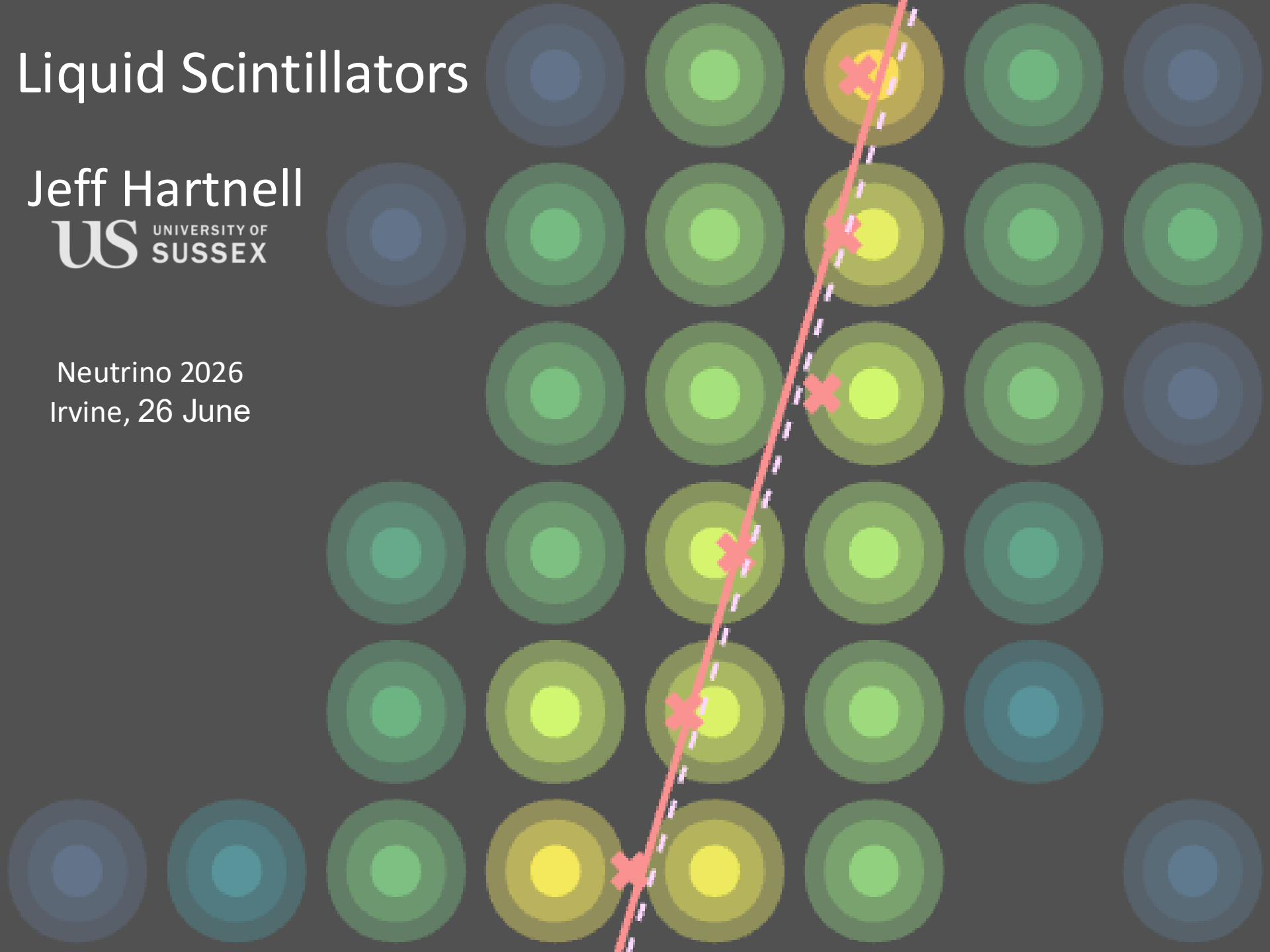


# Liquid Scintillators

Jeff Hartnell  
UNIVERSITY OF SUSSEX

Neutrino 2026  
Irvine, 26 June



# Neutrino Physics with Scintillators

- Discovery of the neutrino
- Solar neutrinos
- Geoneutrinos
- Supernova neutrinos
- Reactor neutrinos
- Atmospheric neutrinos
- Accelerator neutrinos
- $0\nu\beta\beta$  searches



**You've already heard about many  
amazing scintillator detectors**

**Focus here on detector R&D**

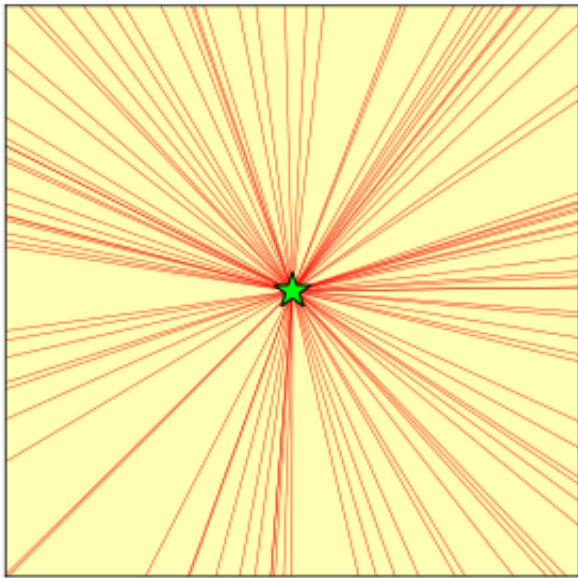
# Introduction

- Hybrid technology
  - Scintillation + Cherenkov light
- LiquidO technology
  - Exploit stochastic light confinement
  - Highly scattering opaque medium + extraction of the light
- $\nu_e$  detection with indium
- CLOUD and SuperChooz

# Approaches to Optical Detectors

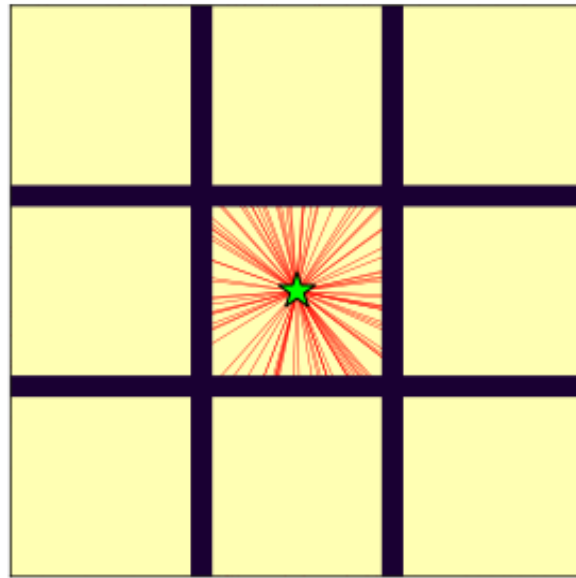
**Transparent**

Single volume



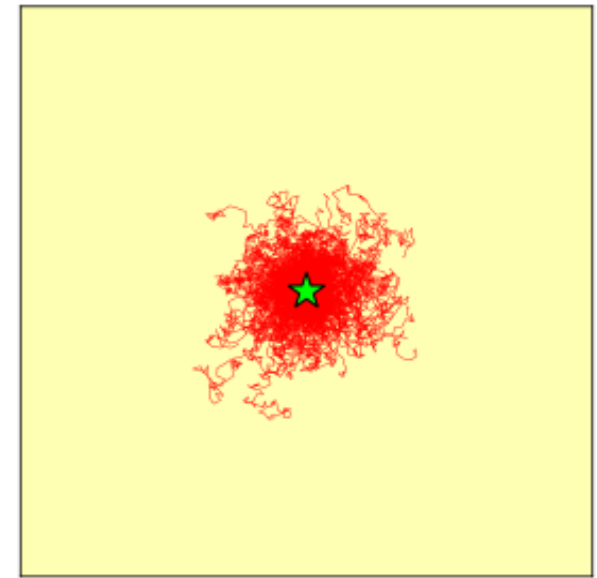
**Transparent**

Segmented



**Opaque**

Single volume  
Self-segmenting

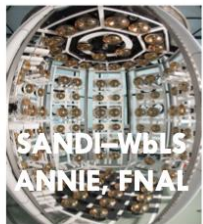
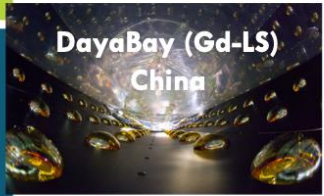


Traditional

**New approach**  
Stochastic light  
confinement

# Enhancing capabilities...

## Metal-doped Liquid Scintillator for neutrino physics and other frontiers since 2000



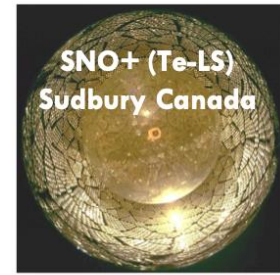
Periodic Table of the Elements © www.elementsdatabase.com

1	H	2	He																																
3	Li	4	Be																																
5	B	6	C	7	N	8	O	9	F	10	Ne																								
11	Na	12	Mg	13	Al	14	Si	15	P	16	S	17	Cl	18	Ar																				
19	K	20	Ca	21	Sc	22	Ti	23	V	24	Cr	25	Mn	26	Fe	27	Co	28	Ni	29	Cu	30	Zn	31	Ga	32	Ge	33	As	34	Se	35	Br	36	Kr
37	Rb	38	Sr	39	Y	40	Zr	41	Nb	42	Mo	43	Tc	44	Ru	45	Rh	46	Pd	47	Ag	48	Cd	49	In	50	Sn	51	Sb	52	Te	53	I	54	Xe
55	Cs	56	Ba	57	La	72	Hf	73	Ta	74	W	75	Re	76	Os	77	Ir	78	Pt	79	Au	80	Hg	81	Tl	82	Pb	83	Bi	84	Po	85	At	86	Rn
87	Fr	88	Ra	89	Ac	104	Unq	105	Unp	106	Unh	107	Uns	108	Uno	109	Une	110	Uun																

- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

- Reactor
- $\beta\beta$
- Solar
- Medical, calibration, LSC, etc

58	Ce	59	Pr	60	Nd	61	Pm	62	Sm	63	Eu	64	Gd	65	Tb	66	Dy	67	Ho	68	Er	69	Tm	70	Yb	71	Lu
90	Th	91	Pa	92	U	93	Np	94	Pu	95	Am	96	Cm	97	Bk	98	Cf	99	Es	100	Fm	101	Md	102	No	103	Lr



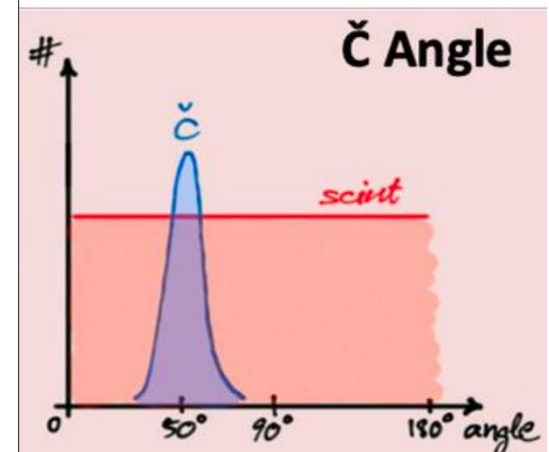
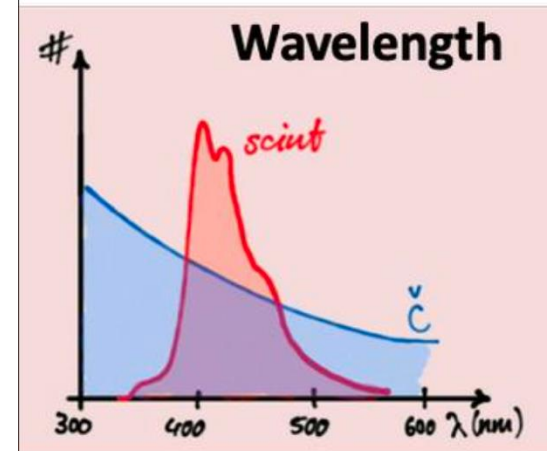
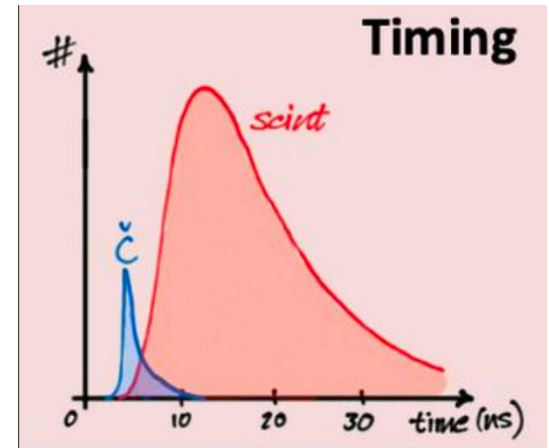
Buck & Yeh, Metal-loaded organic scintillators for neutrino physics, *J. Phys. G: Nucl. Part. Phys.*, 43, 093001 (2016).



Slide from Minfang Yeh's talk at Nu '24

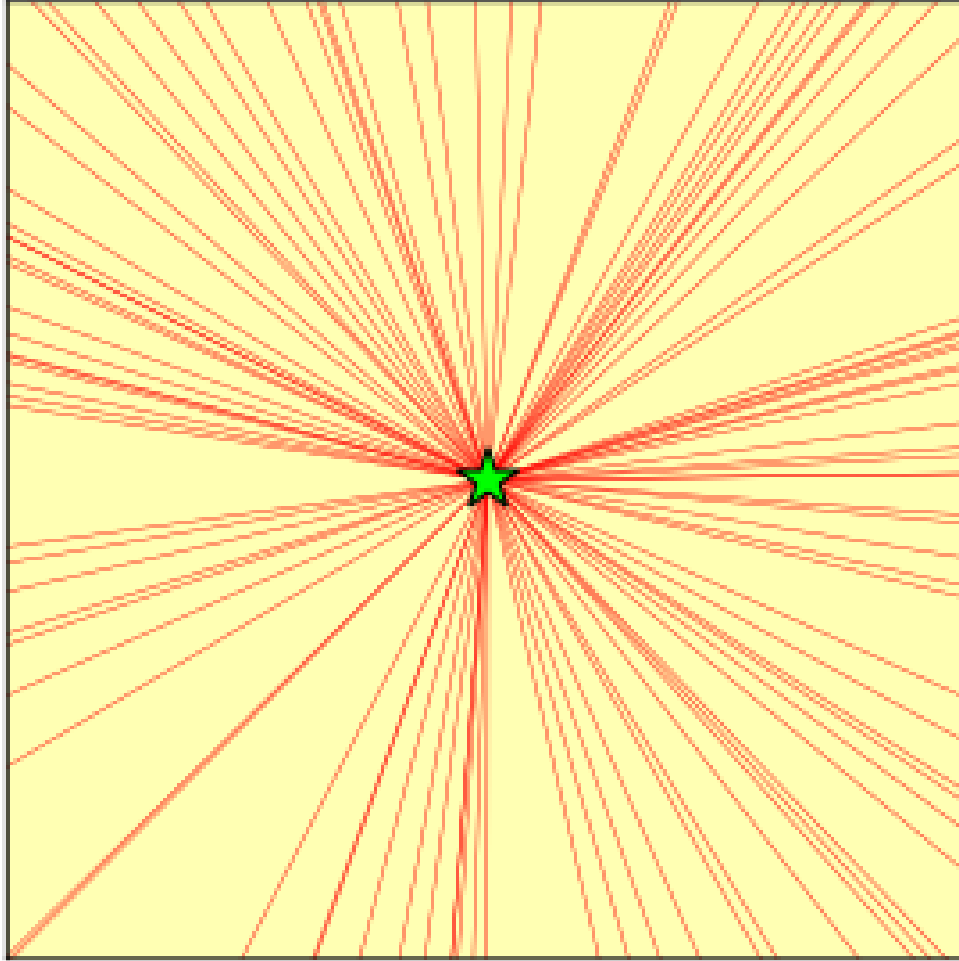
# Hybrid Technology

- Combining
  - high light yield of **scintillation**
  - directionality of **Cherenkov** light
- Demonstrated by Borexino and SNO+
- R&D challenge to better separate the signals
  - Faster detectors
  - Scintillators with optimised timing
  - Wavelength sensitive detectors
- Testbeds and demonstrators
  - ANNIE
  - BNL 1- and 30- tonne detectors
  - NuDot
  - BUTTON
  - Eos
  - Tsinghua/Jinping groups
- THEIA: 25+ kton detector
  - see Josh Klein's talk later today



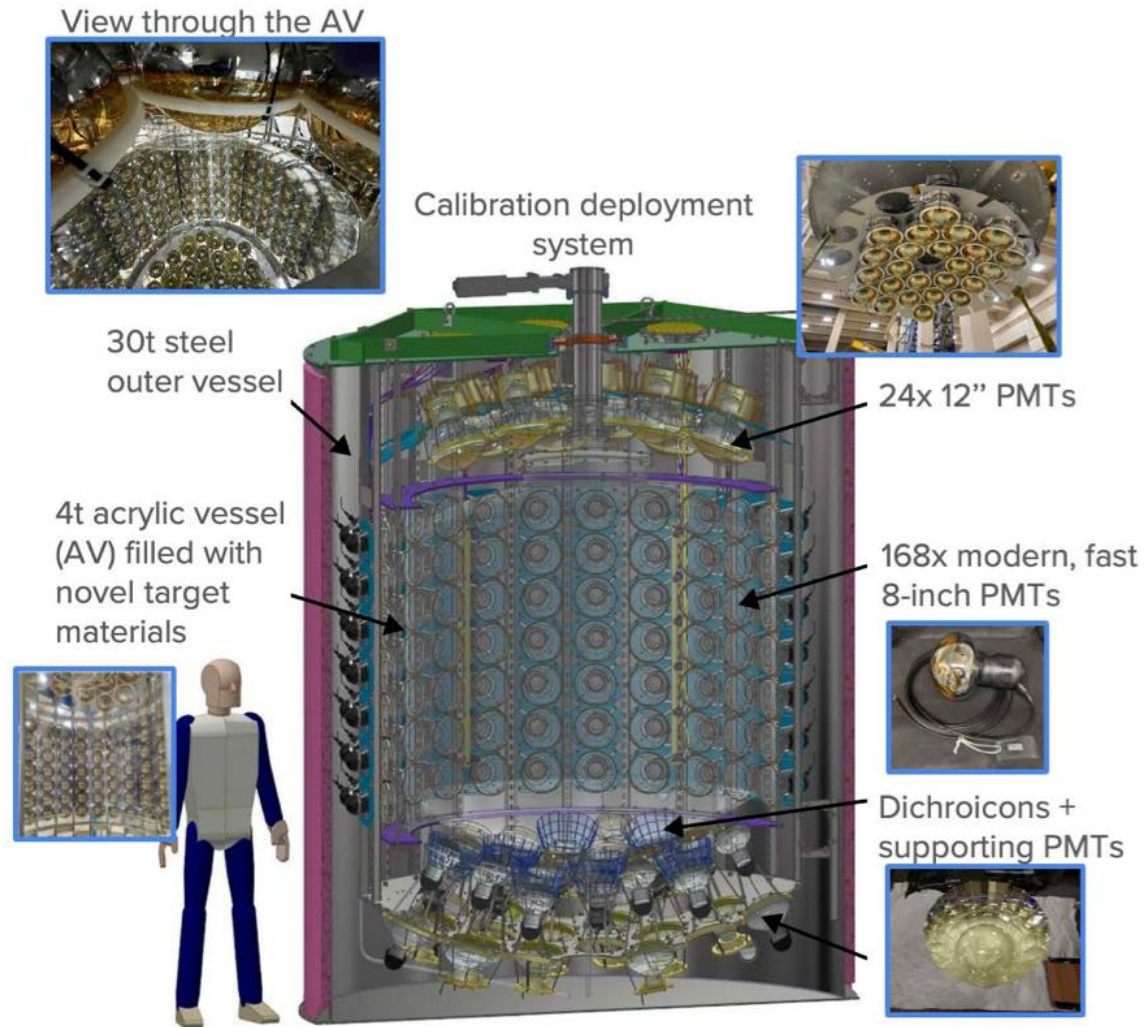
# Transparent

Single volume



# Eos

- Assess performance of key technology
  - novel LS
  - fast ( $\sim 100\text{ps}$ ) PMTs
  - spectral sorting
- Cherenkov + scintillation event reconstruction
- Developing shared framework (RATPAC2 & Chroma) for optical neutrino detection community
- Planning for deployment at SNS
  - Measure  $\nu_e + {}^{16}\text{O}$  cross section, important for supernova neutrinos

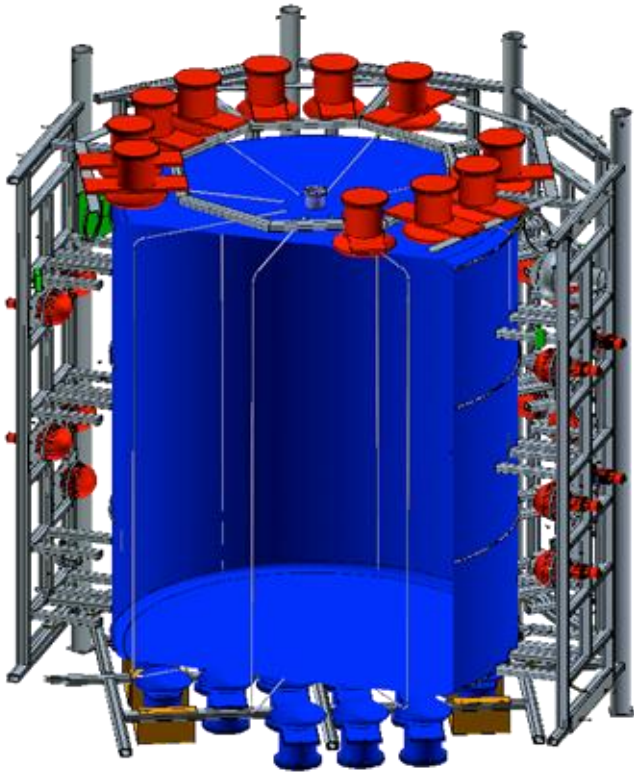


[\*\(JINST 18 P02009, 2023\)\*](#)



# Super-SANDI in ANNIE

- 7 tons Gd-loaded WbLS in nylon vessel
  - Contain particles
  - Reconstruct full event topologies, including proton recoils
  - Deployment in July, neutrinos in Sept.

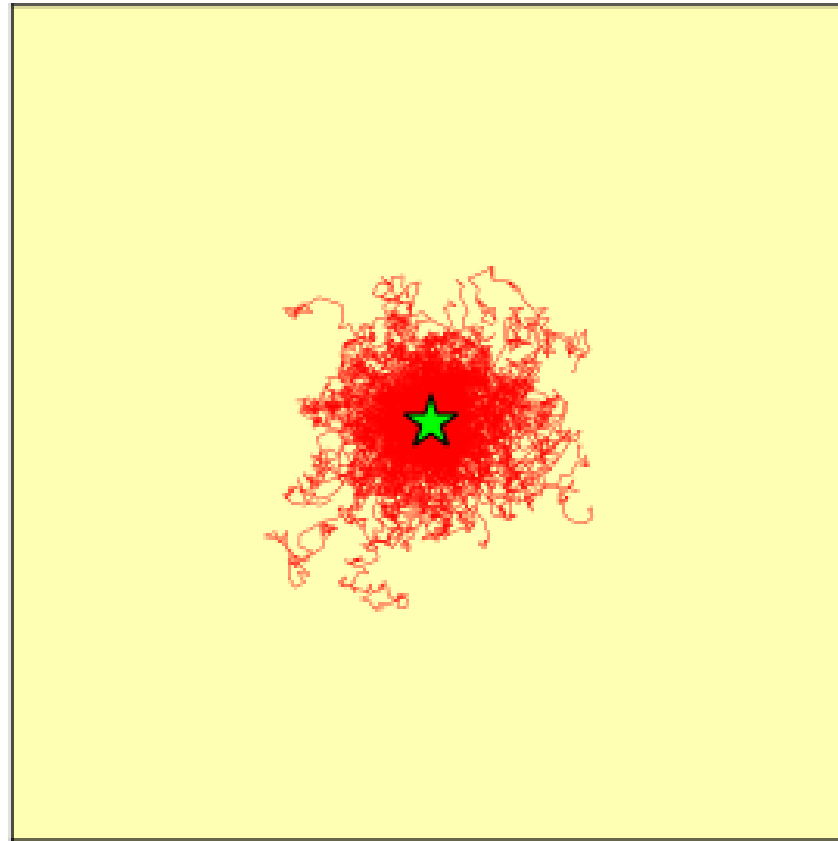


Nylon vessel undergoing pressure test in Mainz

# Exploiting Stochastic Light Confinement

## Opaque

Single volume  
Self-segmenting



# The LiquidO Collaboration



90 scientists

26 academic  
institutions

11 countries

[LiquidO-Contact-L@in2p3.fr](mailto:LiquidO-Contact-L@in2p3.fr)

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

# Opacity

Two ways to make something opaque



Short scattering length



Short absorption length



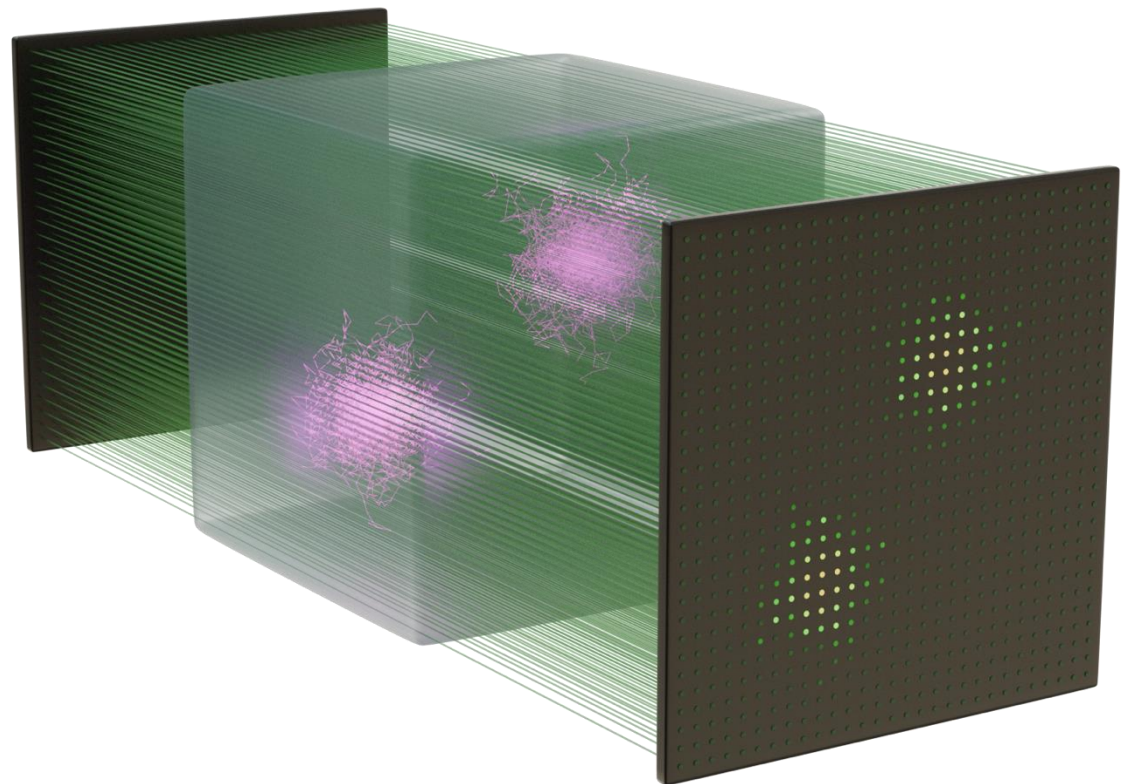


## Exploiting Stochastic Light Confinement

Highly scattering opaque detector medium

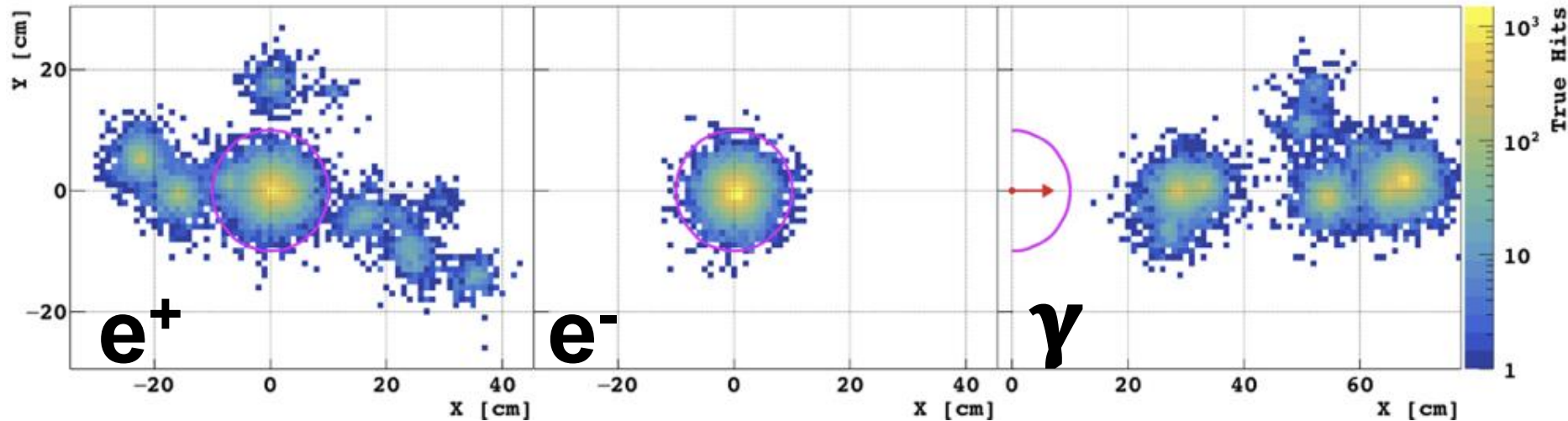
+

Extraction of the light



- Stochastically confine the light with scattering and extract it
- Enables precision topological imaging (self-segmentation)

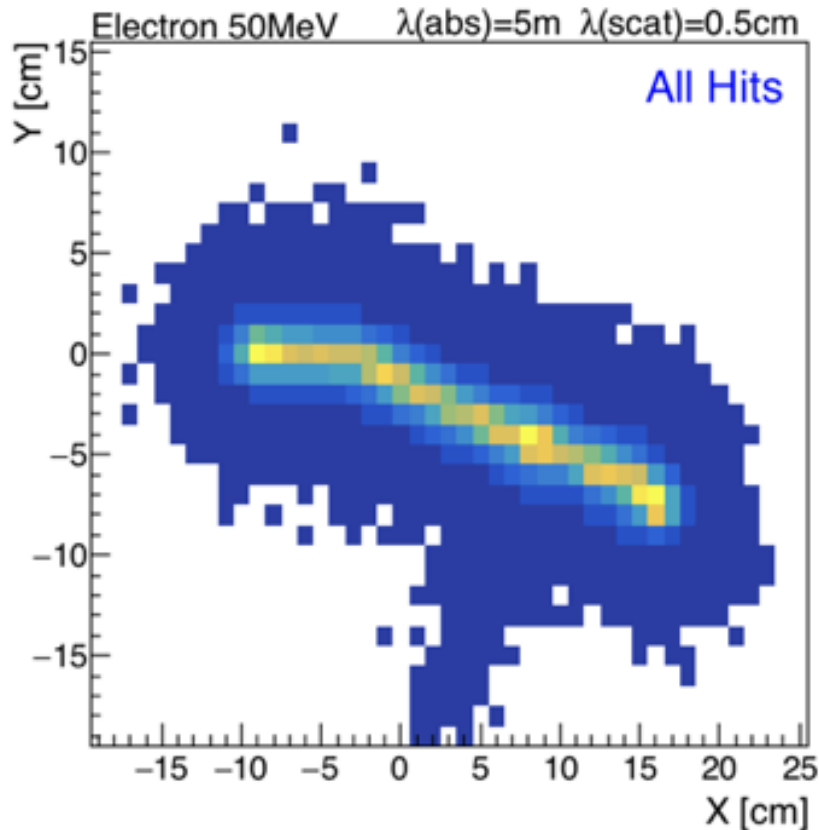
# High-resolution imaging for particle identification



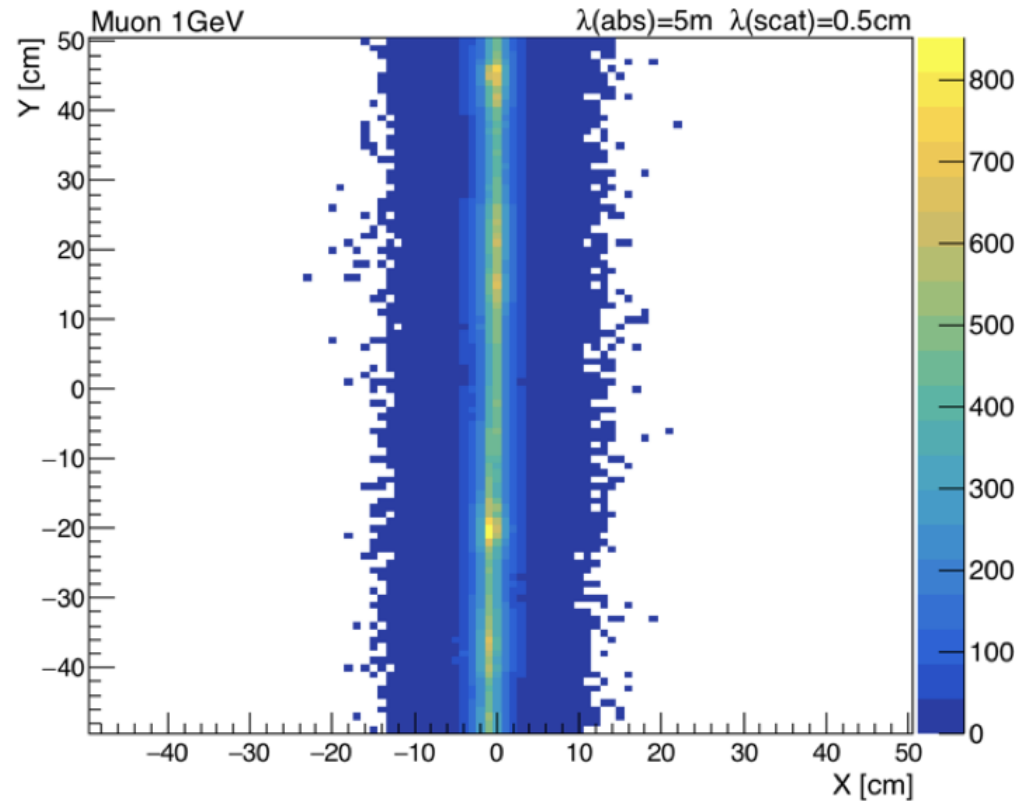
## Low energy: 2 MeV

Distinguish positrons from point-like energy depositions (e.g. electrons, protons, alphas) and from gammas

# High-resolution imaging for particle identification

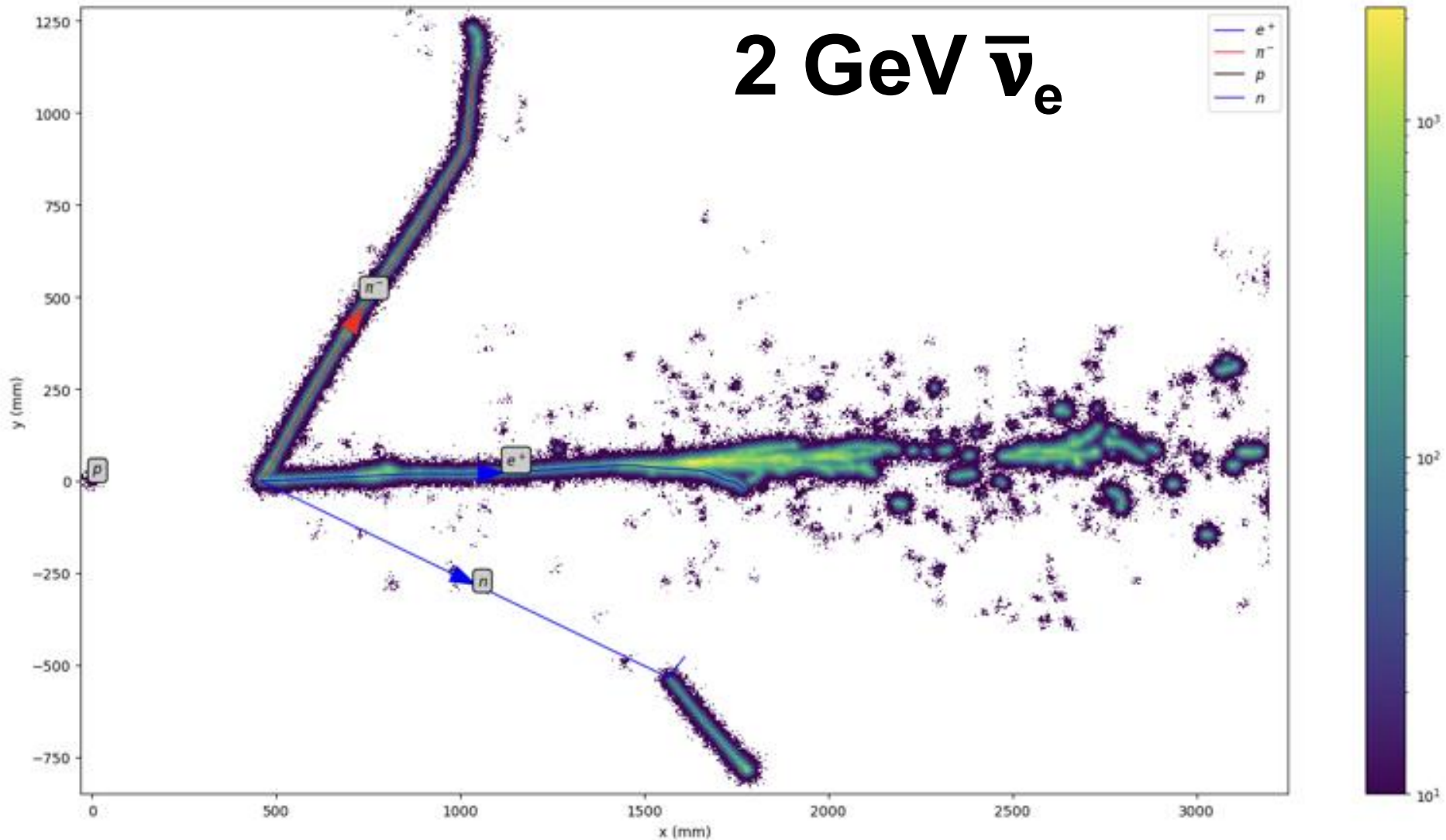


**50 MeV  $e^-$**



**1 GeV  $\mu$**   
(through-going)

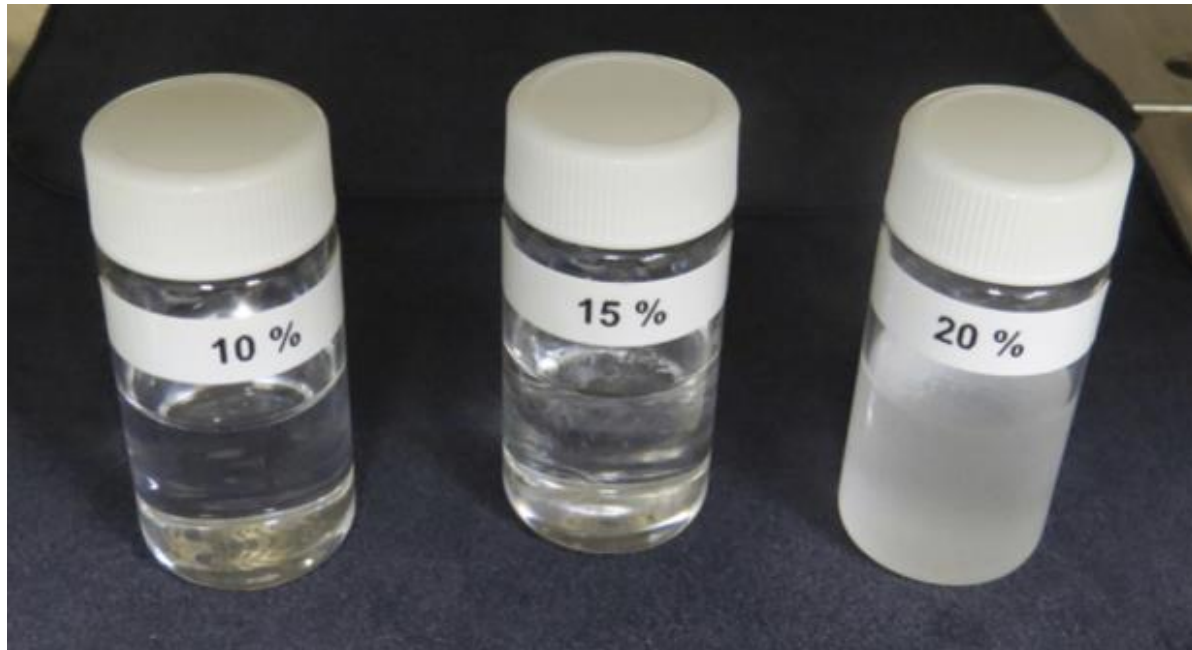
# High-resolution imaging for particle identification



Now the technology...

# (Deliberately) Opaque Scintillator

<https://iopscience.iop.org/article/10.1088/1748-0221/14/11/P11007>



Linear Alkyl Benzene + PPO

“NoWaSH” = +  
Paraffin

Opacity depends on paraffin concentration,  
which changes crystallisation temperature

# Opaque Scintillators R&D

- Multiple approaches
  - Wax additives
    - many different waxes!
  - Emulsions
    - mixtures of water and scintillator
  - Powder additives
  - Other ideas
- Lots of creative work
- Huge openings for further R&D



Waxes, Mainz

<https://iopscience.iop.org/article/10.1088/1748-0221/14/11/P11007>



Water-based scintillator, IST



Opaque water-based liquid scintillator (oWbLS), BNL

[doi.org/10.1016/j.nima.2024.170075](https://doi.org/10.1016/j.nima.2024.170075)

# LiquidO Prototype (France)

10 litres

❖ Water

❖ Transparent

Scintillator

❖ Opaque

Scintillator

Temperature

control

5 → 40 °C



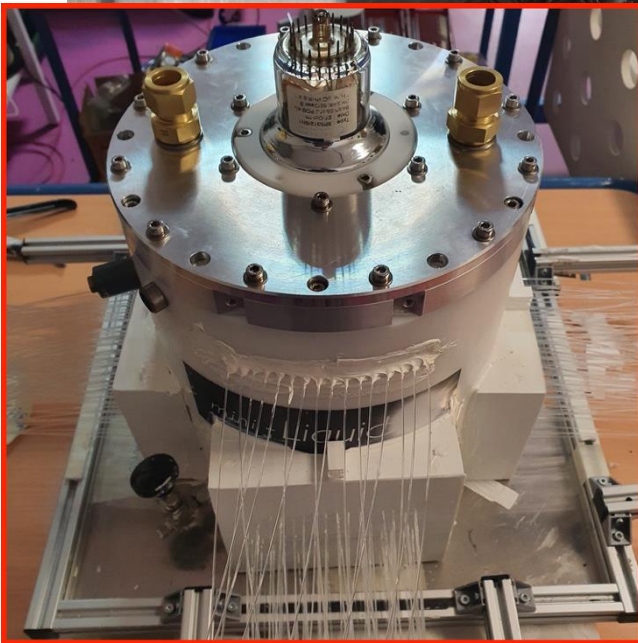
Single electrons

0.4 → 1.8 MeV

Mono-energetic

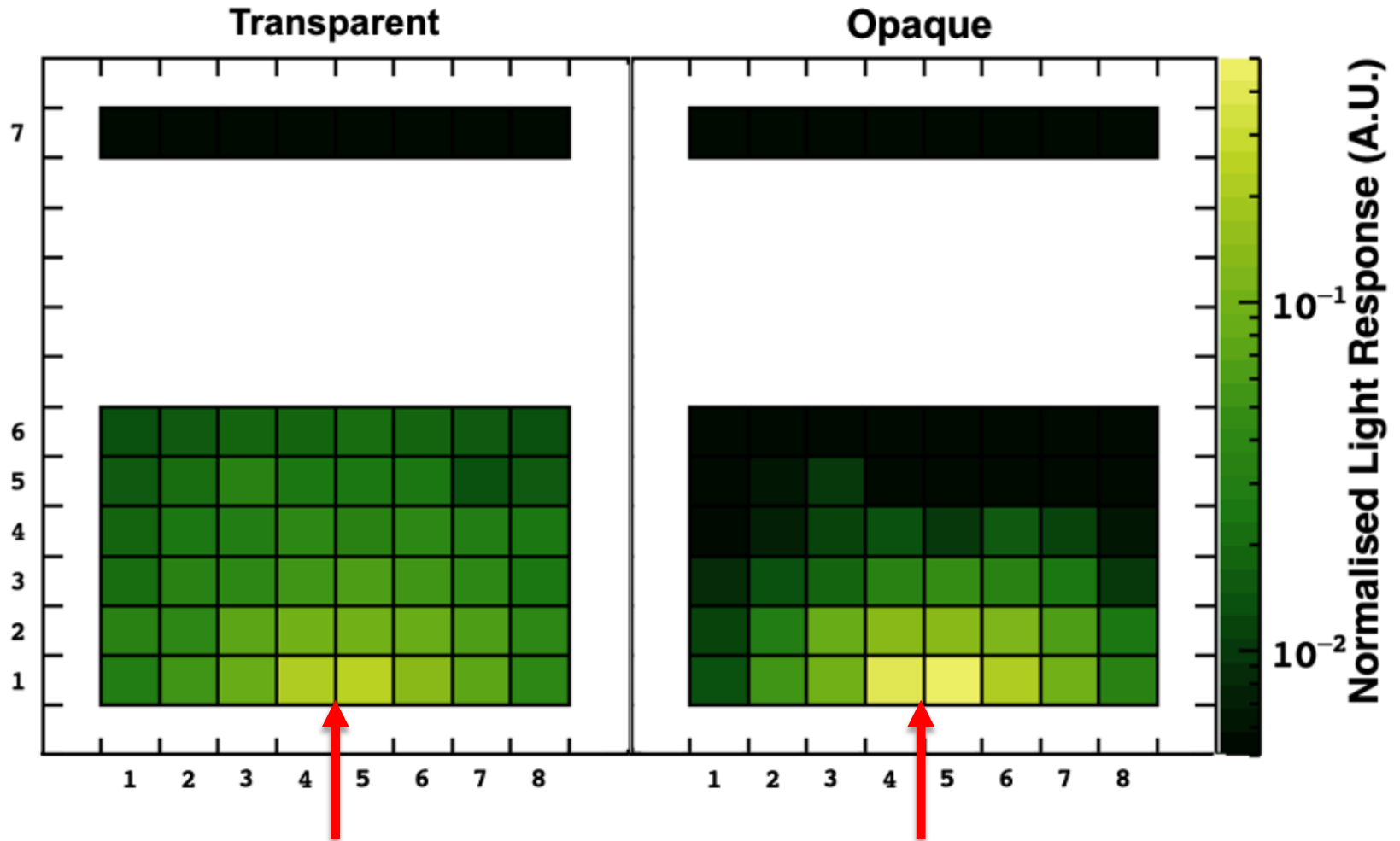
64

channels



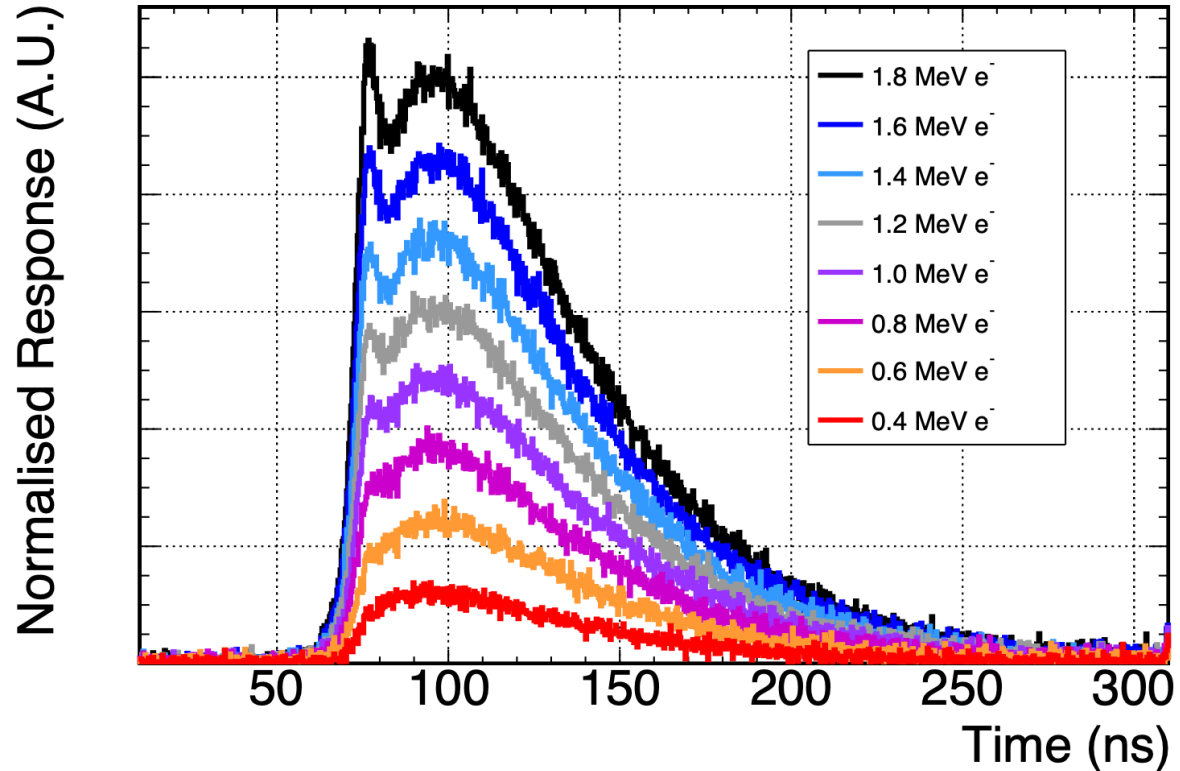
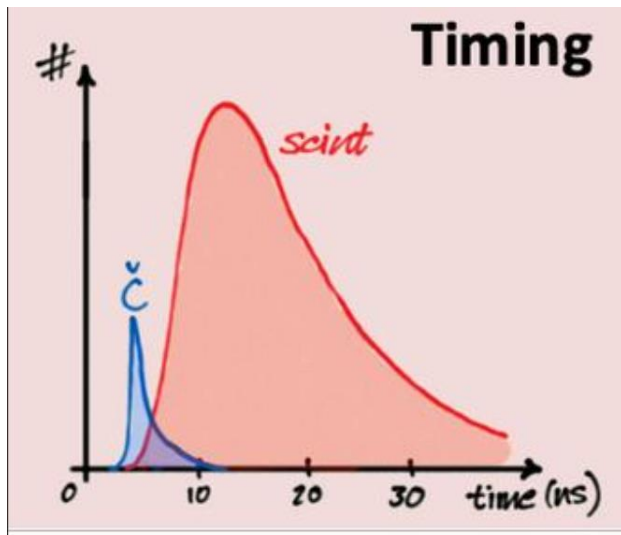
# Stochastic Light Confinement

([arXiv:2503.02541](https://arxiv.org/abs/2503.02541))



Single electrons 0.4  $\rightarrow$  1.8 MeV, mono-energetic

# Hybrid Detection in LiquidO



([arXiv:2503.02541](https://arxiv.org/abs/2503.02541))

# Prototyping

SuperFGD-style “3D” Detector at BNL

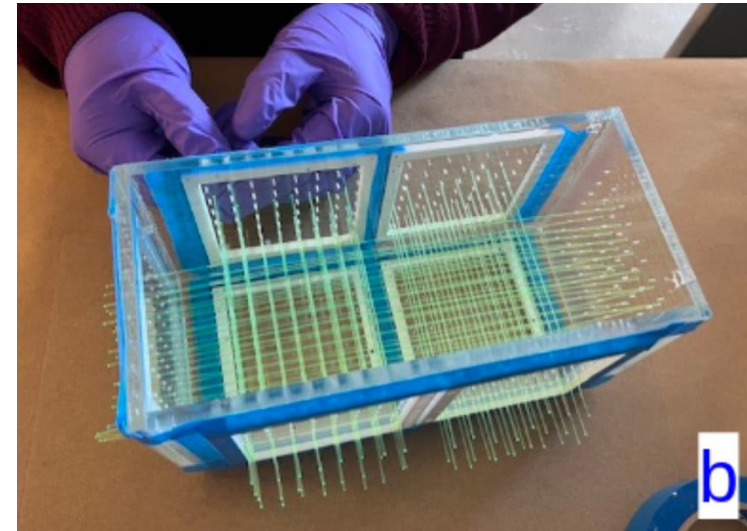
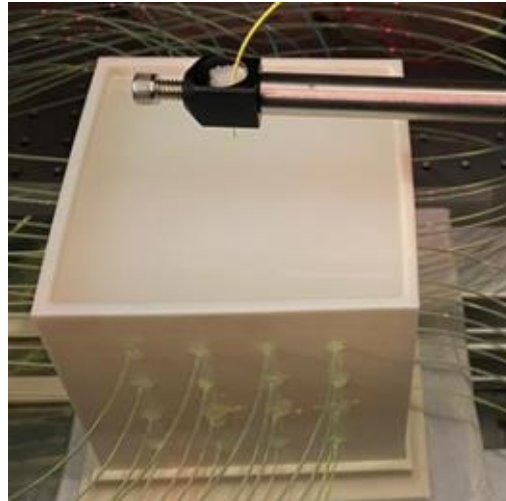
([arXiv:2605.10683](https://arxiv.org/abs/2605.10683))

([Poster by Haohui Che](#))

- Results with gammas, neutrons, muons and protons
- Using opaque emulsion scintillator (oWbLS)

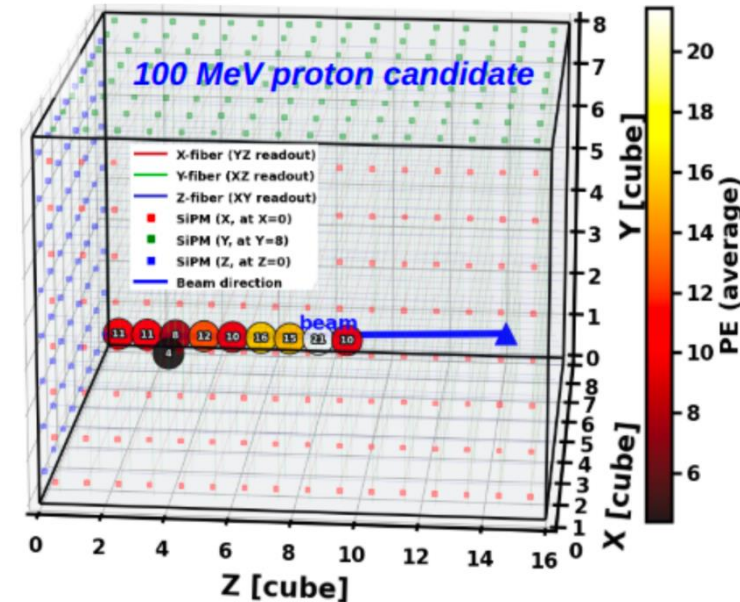
LIME at U. of Michigan

[doi.org/10.1016/j.nima.2024.170075](https://doi.org/10.1016/j.nima.2024.170075)

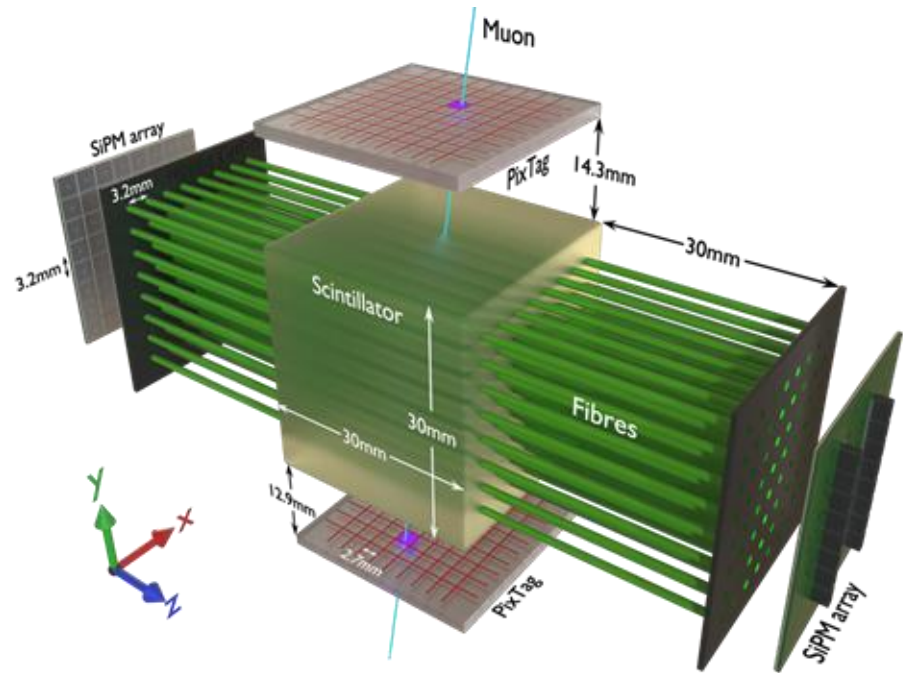


BPULSE at Penn State

([Poster by Garret Wendel](#))

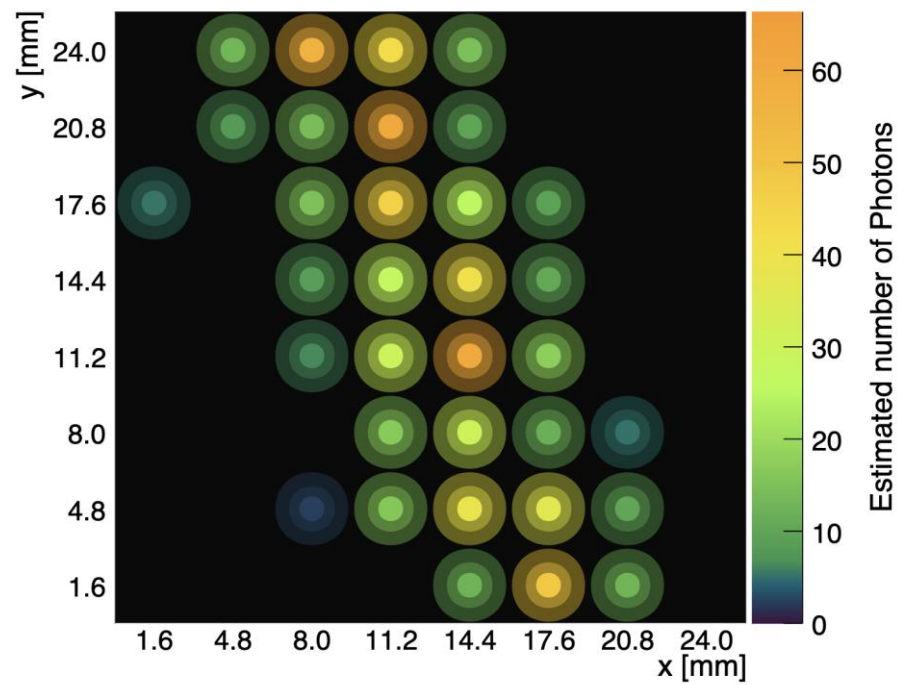
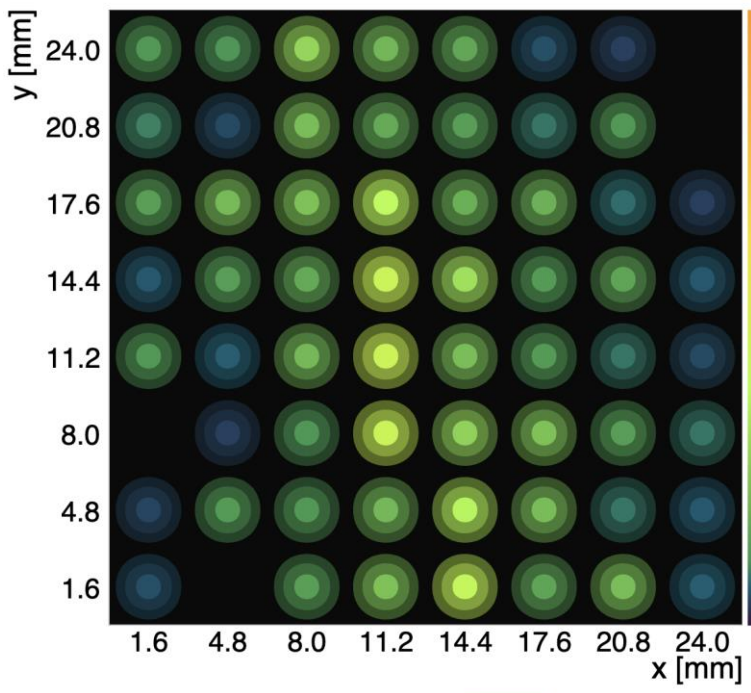
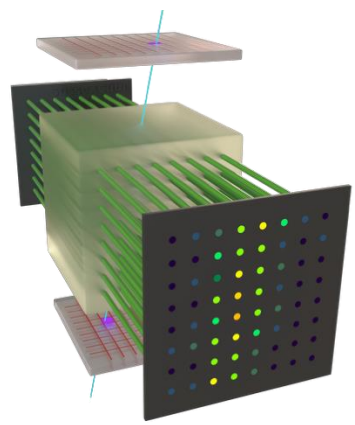
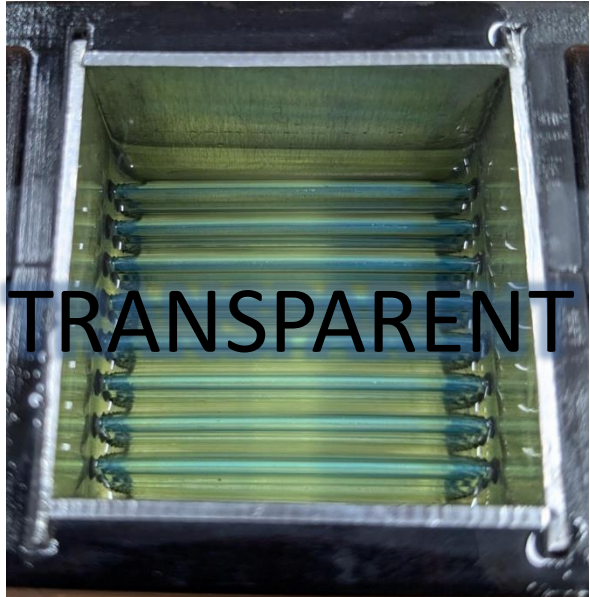


# LiquidO “Cube” Detector



- 3 x 3 x 3 cm<sup>3</sup> scintillator volume
- Waxy opaque scintillator
- ~0.5 mm scattering length

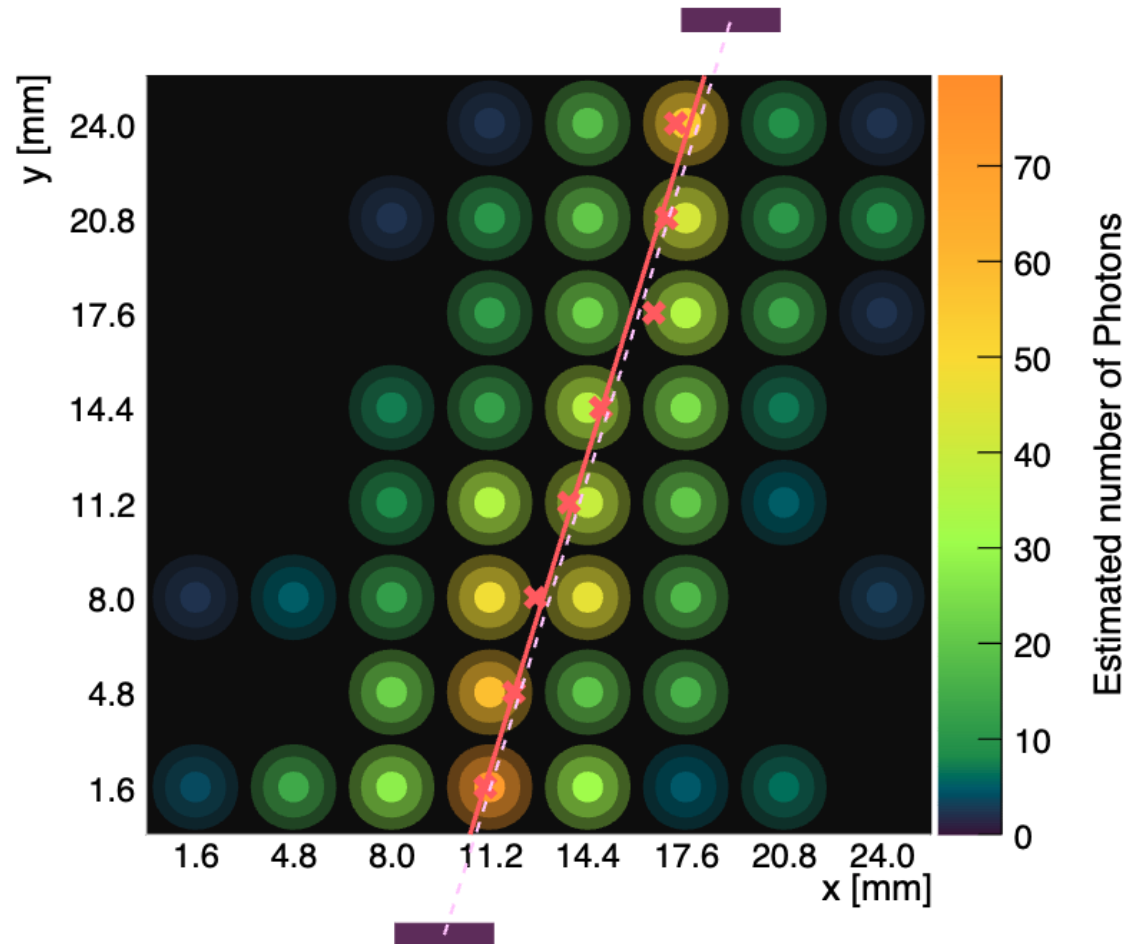
- 64 fibres, 3.2 mm pitch
- SiPM arrays
- PETsys TOFPET2 ASICs



# LiquidO “Cube” Muon Results

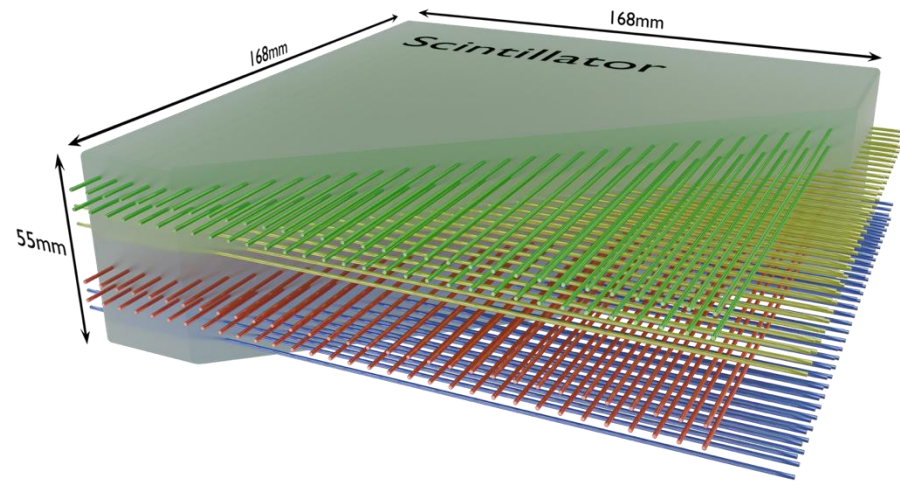
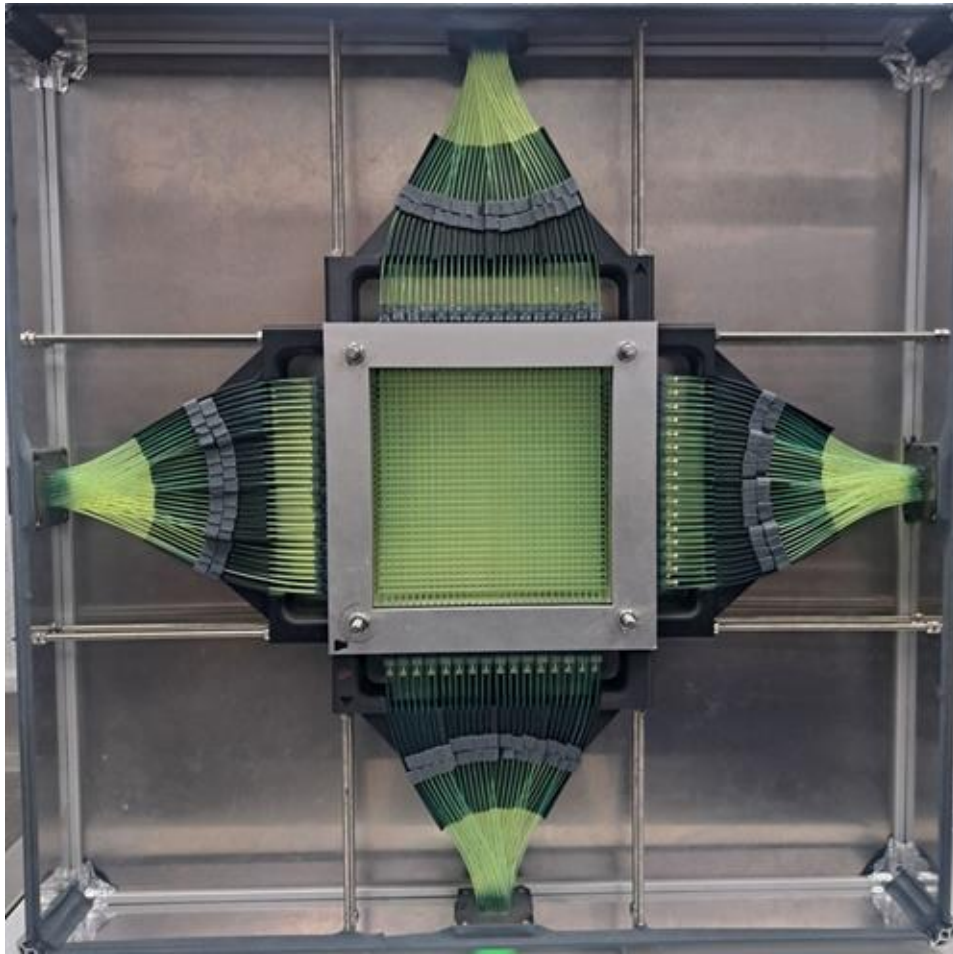
([J. Apilluelo et al., Journal of Instrumentation, Volume 21, January 2026](#))

- High light yield
  - $\sim 170$  PE/MeV
- Position resolution of 0.45 mm per row
  - Twice as precise as a simple segmented detector of the same fibre pitch ( $P/\sqrt{12}$ )
  - Simulations show we can improve to 5-10x better than segmented detector



Can we do something particle  
physics-y with our LiquidO  
detectors?

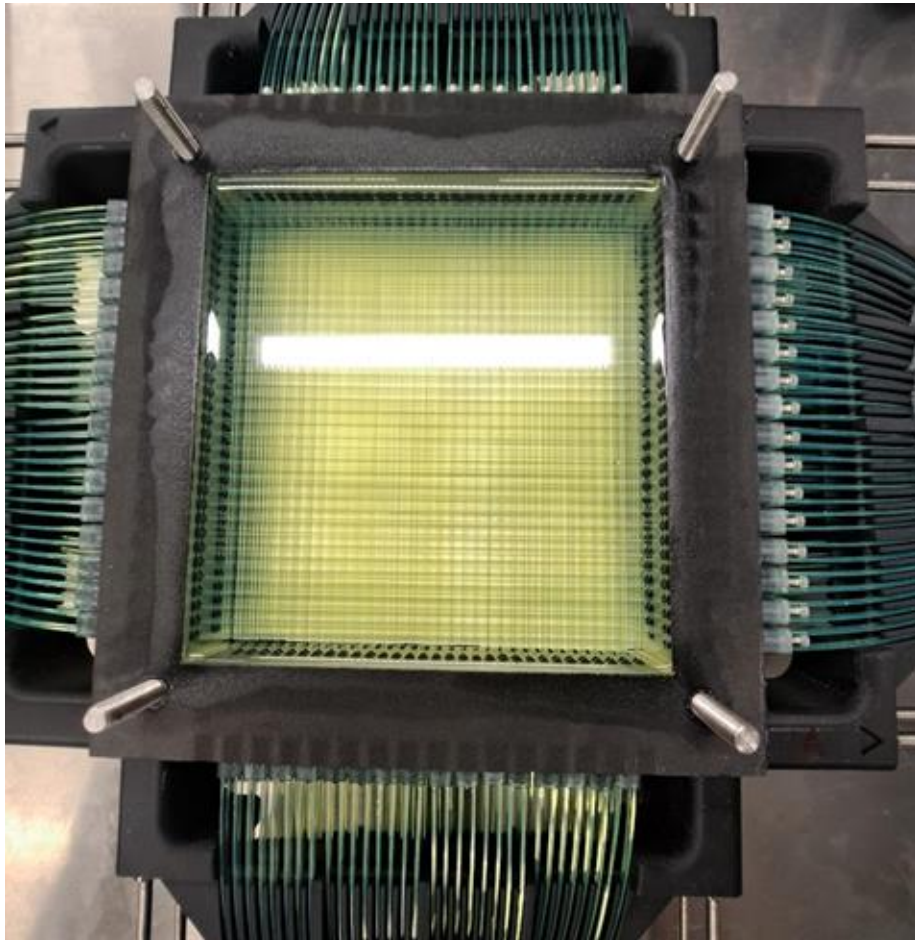
# LiquidO “Tile” Detector



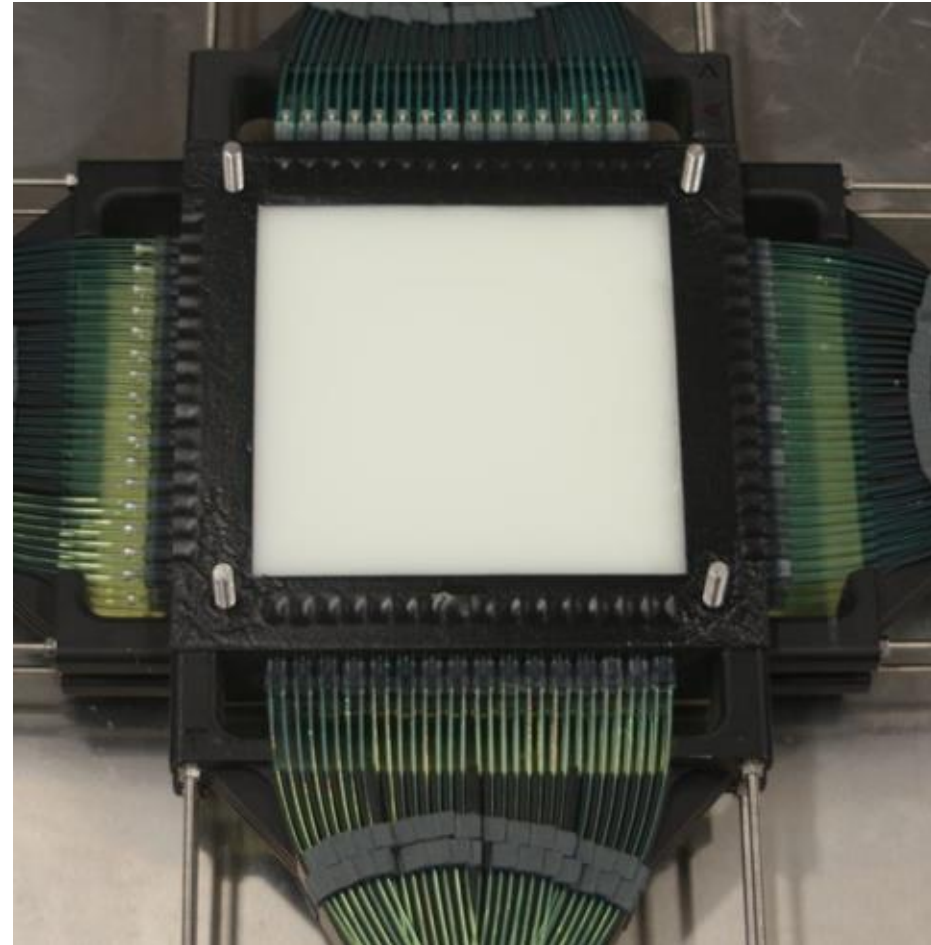
16 x 16 x 5 cm<sup>3</sup> scintillator volume

Fibres, scintillator and readout same as “Cube”

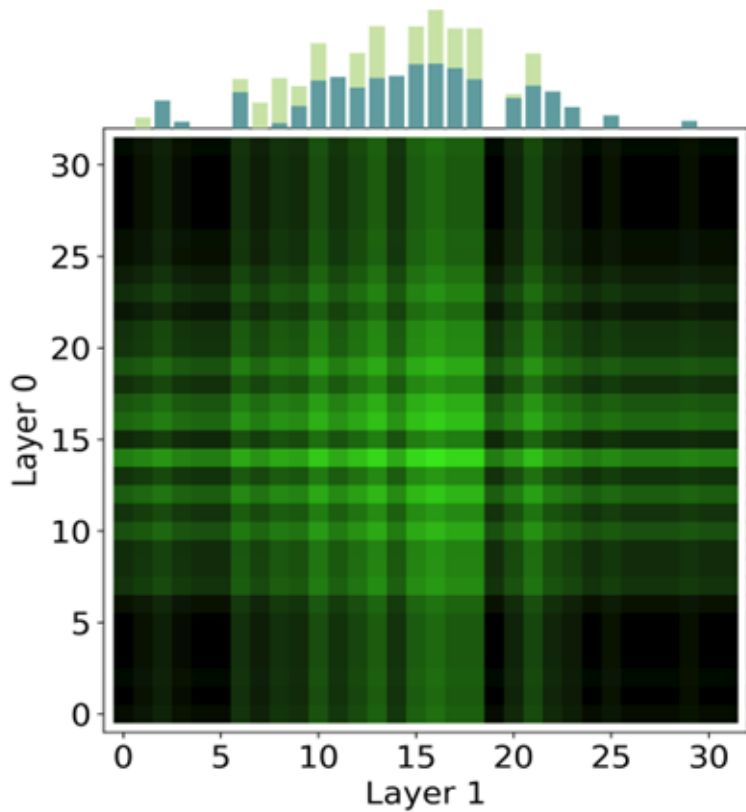
# TRANSPARENT



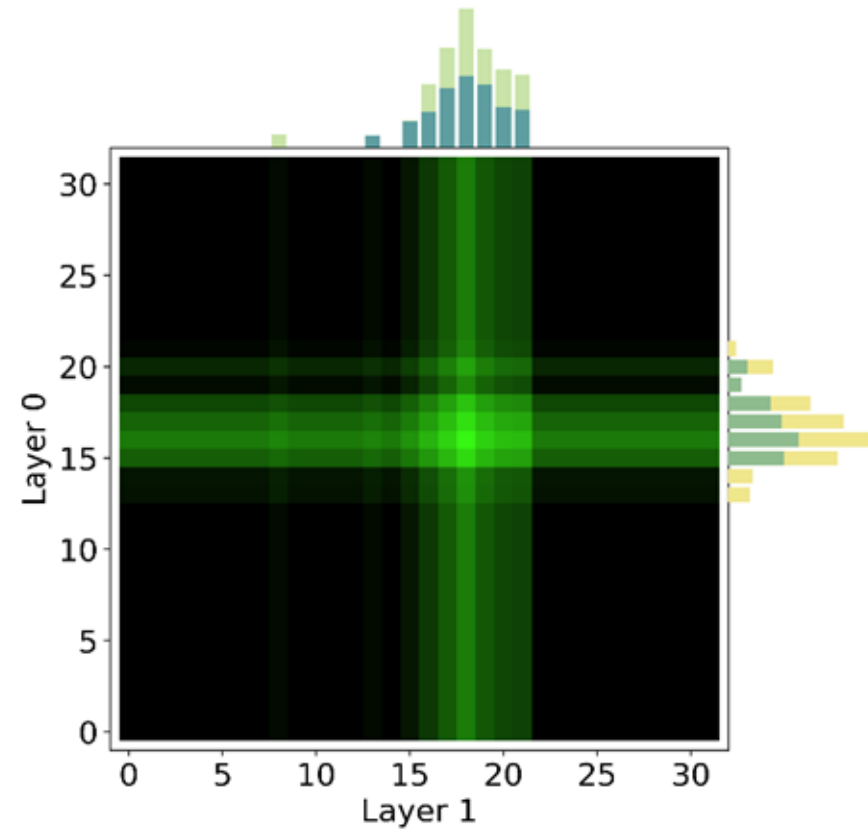
# OPAQUE



# TRANSPARENT



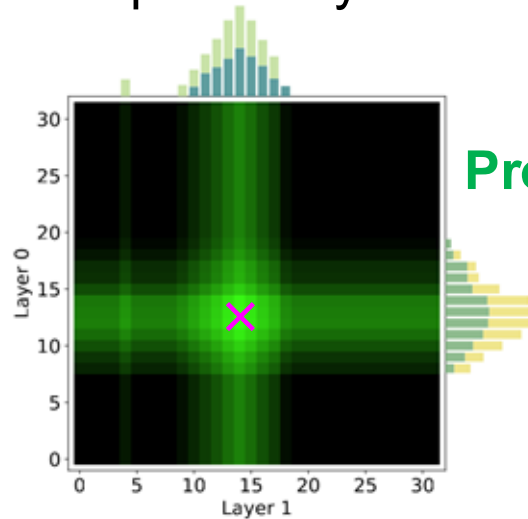
# OPAQUE



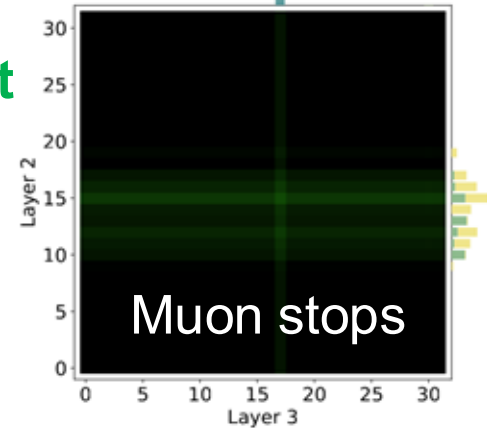
Detect 16,000 cosmic ray muons an hour

# Michel Electrons

Top X+Y layers



Bottom X+Y layers



- Select ~2000 candidates

- energetic delayed coincidence events

- 0.4 to 4.4  $\mu\text{s}$

- 99.5% pure sample

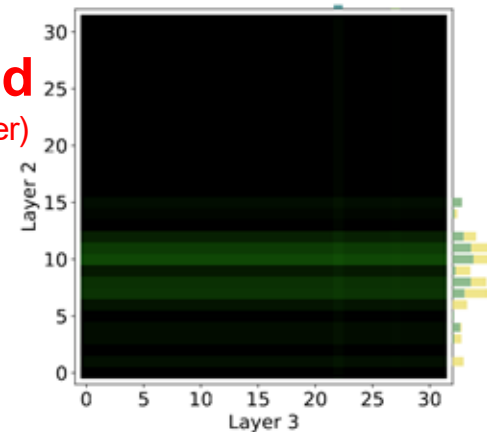
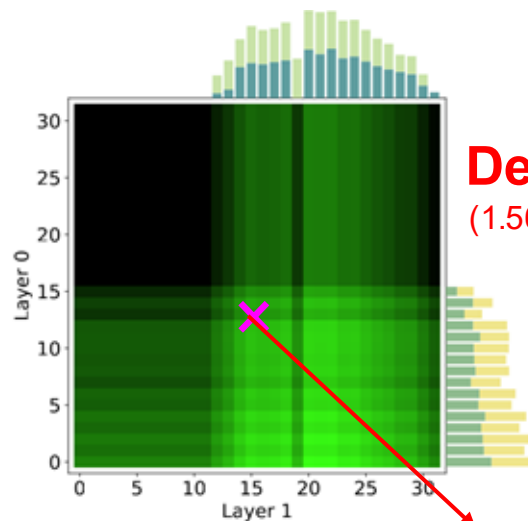
- Lifetime fit gives

- $\tau = (2.16 \pm 0.04) \mu\text{s}$

- Muons downward going

- Michel Electrons isotropic

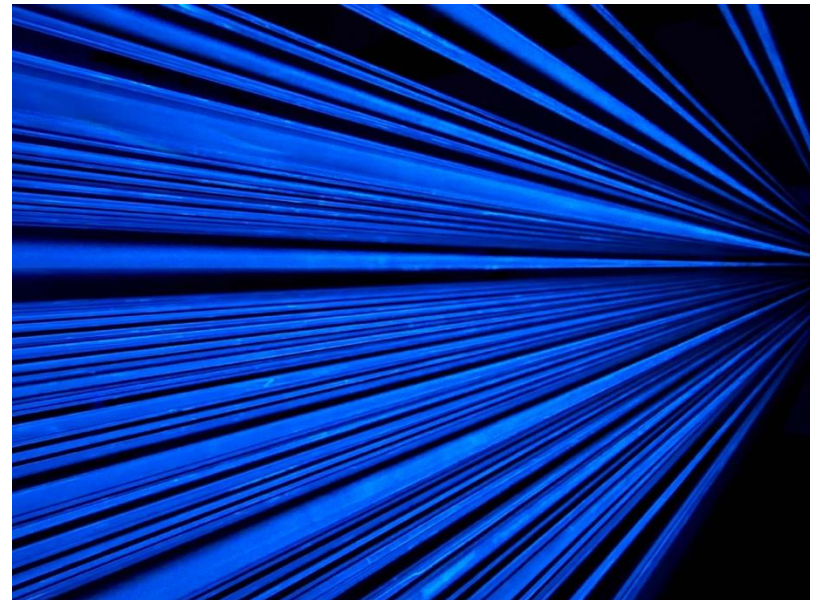
- See some long sideways tracks



Will LiquidO work at scale for  
neutrino physics?

# 2 metre prototype

- Demonstrate LiquidO at scale
- 150 Kuraray B3 (blue) fibres just installed this month
- Initial water-run
  - Muon Cerenkov light observed
- Test bed for opaque scintillators



Next step...

European  
Innovation  
Council



UK Research  
and Innovation

C L O U D

#### International collaboration

- 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)
  - Rutherford Appleton Laboratory (UK)
- ⇒ 21 institutions in 11 countries

#### Spokespersons:

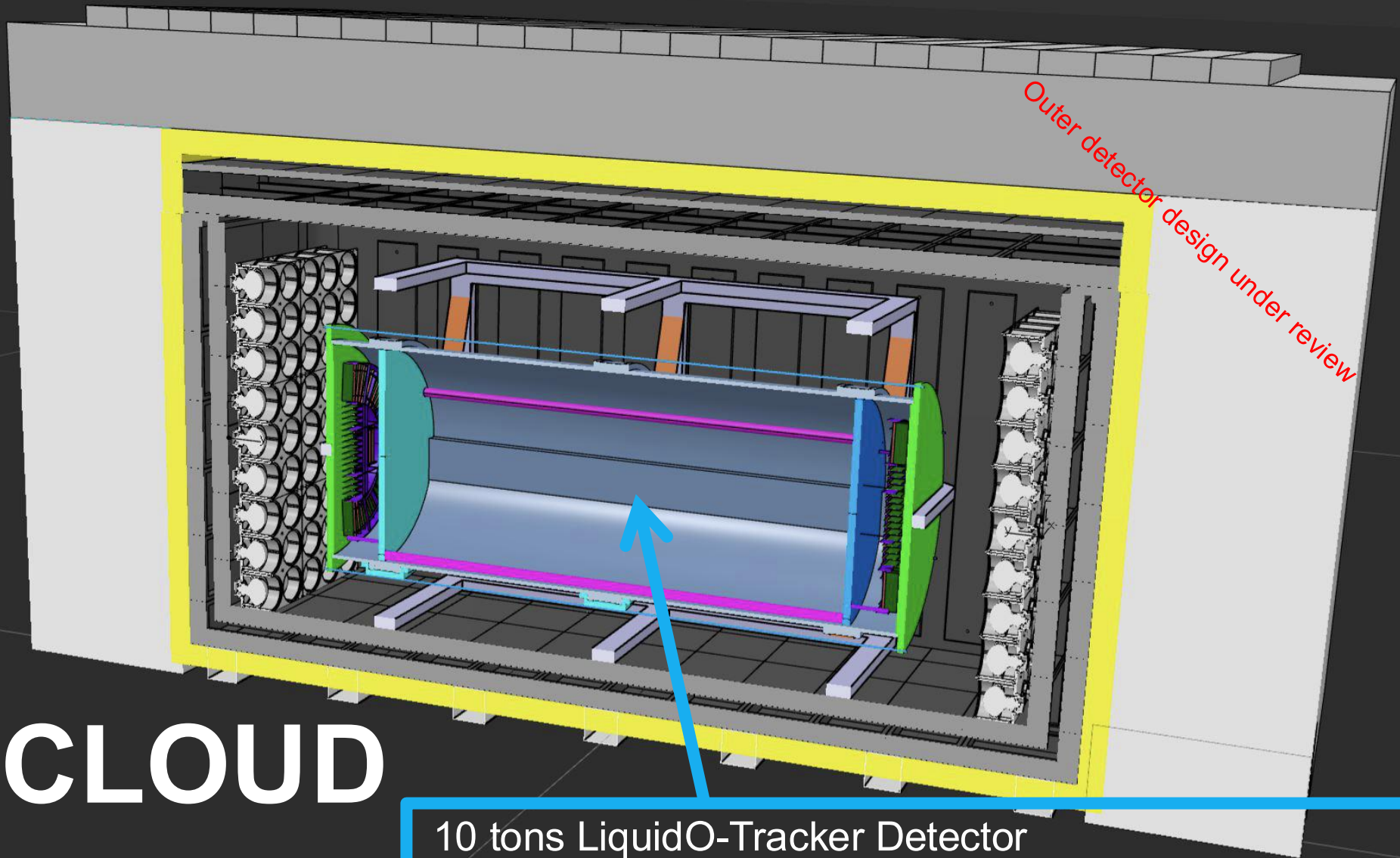
- A. Cabrera — IJCLab / Université Paris-Saclay (France)
- J. Hartnell — Sussex University (UK)

#### IB Chair:

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

<https://antimatter-otech.ijclab.in2p3.fr/> [AM-OTech]

<https://liquido.ijclab.in2p3.fr/nucLOUD> [via LiquidO]



# CLOUD

10 tons LiquidO-Tracker Detector  
Opaque scintillator + 10,000 fibres+SiPMs  
~1.8 m diameter, >200 PE/MeV design, sub-ns timing

# Place by Chooz nuclear reactor

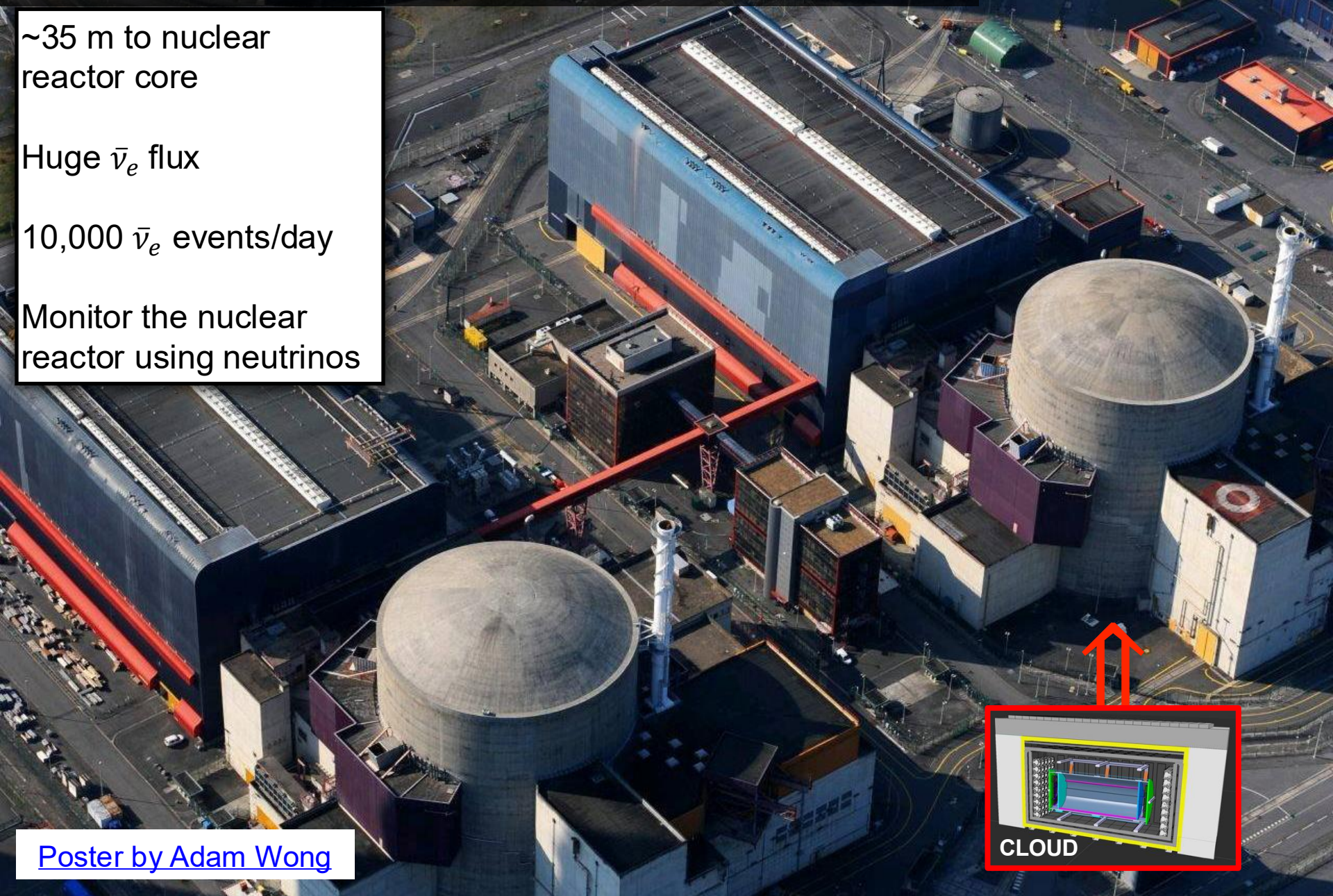


~35 m to nuclear reactor core

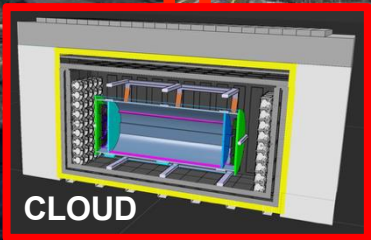
Huge  $\bar{\nu}_e$  flux

10,000  $\bar{\nu}_e$  events/day

Monitor the nuclear reactor using neutrinos



Poster by Adam Wong



# Future plans

# From Bob Svoboda's opening talk...

Letter | Published: 07 April 1934

## The "Neutrino"

[H. BETHE](#) & [R. PEIERLS](#)

*Nature* **133**, 532 (1934) | [Cite this article](#)

**5305** Accesses | **97** Citations | **8** Altmetric | [Metrics](#)

## 1934 Article of Bethe and Peierls

**“-one can conclude that there is no practically possible way of observing the neutrino.”**

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Letter | Published: 07 April 1934

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## 1934 Article of Bethe and Peierls

**“-one can conclude that there is no practically possible way of observing the neutrino.”**

What is practical in 1946 is different than 1934...

**Bruno Pontecorvo**  
**Inverse  $\beta$  Process**

(National Research Council of Canada, Division of Atomic Energy. Chalk River, 1946, Report PD-205. This version was kindly provided by Prof. W.F.Davidson).

# Inverse $\beta$ Decay of $^{115}\text{In} \rightarrow ^{115}\text{Sn}^*$ : A New Possibility for Detecting Solar Neutrinos from the Proton-Proton Reaction

R. S. Raghavan

*Bell Laboratories, Murray Hill, New Jersey 07974*

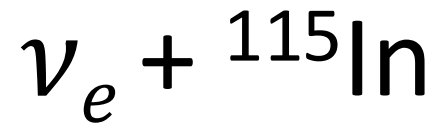
(Received 8 April 1976)

The basis for a low-threshold, high-efficiency, direct-counting detector for solar neutrinos from the  $p$ - $p$  fusion reaction is proposed. The inverse  $\beta$  decay of  $^{115}\text{In}$  to the 614-keV excited state of  $^{115}\text{Sn}$  ( $T_{1/2} = 3.26 \mu\text{sec}$ ) provides a unique delayed-coincidence signature and is estimated to yield a solar-neutrino capture rate of  $\sim 750$  solar neutrino units,  $\sim 85$  of which is due to  $pp + pep$  neutrinos.

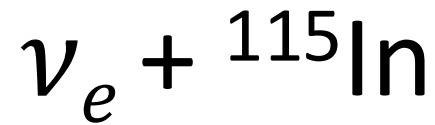
50 years ago

Lots of great work by LENS  
collaboration from early 2000s

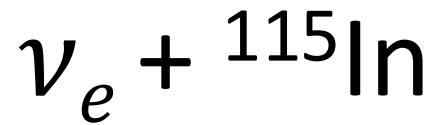
First indium loaded scintillators



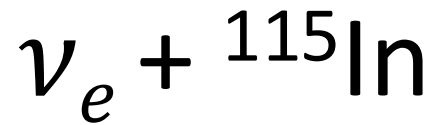
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  - Charged current interaction (get  $\nu_e$  energy)
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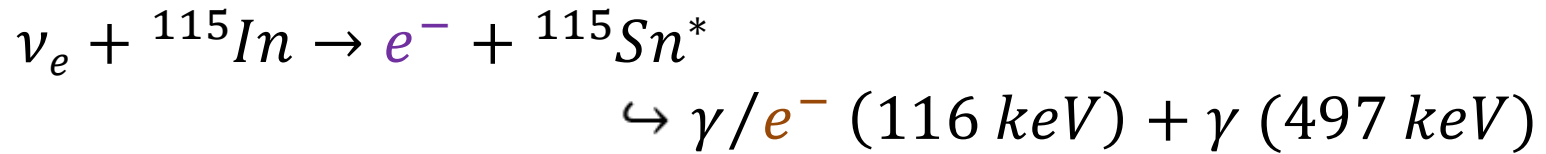
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- **The ugly:**
  - “no practically possible way”?

# Indium and LiquidO

- What is practical in 2026 is different than 1976...



- Signature: multi-fold coincidence
  - Require right particles in right places at right times with right energies...
- LiquidO precision imaging means, e.g.
  - require 1<sup>st</sup>  $e^-$  to be in same cubic cm of detector as 2<sup>nd</sup>  $e^-$
  - require nearby gamma-like 497 keV event in time with 2<sup>nd</sup>  $e^-$

# C L II U D

# S U P E R C H O O Z

CERN Seminar: *“The SuperChooz Experiment: Unveiling the Opportunity”*

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

<https://zenodo.org/record/7504162>

Double Chooz  
"Near" Cavern

"Ultra Near" ~35m

Two huge existing caverns  
50,000 m<sup>3</sup> total  
100 m overburden  
~1 km from reactor!

Double Chooz  
"Far" Cavern

Chooz nuclear reactors

I'm out of time to talk about all the  
physics that can be done with  
LiquidO...

# Neutrino Physics with ~~Scintillators~~ LiquidO

- ~~Discovery of the neutrino~~
- Solar neutrinos
  - <https://www.nature.com/articles/s42005-021-00763-5>
- Geoneutrinos
  - <https://www.nature.com/articles/s42005-026-02518-6>
- Supernova neutrinos
  - <https://indico.cern.ch/event/1215214/>
- Reactor neutrinos
  - <https://indico.cern.ch/event/1215214/>
- Atmospheric neutrinos
  - [https://indico.fnal.gov/event/21535/contributions/63272/attachments/39670/48008/LiquidO\\_MOD2019\\_OchoaRicoux.pdf](https://indico.fnal.gov/event/21535/contributions/63272/attachments/39670/48008/LiquidO_MOD2019_OchoaRicoux.pdf)
- Accelerator neutrinos
  - [https://indico.fnal.gov/event/21535/contributions/63272/attachments/39670/48008/LiquidO\\_MOD2019\\_OchoaRicoux.pdf](https://indico.fnal.gov/event/21535/contributions/63272/attachments/39670/48008/LiquidO_MOD2019_OchoaRicoux.pdf)
- $0\nu\beta\beta$  searches
  - <https://pos.sissa.it/337/028>
  
- (Nucleon decay)
  - <https://indico.cern.ch/event/1215214/>
- (Gamma-ray astronomy)
  - <https://www.sciencedirect.com/science/article/pii/S0927650525000581>

Lots of potential

# Conclusions

- **Hybrid approach**
  - Exploit directionality and PID plus low threshold
  - Multiple test beds: new scintillators, fast photon sensors and spectral sorting
- **Innovative new “LiquidO” technology**
  - Exploit stochastic light confinement
    - Highly scattering opaque medium + extraction of light
  - High-resolution imaging and PID
  - Maturing into high performance deployable detectors
- **Detector R&D is a path to discovery**
  - It changes what is “practically possible”