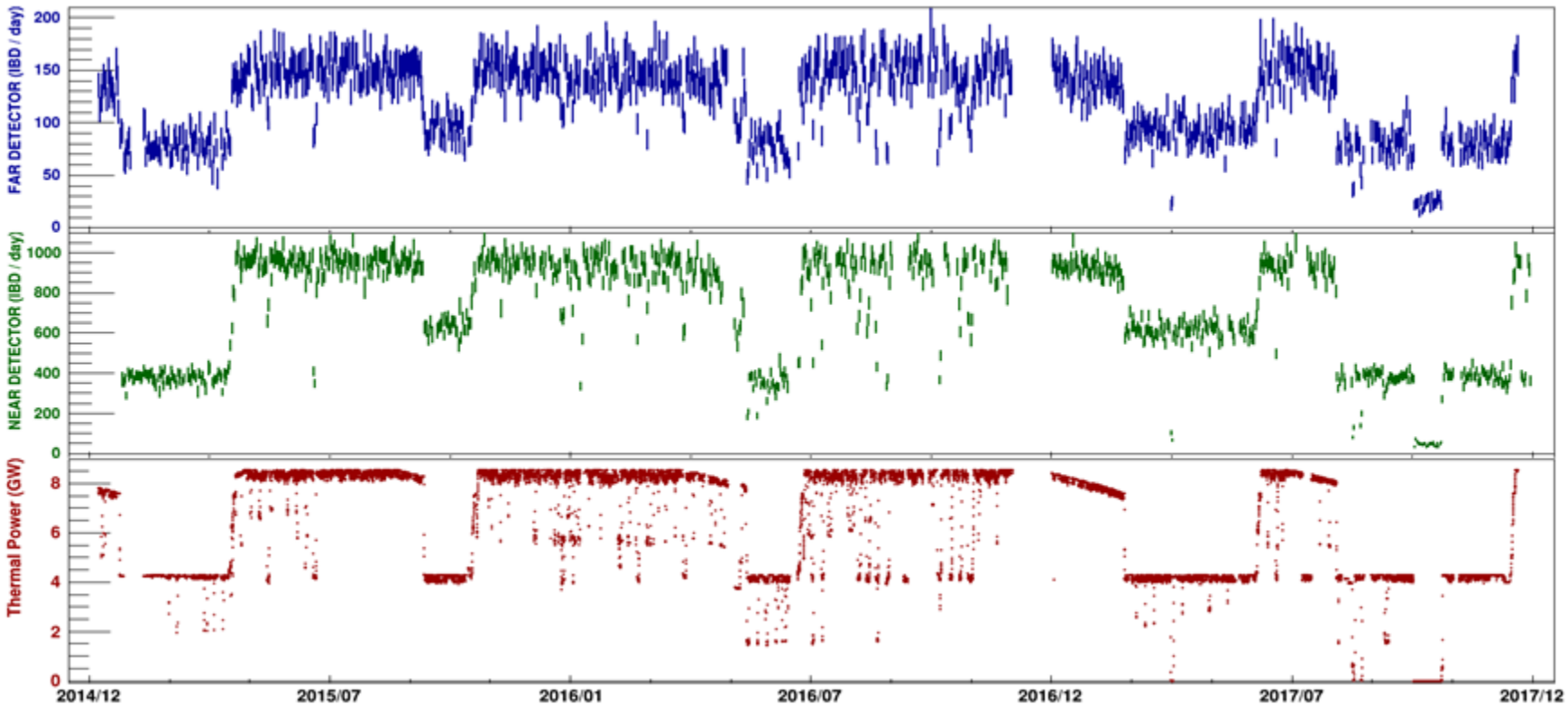


Improvements with LiquidO event classification

- 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



Far Detector

Near Detector

Reactor Thermal Power

CLOUD Phase I: Pure Opaque Scintillator

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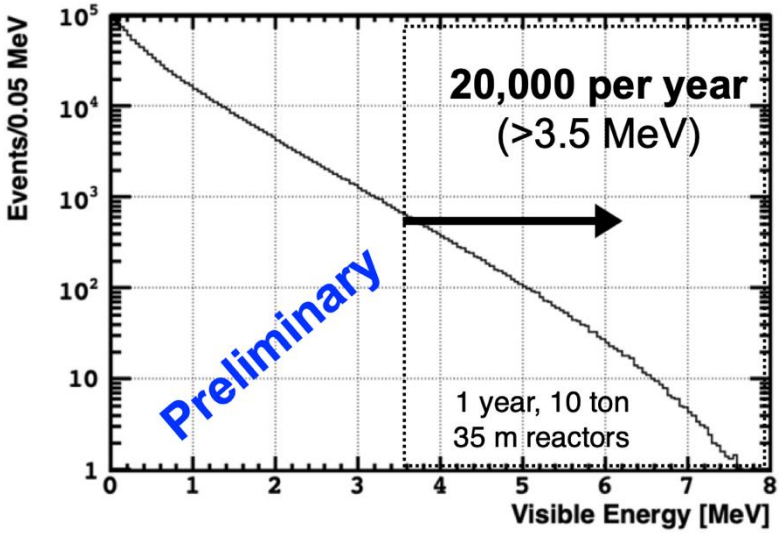
- Electron elastic scattering
  - 5,000 per day
- Challenge:
  - Isolate electrons
  - Require
    - Electron classification
    - Fiducial volume
    - Higher energies
- Probe of $\sin^2(\theta_w)$ at very low energy using antineutrinos



CLOUD Phase II: *Indium* Loading in Scintillator

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- 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

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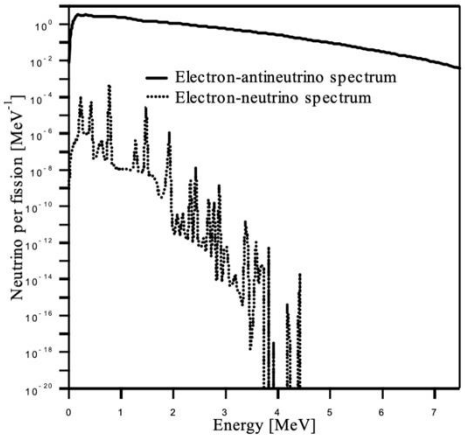
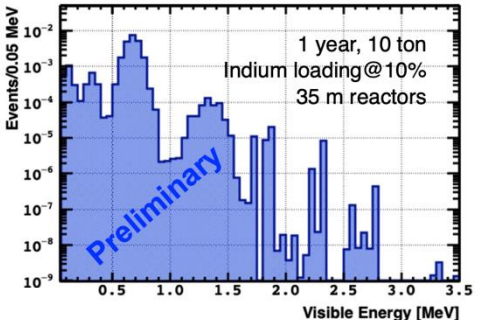
- Fission also produces electron neutrinos
  - Albeit at a vastly reduced rate
- Never been measured!
- 10-ton detector is too small..
- Unless prediction is wrong?
- What could we measure?

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





CLOUD Phase II: *Indium* Loading in Scintillator

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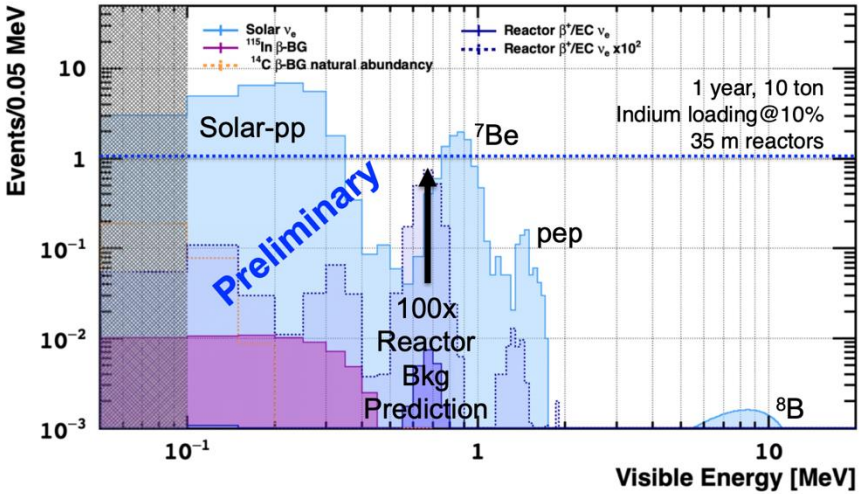
What's the Solar Neutrino Spectrum?



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

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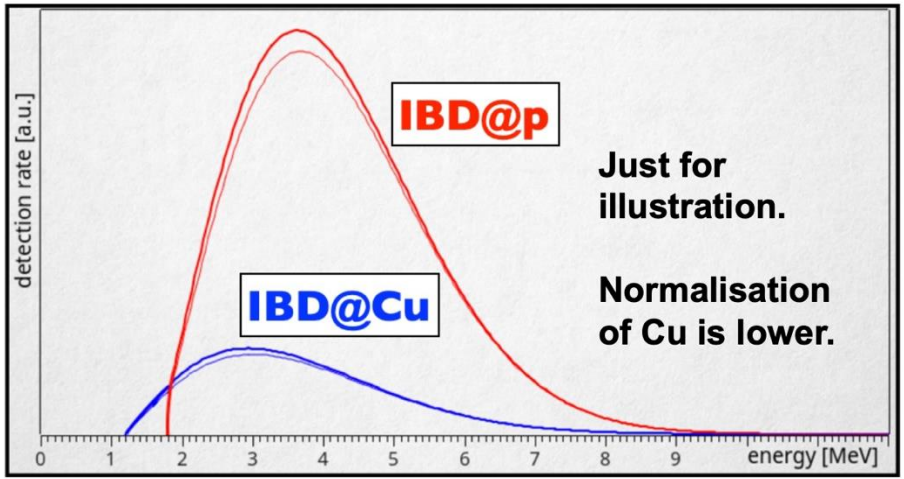
- Electron antineutrino CC with copper nucleus

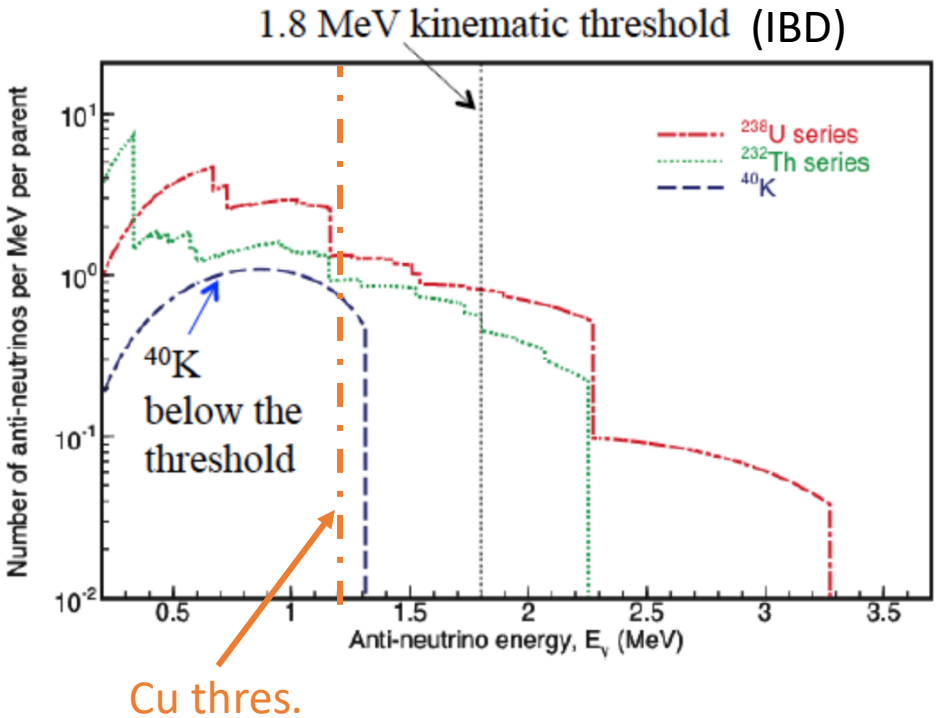
$$\bar{\nu}_e + {}^{63}Cu \rightarrow e^+ + {}^{63}Ni^{(*)}$$
$$\hookrightarrow \gamma\ (87\ keV) \quad \text{[if Ni was excited]}$$

- 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)

CLOUD Phase III: *Copper* Loading in Scintillator





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)

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arXiv:2308.04154

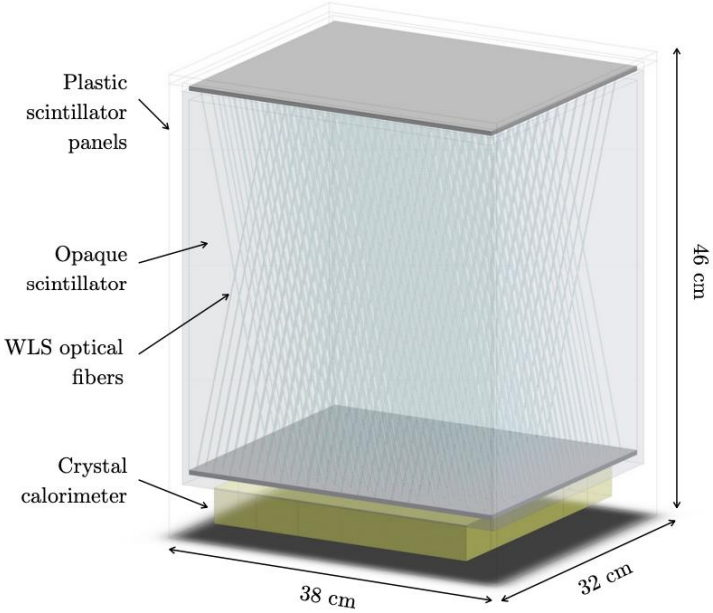
SuperChooz

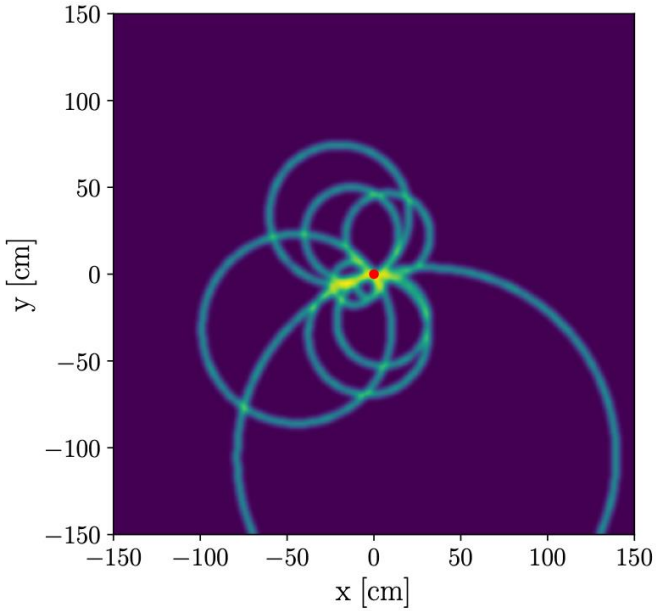
CERN Seminar: ***"The SuperChooz Experiment: Unveiling the Opportunity"***
https://indico.cern.ch/event/1215214/
https://zenodo.org/doi/10.5281/zenodo.7504161

COCOA

COmpact COmpton cAmera:

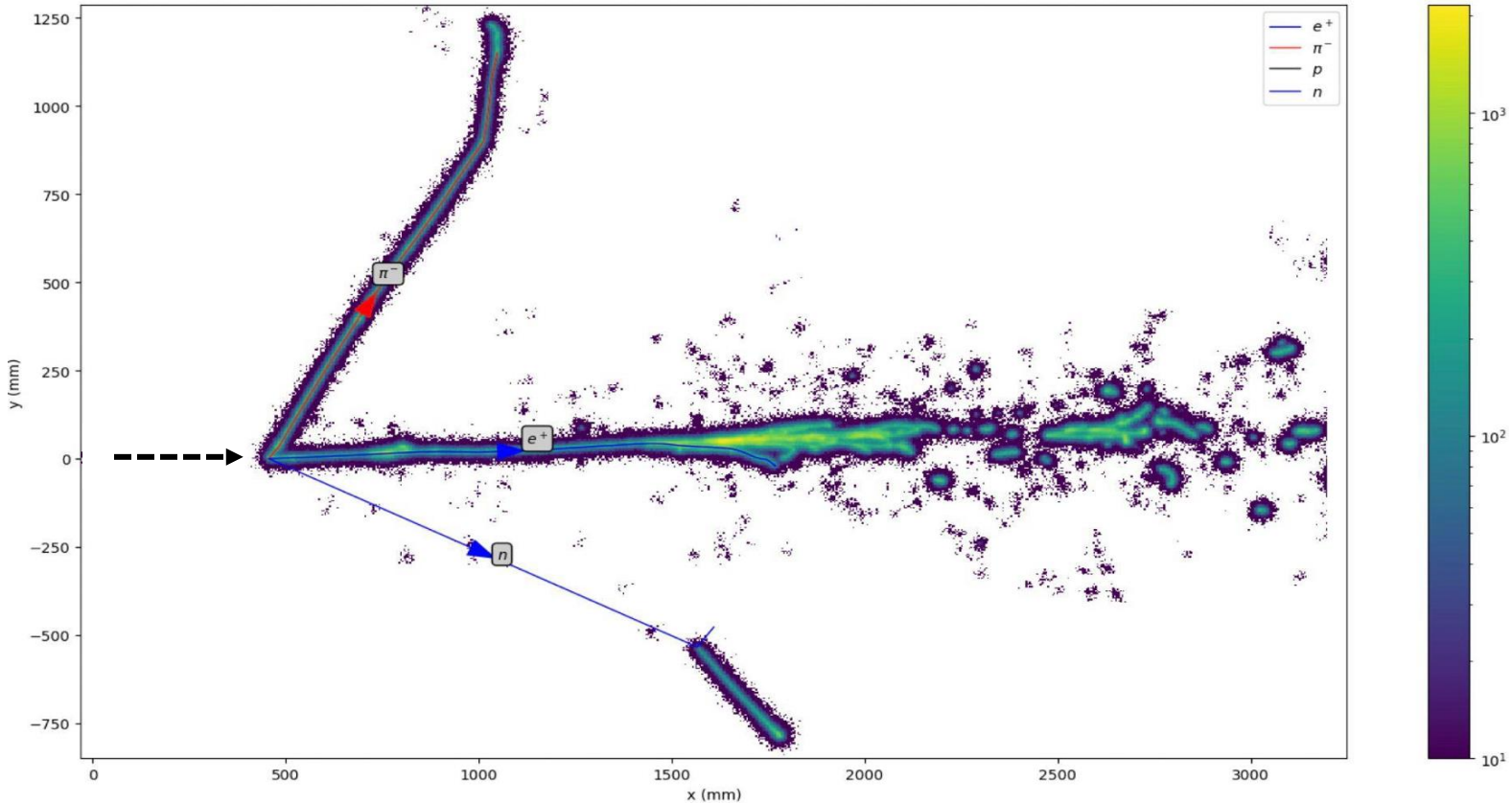
Cost-effective gamma-ray telescope for astrophysical observations in the MeV energy range.





arXiv:2502.20916

GeV neutrino detection



To conclude

Take-home message

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→ Opacity: novel and counter-intuitive way to use light-based detectors

→ Light-based “TPC”; uniform calorimeter; imaging (PID); ToF;

→ Doping: a powerful by-product

→ LiquidO R&D progressing rapidly and steadily

→ New **CLOUD** experiment will find technical solutions and verify LiquidO capabilities for reactor antineutrino detection at surface in the next years

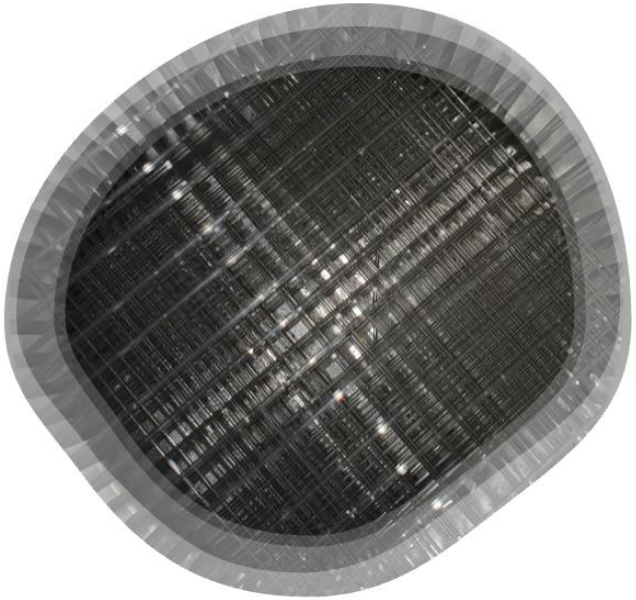
→ **Final thought:** LiquidO is a whole new way of thinking about the detector and neutrino experiments

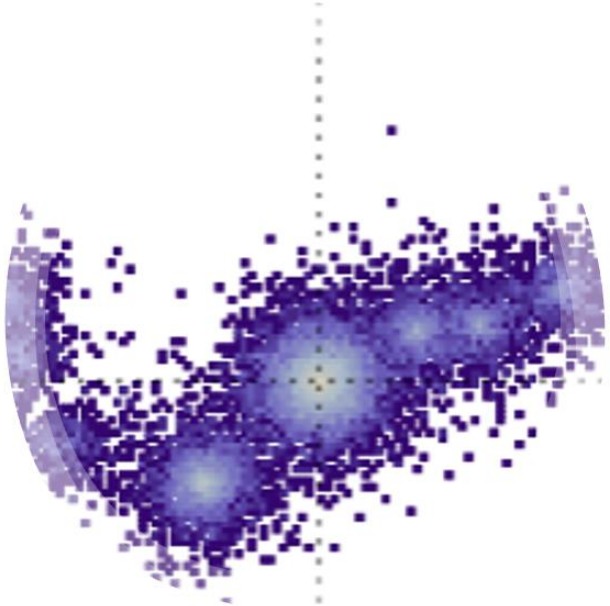
→ Expect many great ideas we haven’t even imagined yet!

LiquidO Consortium

- 90 scientists
- 26 institutions
- 11 countries

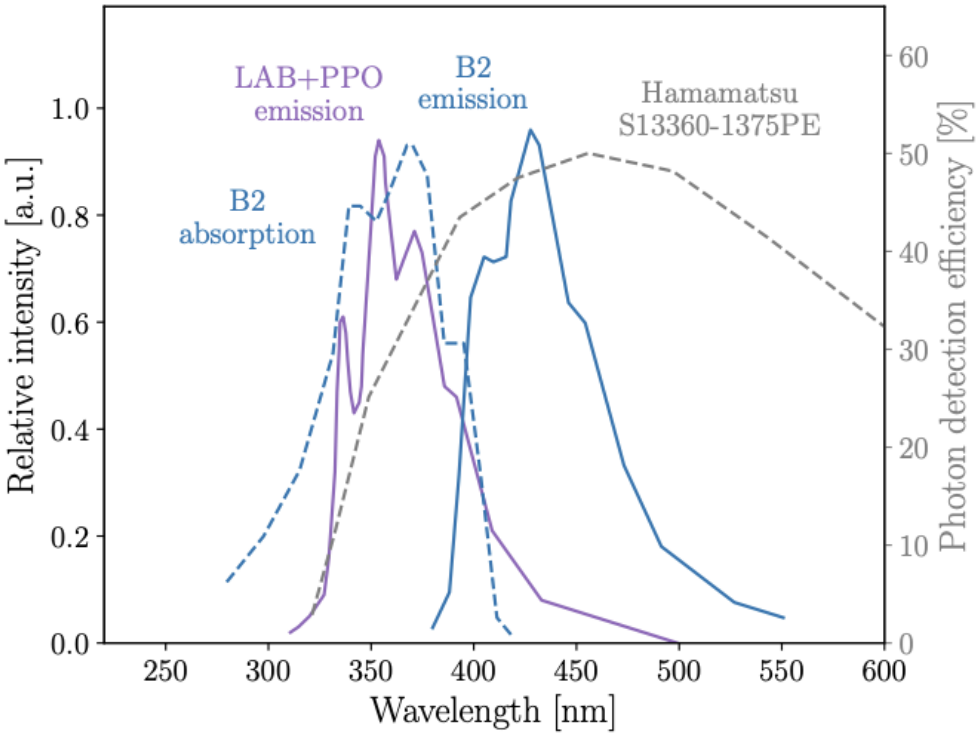
https://liquido.ijclab.in2p3.fr/



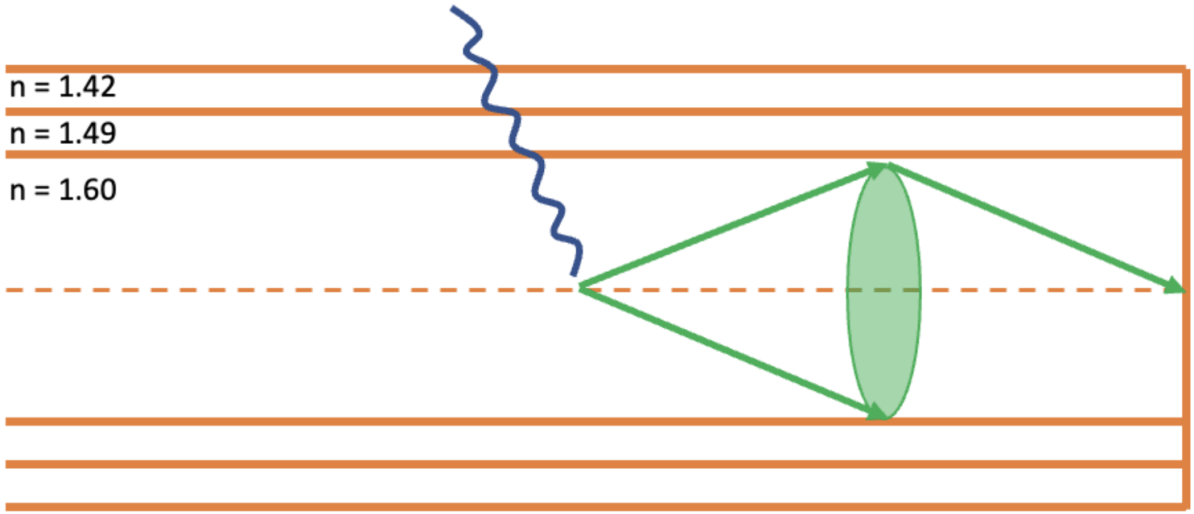


Thank you!

Emission, absorption, re-emission, collection



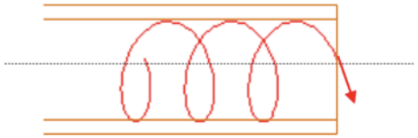
Wavelength-shifting fibres



$$\varepsilon_{trap} = \frac{1}{4\pi}\int_0^{90^o-\theta_c} 2\pi \sin\theta d\theta$$

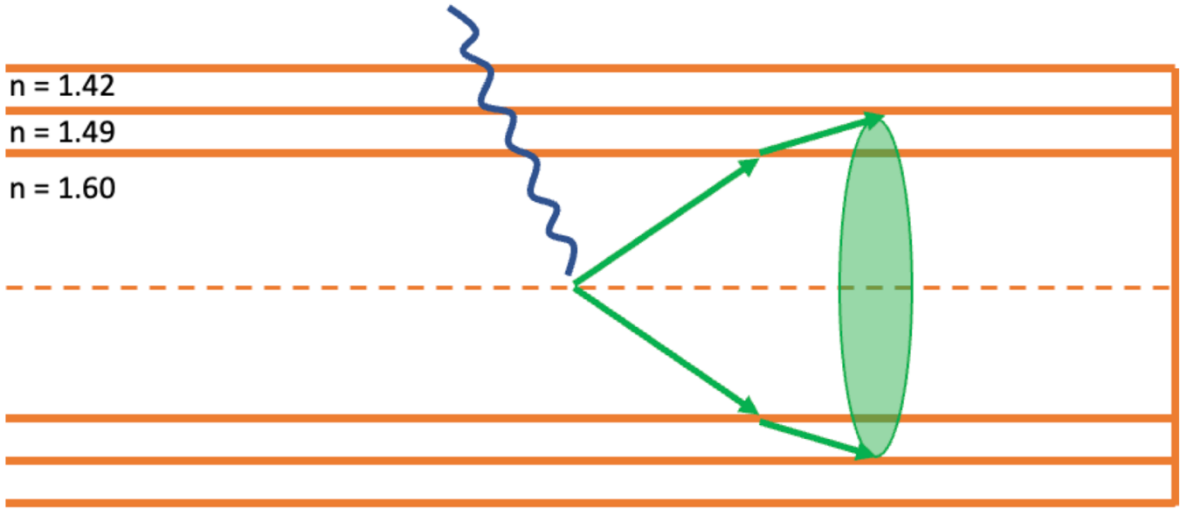
$\gtrsim$ 3.1% (per side)

Helical / skew paths:



From SG specs: $\varepsilon_{trap} \sim 7\%$ for events near core/clad interface

Wavelength-shifting fibres



$$\varepsilon_{trap} = \frac{1}{4\pi}\int_0^{90^o-\theta_c} 2\pi \sin\theta d\theta$$

$\gtrsim$ 5.3% (per side)

(x1.7 more light)

Water-based opaque scintillators

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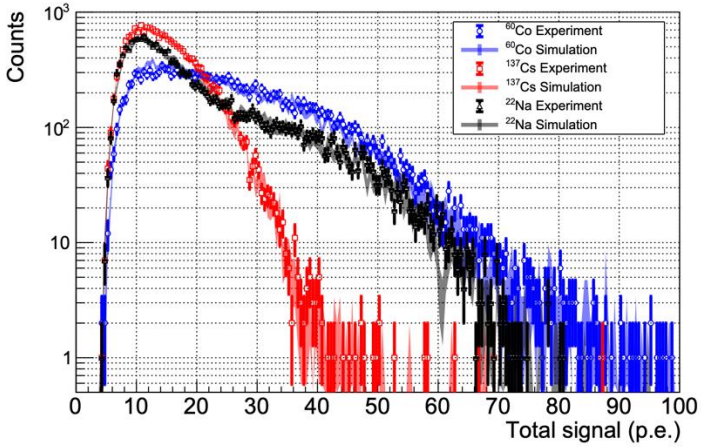
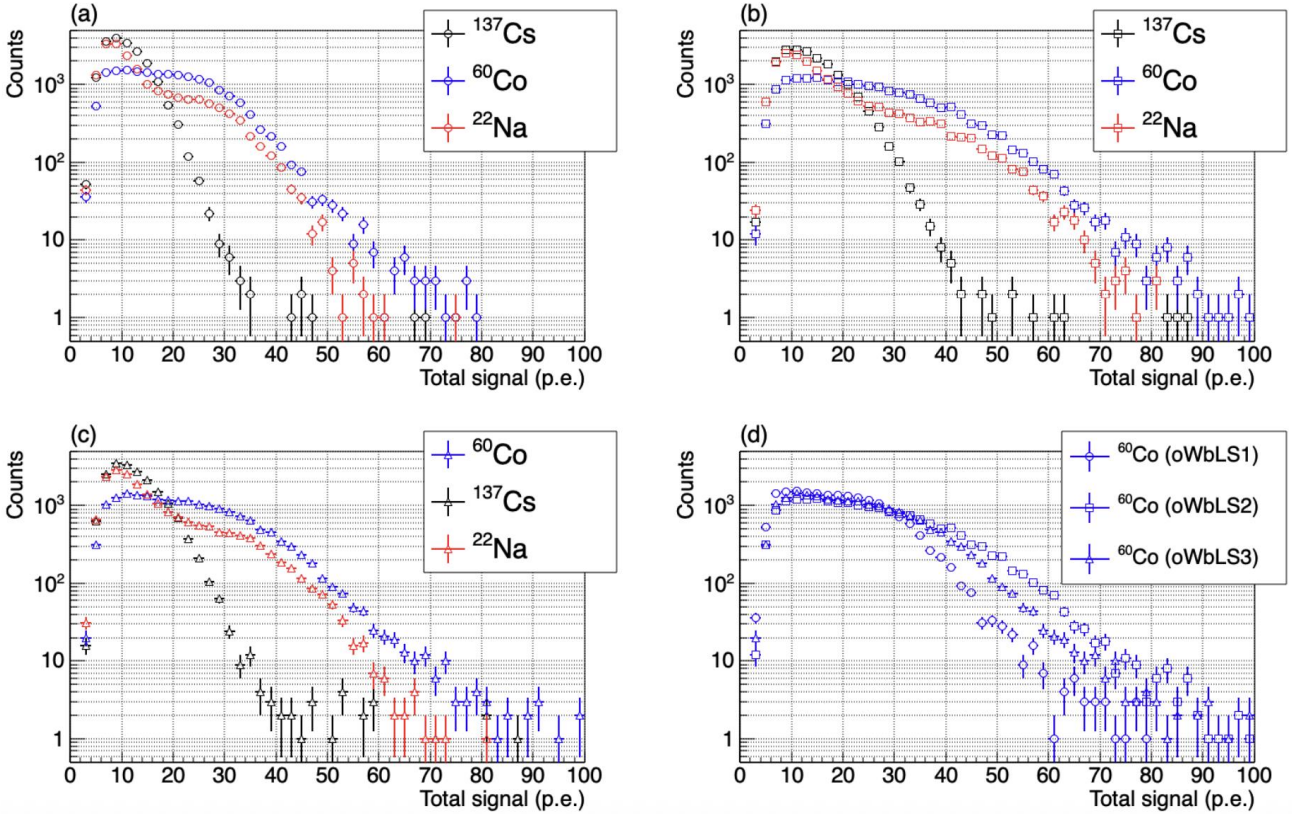
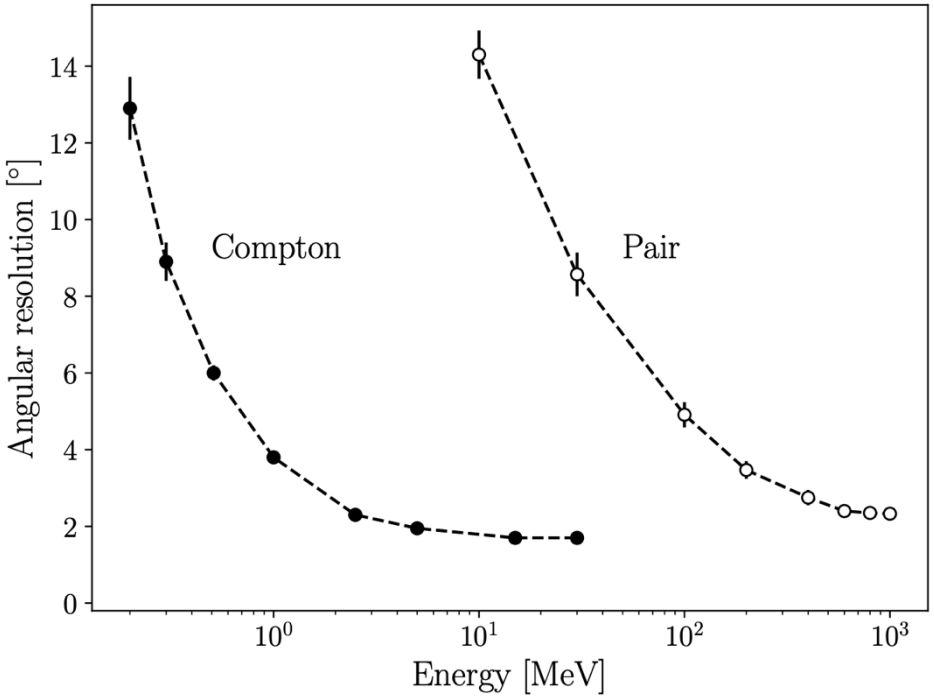
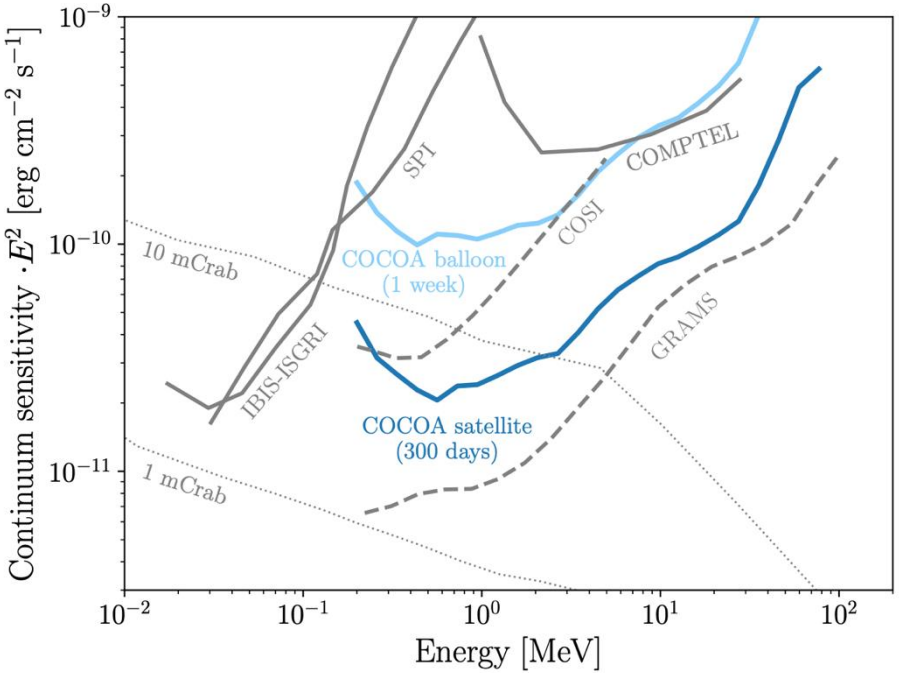
arXiv:2406.13054



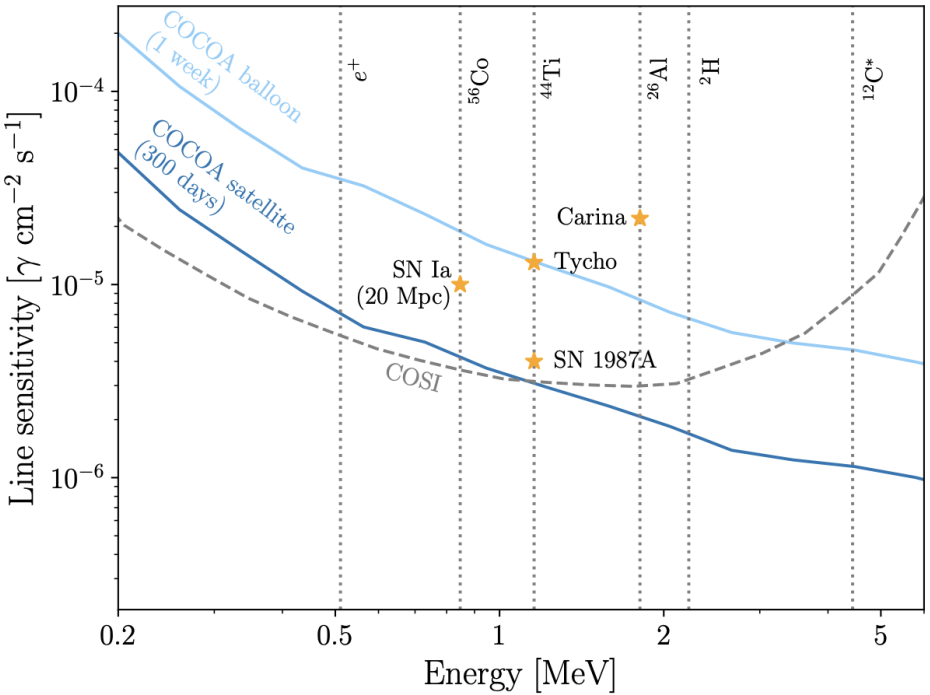


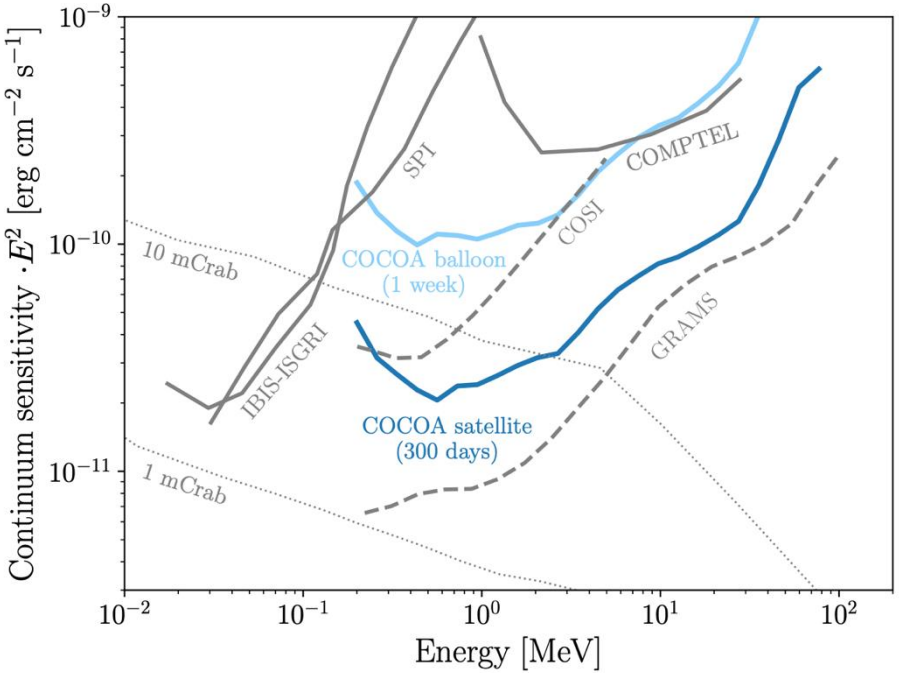
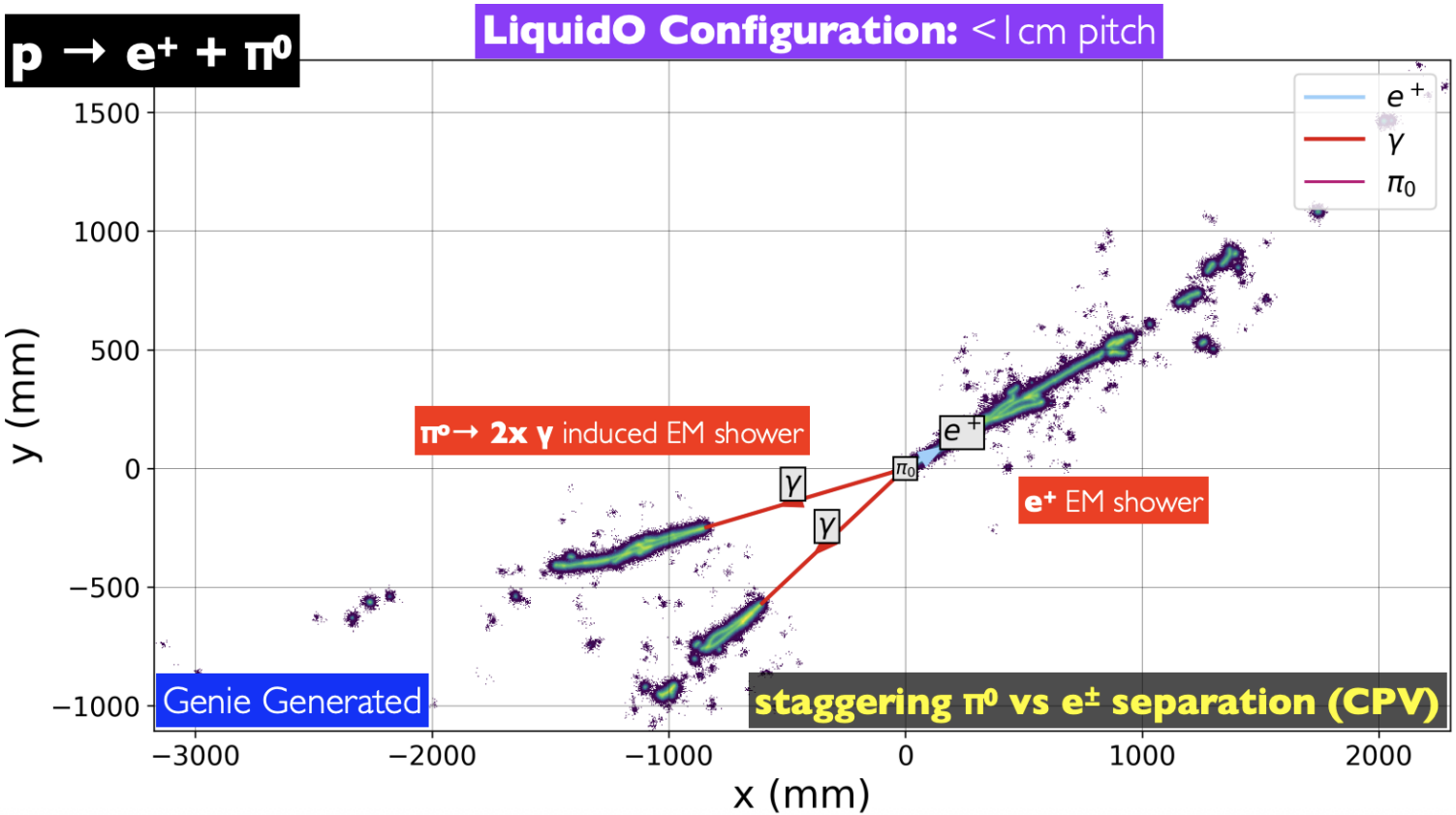
COCOA


Angular resolution [°]
Energy [MeV]
Compton
Pair


Continuum sensitivity · E^2 [erg cm^{-2} s^{-1}]
Energy [MeV]
10 mCrab
1 mCrab
SPI
COMPTEL
COSI
IBIS-ISGRI
GRAMS
COCOA balloon
(1 week)
COCOA satellite
(300 days)

COCOA


COCOA balloon
(1 week)
COCOA satellite
(300 days)
e^+
^{56}Co
^{44}Ti
^{26}Al
^{2}H
^{12}C*
Carina
Tycho
SN Ia
(20 Mpc)
SN 1987A
COSI
Line sensitivity [γ cm^{-2} s^{-1}]
Energy [MeV]


SPI
COMPTEL
COSI
10 mCrab
COCOA balloon
(1 week)
IBIS-ISGRI
GRAMS
COCOA satellite
(300 days)
1 mCrab
Continuum sensitivity $\cdot E^2$ [erg cm^{-2} s^{-1}]
Energy [MeV]

Proton decay