on behalf of the **LiquidO consortium**…

L I Q U I D O

technology born for antineutrino detection

IAEA International Atomic Energy Agency

3rd IAEA Technical Workshop on Antineutrino
SNU, Seoul (South Korea) — April 2025

Anatael Cabrera
CNRS / Université Paris-Saclay — IJCLab (Orsay) / LNCA (Chooz)
France

Scientific collaboration @ Institute of Astrophysics of the Canaries.
Spain

(co)spokesperson:
- DoubleChooz
- LiquidO
- CLOUD — AntiMatter-OTech (EIC)
- SuperChooz Pathfinder

LiquidO Collaboration$^{(a-z)*}$

J. Apilluelo[z], L. Asquith[b], E. F. Bannister[b], N. P. Barradas[kα], C. L. Baylis[b], J. L. Beney[p], M. Berberan e Santos[kβ], X. de la Bernardie[p], T. J. C. Bezerra[b], M. Bongrand[p], C. Bourgeois[q], D. Breton[q], J. Busto[n], A. Cabrera[q,c], A. Cadiou[p], E. Calvo[l], M. de Carlos Generowicz[b], E. Chauveau[f], B. J. Cattermole[b], M. Chen[h], P. Chimenti[i], D. F. Cowen[xα,xβ], S. Kr. Das[b], S. Dusini[rα], A. Earle[b], M. Felizardo[kα], C. Frigerio Martins[i], J. Galán[z], J. A. García[z], A. Gibson-Foster[b], C. Girard-Carillo[mα], W. C. Griffith[b], J. J. Gómez-Cadenas[u], M. Guitière[p], F. Haddad[p], J. Hartnell[b], A. Holin[d], I. G. Irastorza[z], I. Jovanovic[a], A. Kling[kα], L. Koch[mα], P. Lasorak[b], J. F. Le Du[q,c], F. Lefevre[p], P. Loaiza[q], J. A. Lock[b], G. Luzón[z], J. Maalmi[q], J. P. Malhado[j], F. Mantovani[eα,eβ], J. G. Marques[kα], C. Marquet[f], M. Martínez[z], J. T. Moffat[xβ], D. Navas-Nicolás[l], H. Nunokawa[t], J. P. Ochoa-Ricoux[g], T. Palmeira[kβ], C. Palomares[l], D. Petyt[d], P. Pillot[p], A. Pin[f], J. C. C. Porter[b], M. S. Pravikoff[f], S. Richards[d], N. Rodrigues[kβ], M. Roche[f], R. Rosero[y], B. Roskovec[s], M. L. Sarsa[z], A. Serafini[rα,rβ], C. Shepherd-Themistocleous[d], W. Shorrock[b], M. Silva[kγ], L. Simard[q], M. Sisti[o], S. R. Soleti[u], D. Stocco[p], V. Strati[eα,eβ], J. S. Stutzmann[p], F. Suekane[v], N. Tuccori[b], A. Verdugo[l], B. Viaud[p], S. M. Wakely[mα], A. Weber[mα], G. Wendel[xβ], A. S. Wilhelm[a], A. W. R. Wong[b], M. Yeh[y], and F. Yermia[p]

[a]Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, MI, USA
[b]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[c]LNCA Underground Laboratory, CNRS, EDF Chooz Nuclear Reactor, Chooz, France
[d]Rutherford Appleton Laboratory, Didcot, Oxford, United Kingdom
[eα]INFN, Sezione di Ferrara, Ferrara, Italy
[eβ]Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Ferrara, Italy
[f]Université de Bordeaux, CNRS, LP2I Bordeaux, Gradignan, France
[g]Department of Physics and Astronomy, University of California at Irvine, Irvine, CA, USA
[h]Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Canada
[i]Departamento de Física, Universidade Estadual de Londrina, Londrina, Brazil
[j]Department of Chemistry, Imperial College London, London, United Kingdom
[kα]CT2N, Instituto Superior Tecnico, Universidade de Lisboa, Lisbon, Portugal
[kβ]iBB, Instituto Superior Tecnico, Universidade de Lisboa, Lisbon, Portugal
[kγ]IDMEC, Instituto Superior Tecnico, Universidade de Lisboa, Lisbon, Portugal
[l]CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, Spain
[mα]Johannes Gutenberg-Universität Mainz, Institut für Physik, Mainz, Germany
[o]INFN, Sezione di Milano-Bicocca, Milano, Italy
[n]Université de Aix Marseille, CNRS, CPPM, Marseille, France
[p]Nantes Université, IMT-Atlantique, CNRS, Subatech, Nantes, France
[q]Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
[rα]INFN, Sezione di Padova, Padova, Italy
[rβ]Dipartimento di Fisica e Astronomia, Università di Padova, Padova, Italy
[s]Institute of Particle and Nuclear Physics, Charles University, Prague, Czech Republic
[t]Department of Physics, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, Brazil
[u]Donostia International Physics Center, Basque Excellence Research Centre, San Sebastián/Donostia, Spain
[v]RCNS, Tohoku University, Sendai, Japan
[xα]Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA, USA
[xβ]Department of Physics, Pennsylvania State University, University Park, PA, USA
[y]Brookhaven National Laboratory, Upton, NY, USA
[z]Centro de Astropartículas y Física de Altas Energías (CAPA), Universidad de Zaragoza, Zaragoza, Spain

Spokespersons:
• A. Cabrera — IJCLab / Université Paris-Saclay (France)
• F. Suekane — Tohoku University / RCNS (Japan)

Contact: LiquidO-Contact-L@in2p3.fr

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

LiquidO: light detector with **opaque** medium

⟹ event-wise **imaging⊕topology** & **PID** (high doping scenario)

what's LiquidO?

each energy deposition…

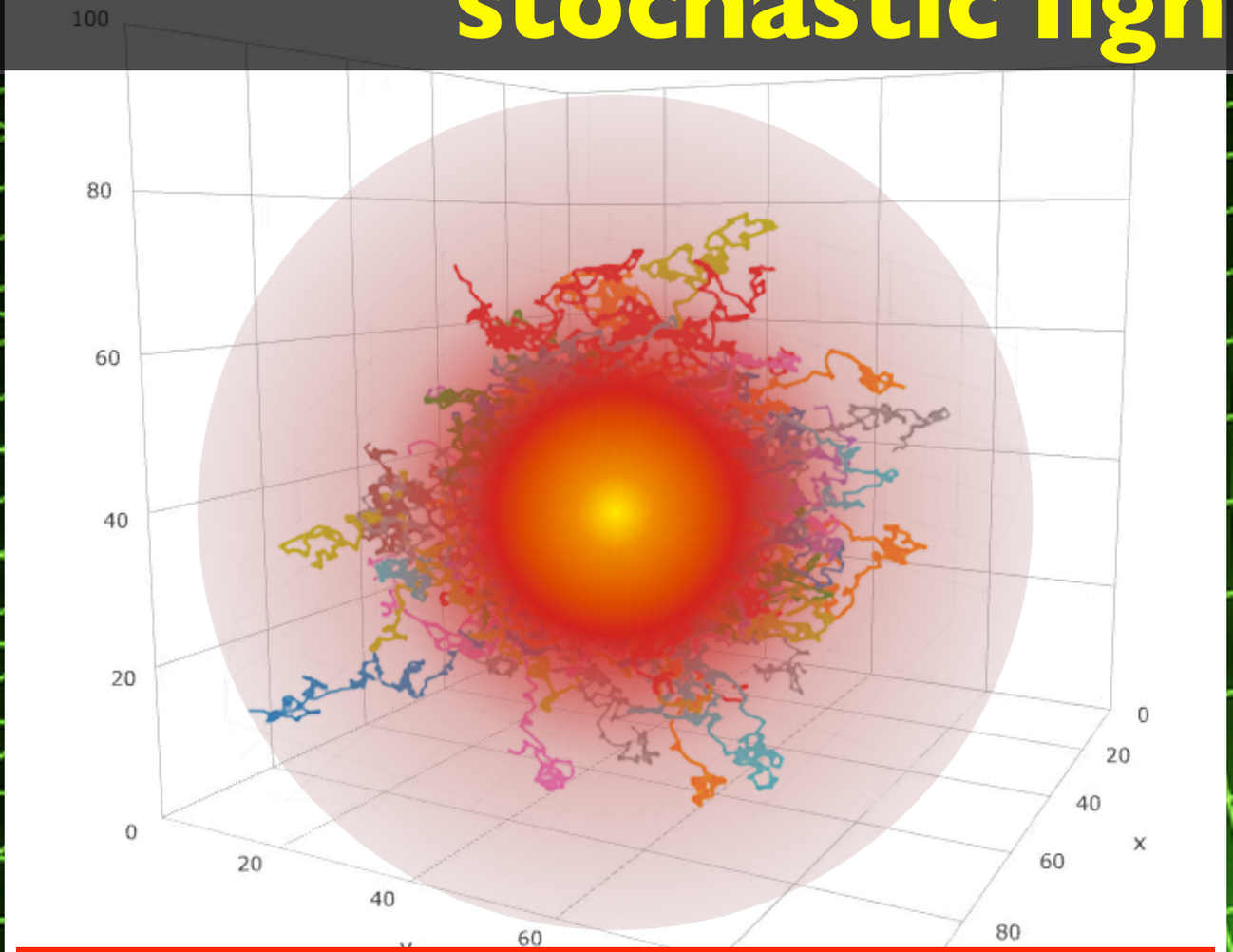
- **points 3D**(*x*,*y*,*z*) & **energy 1D**(*E*)
  ⟹ **lines** (i.e. point-sequence)

- **time 1D**(*t*) — optional (generally available)

"energy-flow" → energy-points ordered in **time**

(dynamic) **imaging** building-blocks…

stochastic light confinement



LiquidO→ photon's "random walk" (self-confinement)

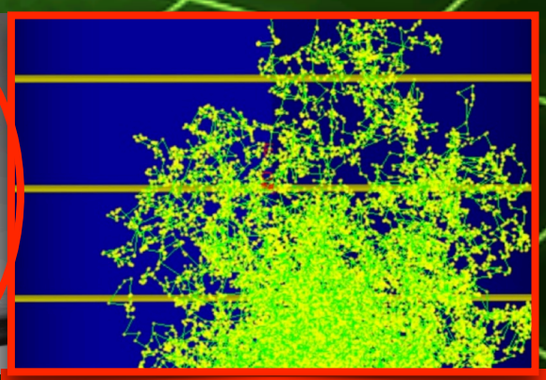
- **scattering→random walk→light ball** [order 1cm]
  - scattering mean-free-path order 1mm: $\times 10^{-4}$ smaller than usual
- **lossless (elastic) light scattering:**
  - **Mie scattering:** achromatic & tiny losses ["cloudy" touch]
  - **Rayleigh scattering:** chromatic & lossless
  - **Internal Reflection** (Snell's law lossless)

  warning: avoid reflection (losses @ order ~1%/reflection)

LiquidO ⇔ unique stochastic light confinement

⟹ **must NOT be transparent!!**

Transparency
λ(scattering)**≥10m**



Rayleigh & Mie Scattering
λ(scattering)**≤1cm**

inducing light to a point (lossless)...

how LiquidO looks like?

highly absobing material ⟹ low attenuation length

[LiquidO: similar to today's technology — somewhat relaxed]

never GOOD

LiquidO looks **milky** or **cloudy**

highly scattering material ⟹ low atteniation length (too)

[LiquidO: ~10^4x more scattering than before]

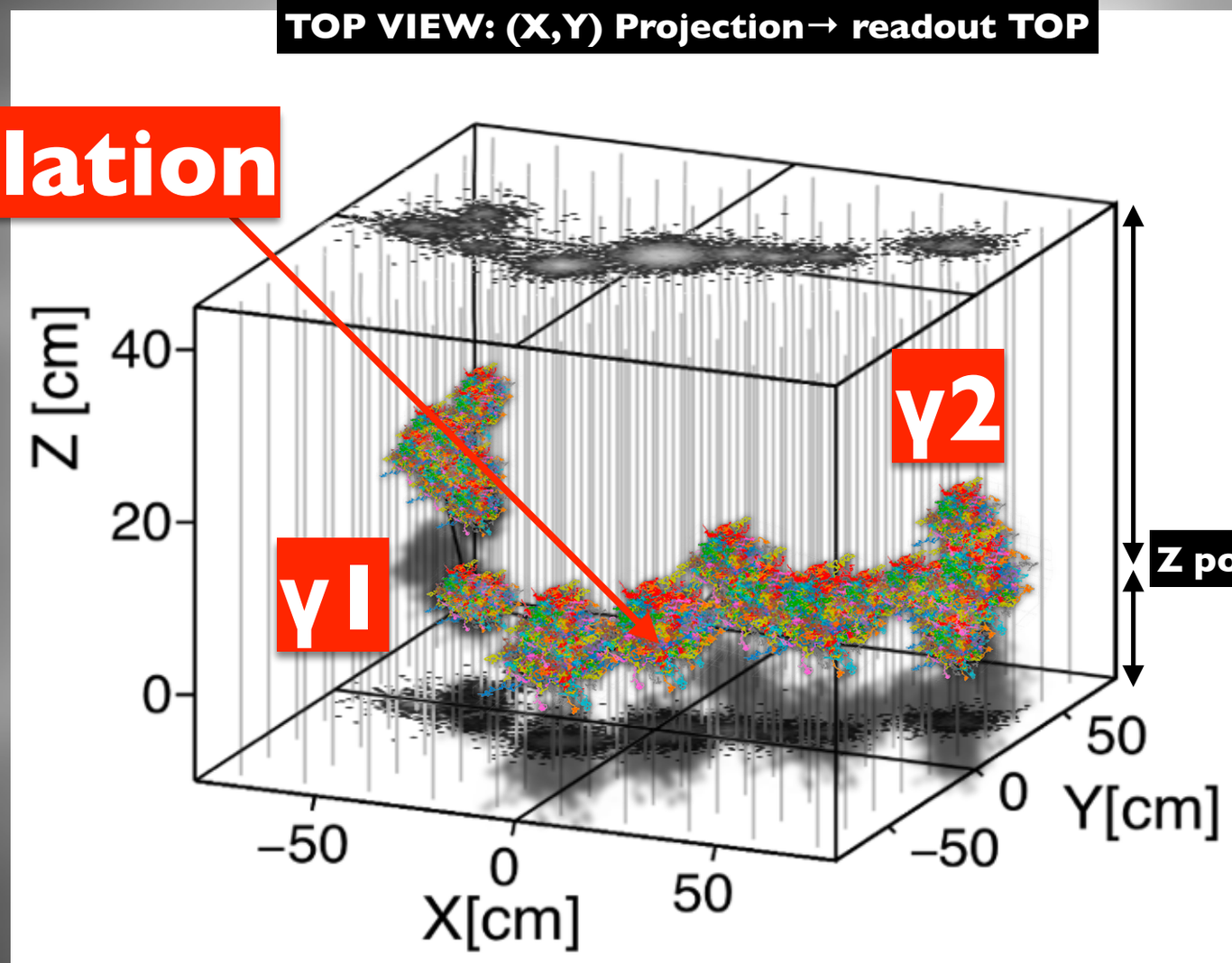
this is good!

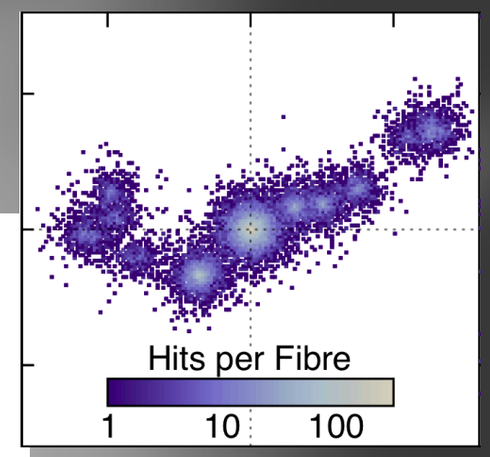
building a LiquidO event...

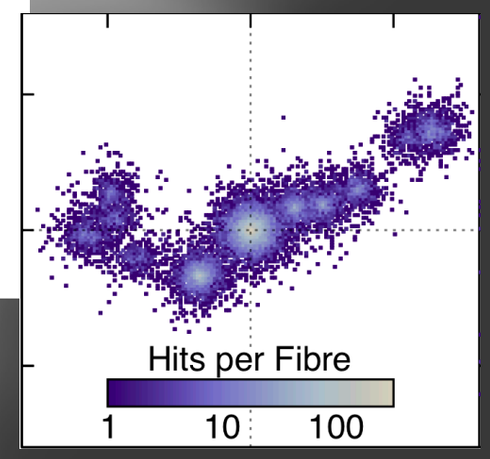
Topology (X,Y) direct & native (PID)→ possible mm vertex precision

Simplest LiquidO: 1D lattice (fibres along Z-axis only) — **axial configuration**

TOP VIEW: (X,Y) Projection→ readout TOP



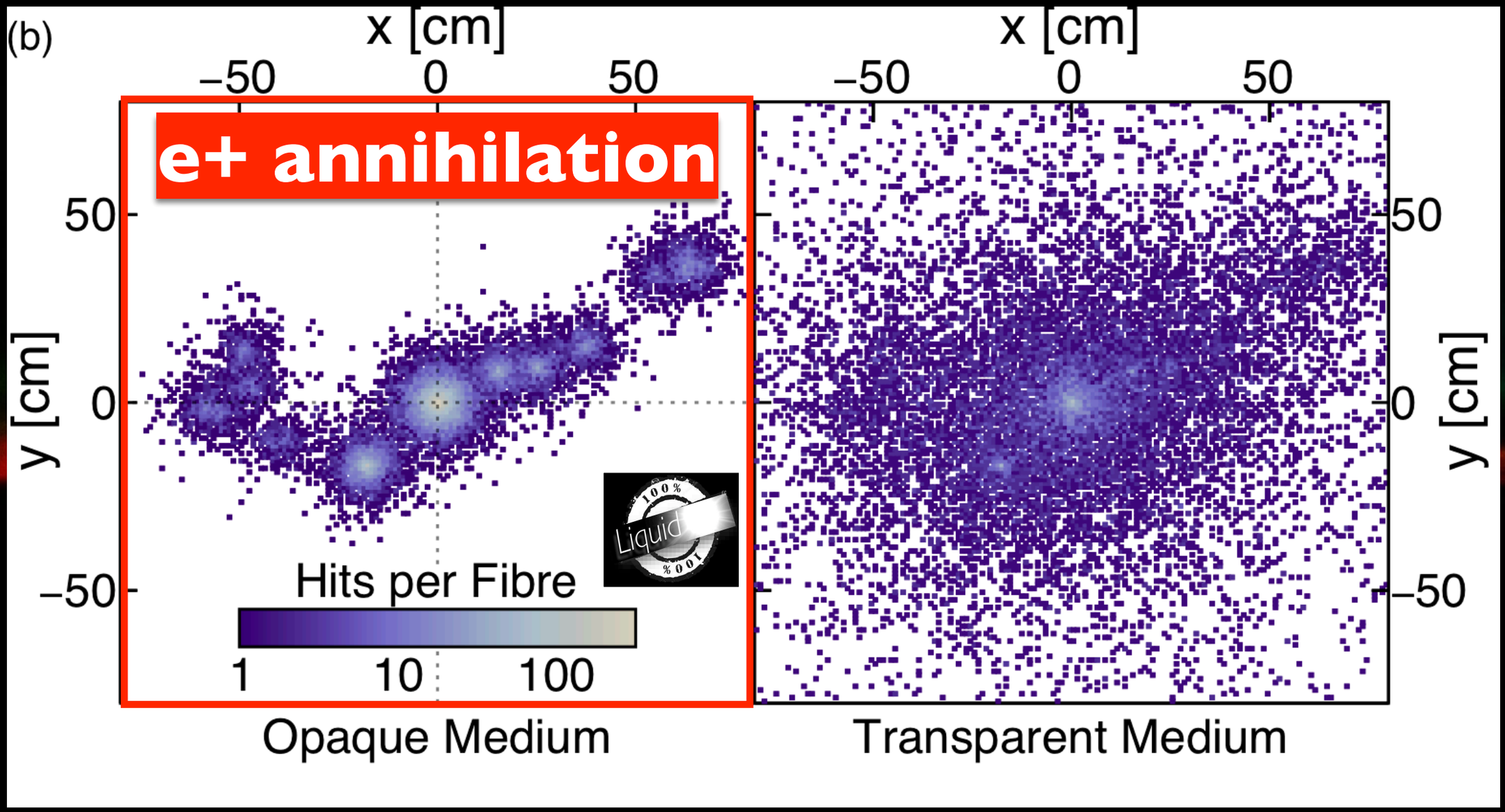




BOTTOM VIEW: (X,Y) Projection→ readout BOTTOM

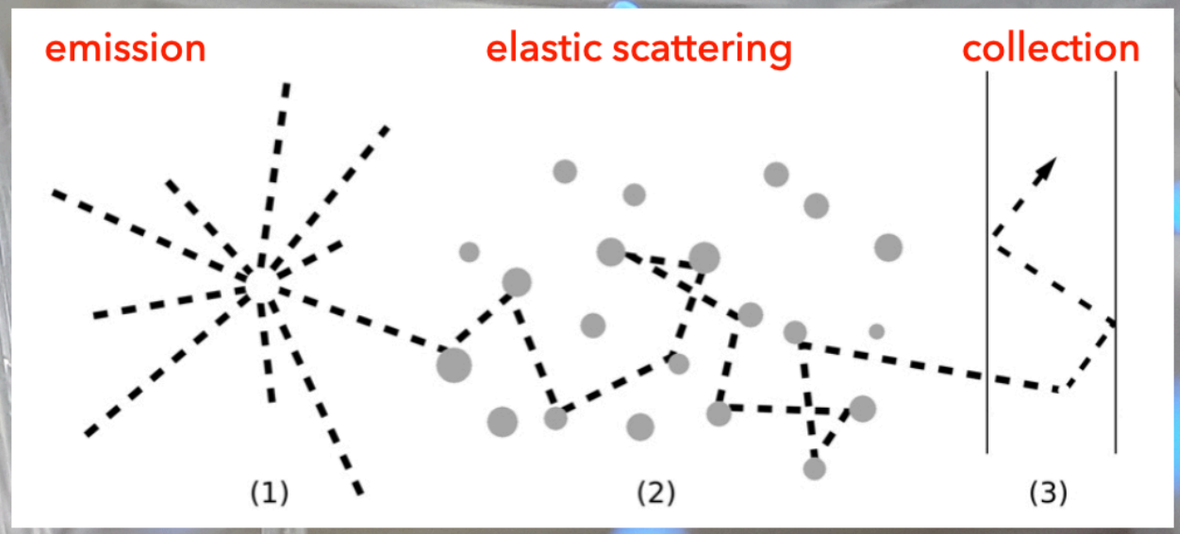
opaque medium→stochastic light confinement (**self-segmentation**)

LiquidO: sub-nuclear MeV imaging…



opaque medium → stochastic light confinement

(**self-segmentation**)

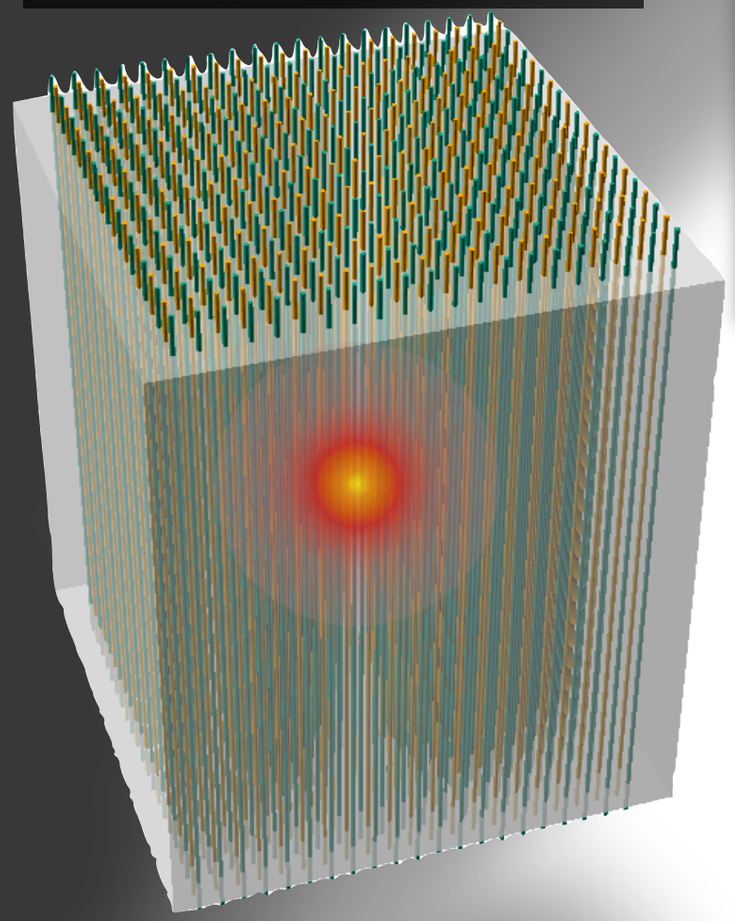


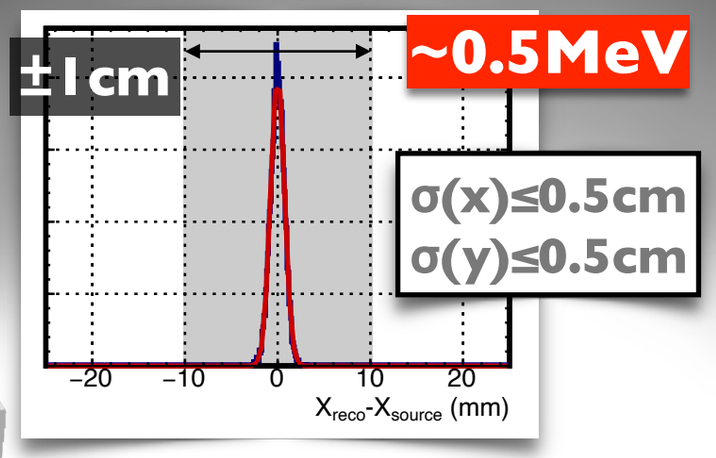
FIBRES: A MUST (SO FAR)

wave-shifting or scintillating fibres — clear fibres are **≈useless**

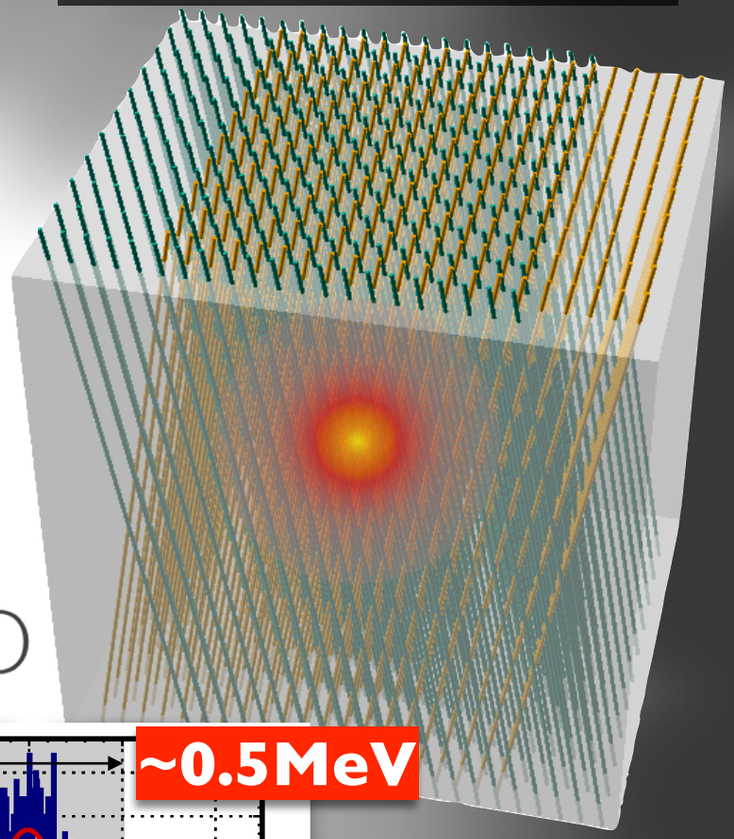
novel LiquidO engineering…

LiquidO axial-fibres
"parallel"

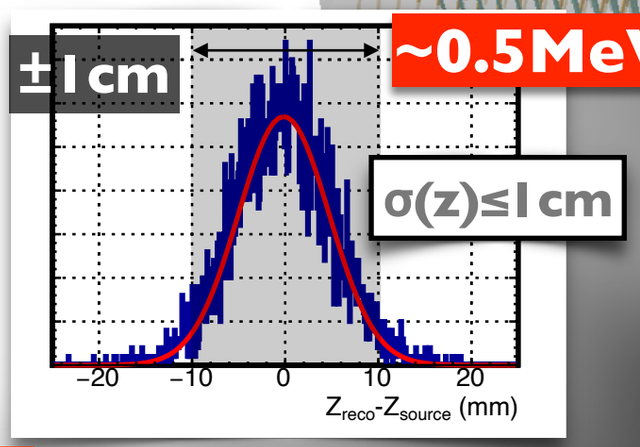




LiquidO axial-fibres
"crossed"



L I Q U I D



1x Axis(Z) — low cost & simplicity
- (X,Y): topology→ **mm resolution** (robust)
- Z: **timing**→ **few cm resolution** →**some fragility:** light yield, rise-time, etc

2x Axes — complexity & cost…
- (X,Y,Z): topology→ **mm resolution** (robust)
- (X,Y,Z): timing→ cheap-readout / over-constrained

3x Axes — useless?

"1x" Axis(twisted-Z @ ≤10°**) — development**
- (X,Y): topology→ **mm resolution** (robust)
- Z: topology→ **≤1cm resolution** (robust)
- (X,Y,Z): timing→ over-constrain & **energy-flow**

more Axes: necessary?

Anatael Cabrera (CNRS-IN2P3) — IJCLab / Université Paris-Saclay (Orsay)

DRD2@CERN WORKSHOP

OPAQUE SCINTILLATION

Anatael Cabrera (CNRS / Université Paris-Saclay - IJCLab@Orsay / LNCA@Chooz)

https://doi.org/10.5281/zenodo.10629927

pioneering opaque scintillation...

	Solvent	Scintillator I	Scintillator II	Photosensor
transparent	•quantum energy "collector" •transparent medium	•main scintillation emission	•scintillation emission (colour shift to "reder")	•single-photon detection
example	LAB	PPO	Bis-MSB (optional)	PMT (QE≤30%) (ultimate spectral sensitivity)
fraction	≥99% (transparent medium)	≤1%	≤1%	≥10% photo-coverage
opaque	•quantum energy "collector" •opaque medium	•main scintillation emission	•fibre light collection •scintillation emission (colour shift to "reder")	•single-photon detection
example	LAB⊕X (opacity: X doping)	PPO	Kuraray-B3 (a must)	SiPM (QE≤60%) (ultimate spectral sensitivity)
fraction	~99% (opaque medium)	≤1% (the same)	~1% (LiquidO)	(not easy metric)

Naive light yield estimation for comparison in the **"small detector" limit** (i.e. neglect attenuation effects)

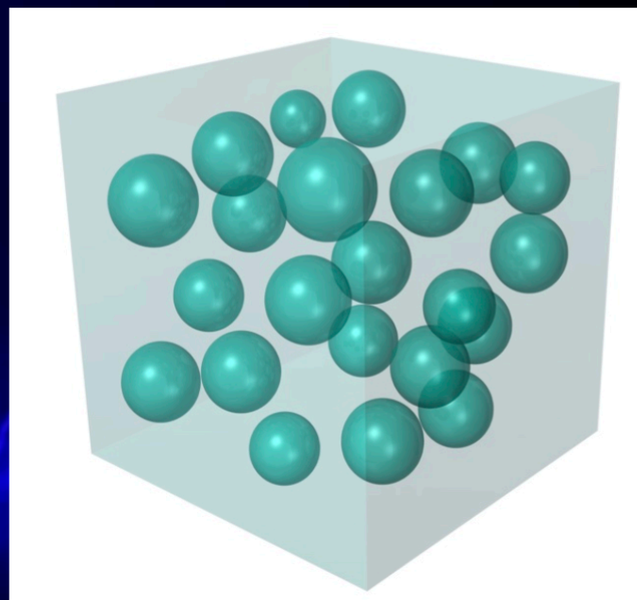
- **Transparent:** easy hundreds of PE/MeV [JUNO: up to order 1000] – ultimately limited by **PMT-QE**.
- **Opaque:** potential for hundreds of PE/MeV – ultimately limited by **Fibre's Trapping** [under demonstration]

arXiv:1807.00628

FIRST "MICRO-CRYSTAL" PROOF-OF-PRINCIPLE — FRANCE CIRCA 2018

pulverised inorganic µ-Crystals in a liquid system (scintillating or not) to maximise light output

note: possible quantum energy transfer under active R&D



Anatael Cabrera (CNRS / Université Paris-Saclay)

pioneering **opaque scintillation** — a byproduct of **LiquidO**

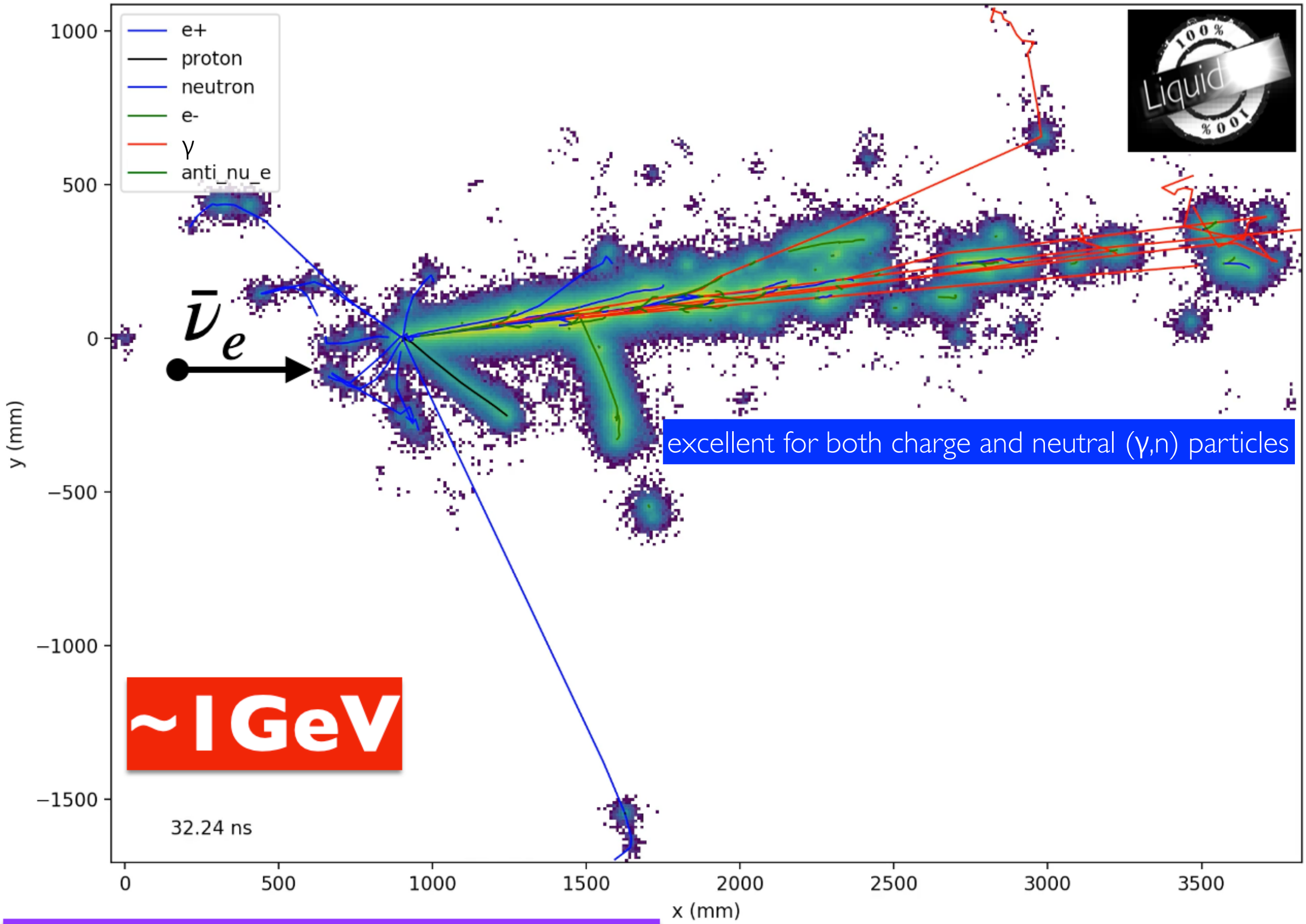
FIRST “NOWASH” SYSTEM (PROTOTYPING) — GERMANY CIRCA 2018

Anatael Cabrera (CNRS / Université Paris-Saclay)

arXiv:1908.03334

a LiquidO event...

energy flow: EM evolution of energy in time



≥100MeV: accelerator, atmospheric, p-decay, etc

≳0.1MeV

topology	physics	LiquidO Information	
point	unresolved (≲few cm)	**point-like**	sub-mm possible (primitive)
track	points-like sequence	**track-like**	sub-mm possible (enhanced)
point's ⊕ track's	complex event	combination ⊕ **timing**	reconstruction (energy⊕x,y,z⊕t)

input 5D→ energy-flow, kinematics($\bar{p}$), **PID**, etc (derived)

imaging & outcome (upon reco)…

LiquidO results...

First Release at CERN July 2019 (detector seminar)

https://indico.cern.ch/event/823865/

nature communications physics

Article | Open access | Published: 21 December 2021

Neutrino physics with an opaque detector

LiquidO Consortium

Communications Physics **4**, Article number: 273 (2021) | Cite this article

8831 Accesses | **27** Altmetric | Metrics

Abstract

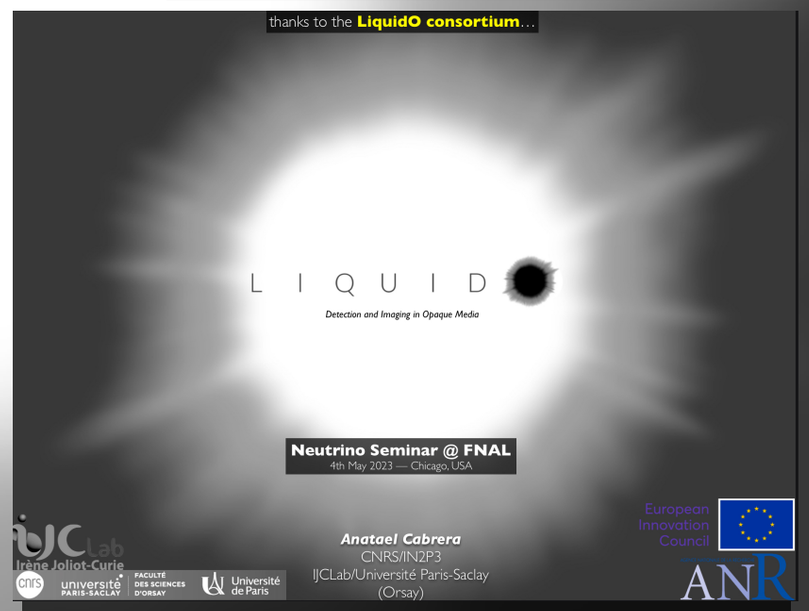
In 1956 Reines & Cowan discovered the neutrino using a liquid scintillator detector. The neutrinos interacted with the scintillator, producing light that propagated across transparent volumes to surrounding photo-sensors. This approach has remained one of the most widespread and successful neutrino detection technologies used since. This article introduces a concept that breaks with the conventional paradigm of transparency by confining and collecting light near its creation point with an opaque scintillator and a dense array of optical fibres. This technique, called LiquidO, can provide high-resolution imaging to enable efficient identification of individual particles event-by-event. A natural affinity for adding dopants at high concentrations is provided by the use of an opaque medium. With these and other capabilities, the potential of our detector concept to unlock opportunities in neutrino physics is presented here, alongside the results of the first experimental validation.

www.nature.com/articles/s42005-021-00763-5

Neutrino 2022
(June 2022)

https://zenodo.org/record/6697273

FNAL Seminar 2023
(May 2023)



https://zenodo.org/records/7922021

LiquidO Official WEB: https://liquido.ijclab.in2p3.fr/

latest results — March 2025

The Stochastic Light Confinement of LiquidO

LiquidO Collaboration[(a−z)*]

J. Apilluelo[l,z], L. Asquith[b], E. F. Bannister[b], N. P. Barradas[kα], J. L. Beney[p], M. Berberan e Santos[kβ], X. de la Bernardie[p], T. J. C. Bezerra[b], M. Bongrand[p], C. Bourgeois[q], D. Breton[q], C. Buck[1], J. Busto[n], K. Burns[q], A. Cabrera[q,c,2], A. Cadiou[p], E. Calvo[l], E. Chauveau[f], B. J. Cattermole[b], M. Chen[h], P. Chimenti[i], D. F. Cowen[xα,xβ], S. Dusini[rα], A. Earle[b], M. Felizardo[kα], C. Frigerio Martins[i], J. Galán[z], J. A. García[z], R. Gazzini[q], A. Gibson-Foster[b], C. Girard-Carillo[mα], B. Gramlich[1], M. Grassi[2,rβ], W. C. Griffith[b], J. J. Gómez-Cadenas[u], M. Guitière[p], F. Haddad[p], J. Hartnell[b], A. Holin[d], I. G. Irastorza[z], I. Jovanovic[a], A. Kling[kα], L. Koch[mα], P. Lasorak[b], J. F. Le Du[q,c], C. Lefebvre[h], F. Lefevre[p], P. Loaiza[q], J. A. Lock[b], G. Luzón[z], J. Maalmi[q], J. P. Malhado[j], F. Mantovani[eα,eβ], J. G. Marques[kα], C. Marquet[f], M. Martínez[z], D. Navas-Nicolás[q,l], H. Nunokawa[t], M. Obolensky[2], J. P. Ochoa-Ricoux[g], T. Palmeira[kβ], C. Palomares[l], B. Pedras[kβ], D. Petyt[d], P. Pillot[p], A. Pin[f], J. C. C. Porter[b], M. S. Pravikoff[f], N. Rodrigues[kβ], M. Roche[f], R. Rosero[y], B. Roskovec[s], N. Roy[q], M. L. Sarsa[z], S. Schoppmann[mβ,1], A. Serafini[rα,rβ], C. Shepherd-Themistocleous[d], W. Shorrock[b], M. Silva[kγ], L. Simard[q], S. R. Soleti[u], H. Th. J. Steiger[mα,mβ], D. Stocco[p], V. Strati[eα,eβ], J. S. Stutzmann[p], F. Suekane[v], A. Tunc[mα], N. Tuccori[b], A. Verdugo[l], B. Viaud[p], S. M. Wakely[mα], A. Weber[mα], G. Wendel[xβ], A. S. Wilhelm[a], M. Yeh[y], and F. Yermia[p]

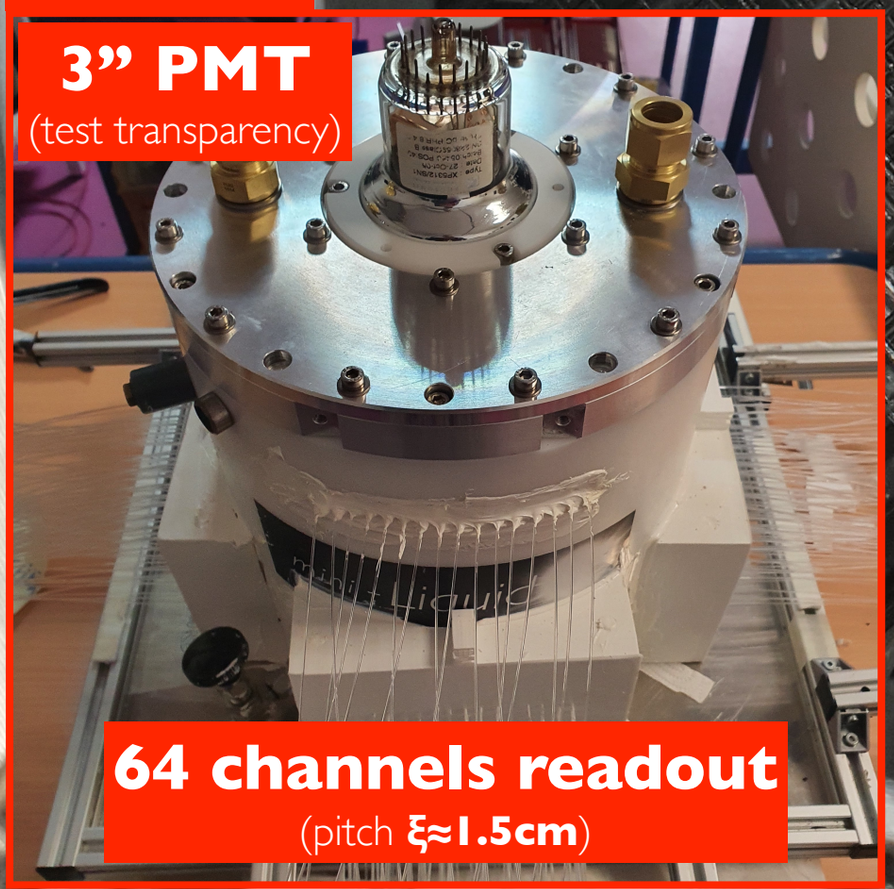
arXiv:2503.02541 — under publication

LiquidO's prototype MINI-II (upgrade)

data taking since 2021

overall view

3" PMT
(test transparency)

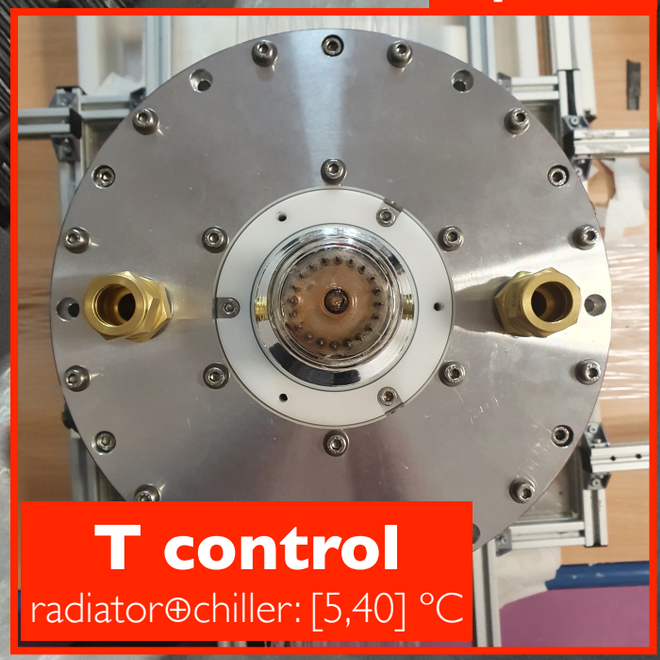


64 channels readout
(pitch **ξ≈1.5cm**)

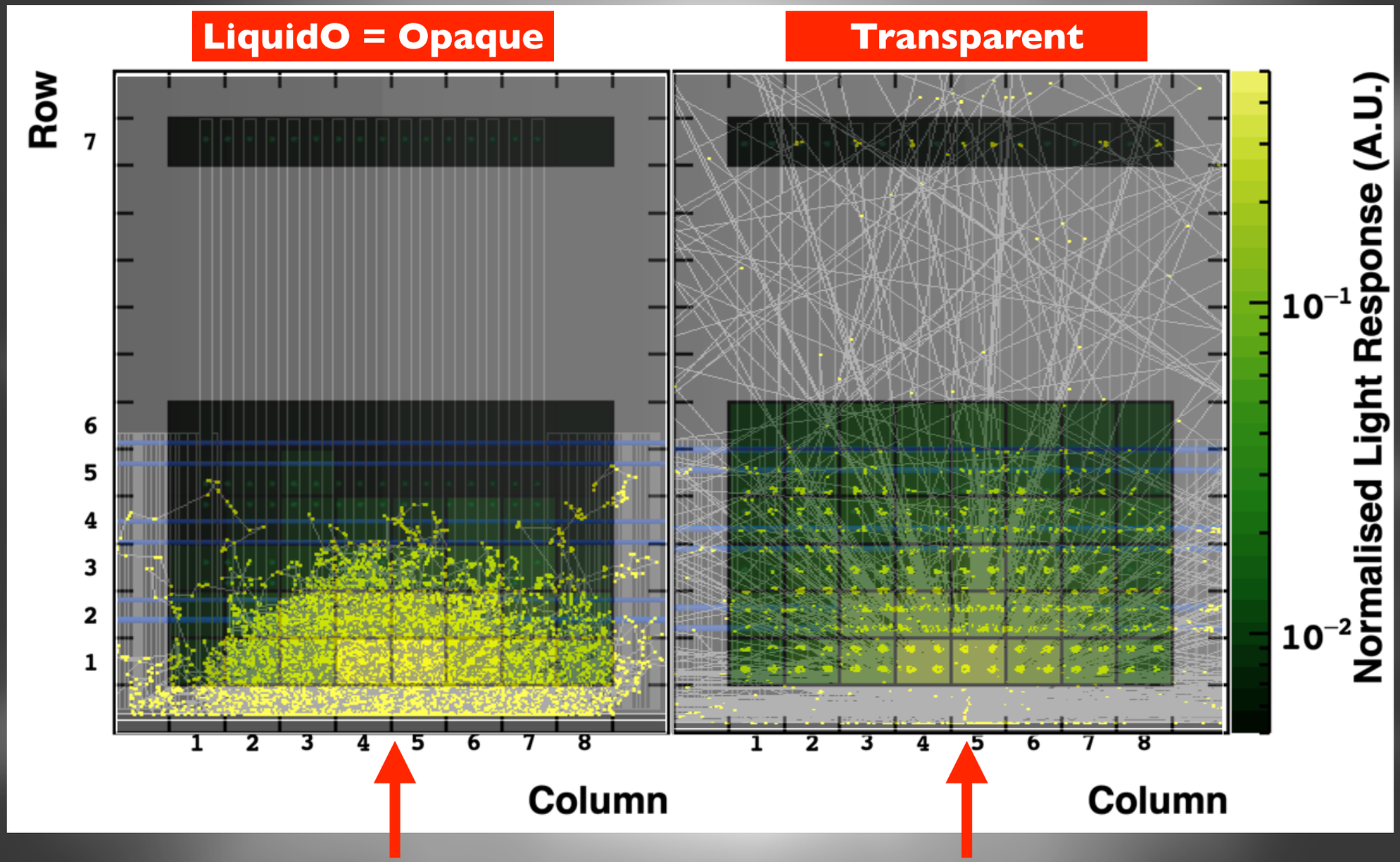
single electrons
[0.4,1.8]MeV mono-energetic

~10L multi-media
- water (transparent)
- scintillator (transparent)
- scintillator (transparent↔opaque)

top view

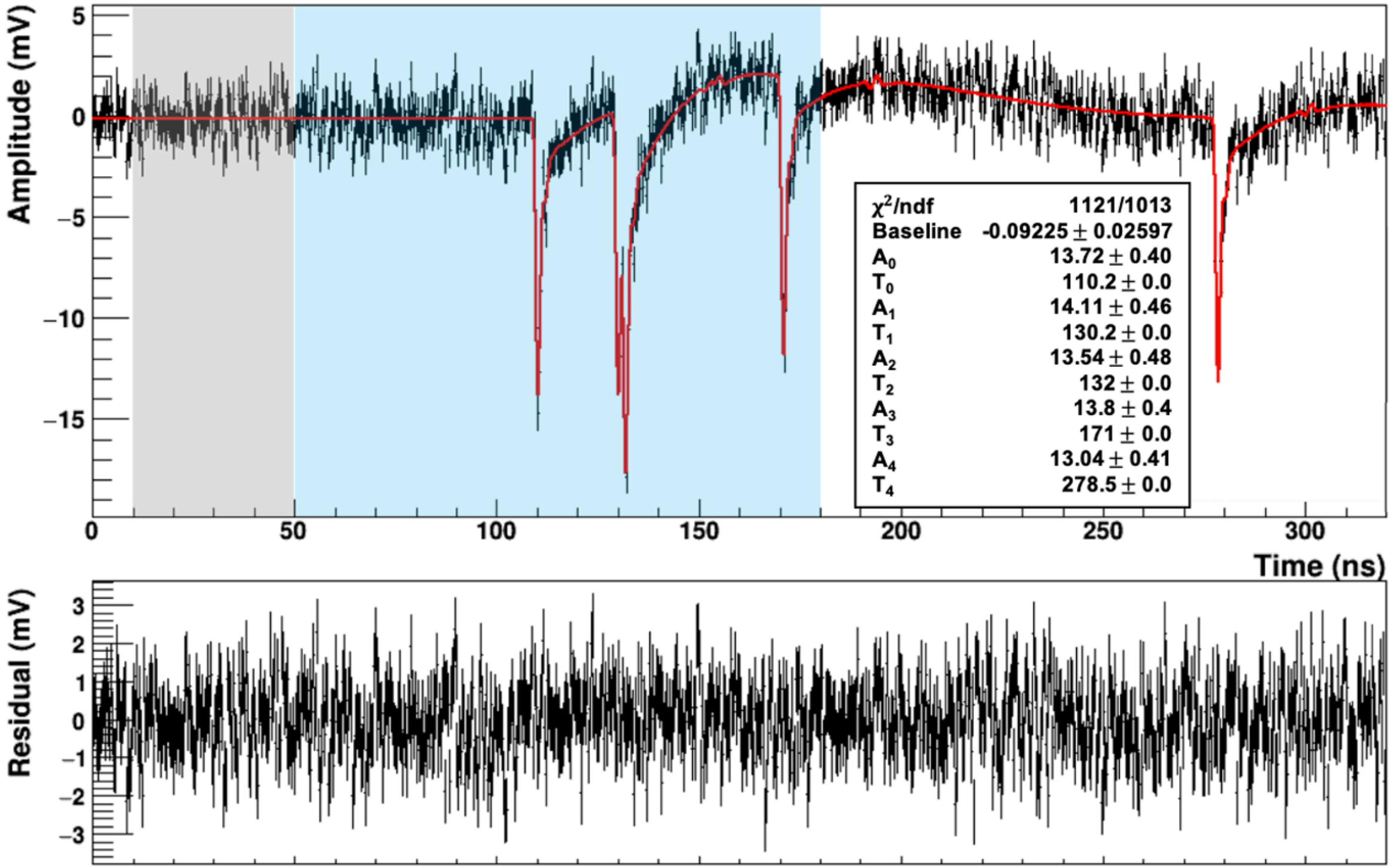


T control
radiator⊕chiller: [5,40] °C



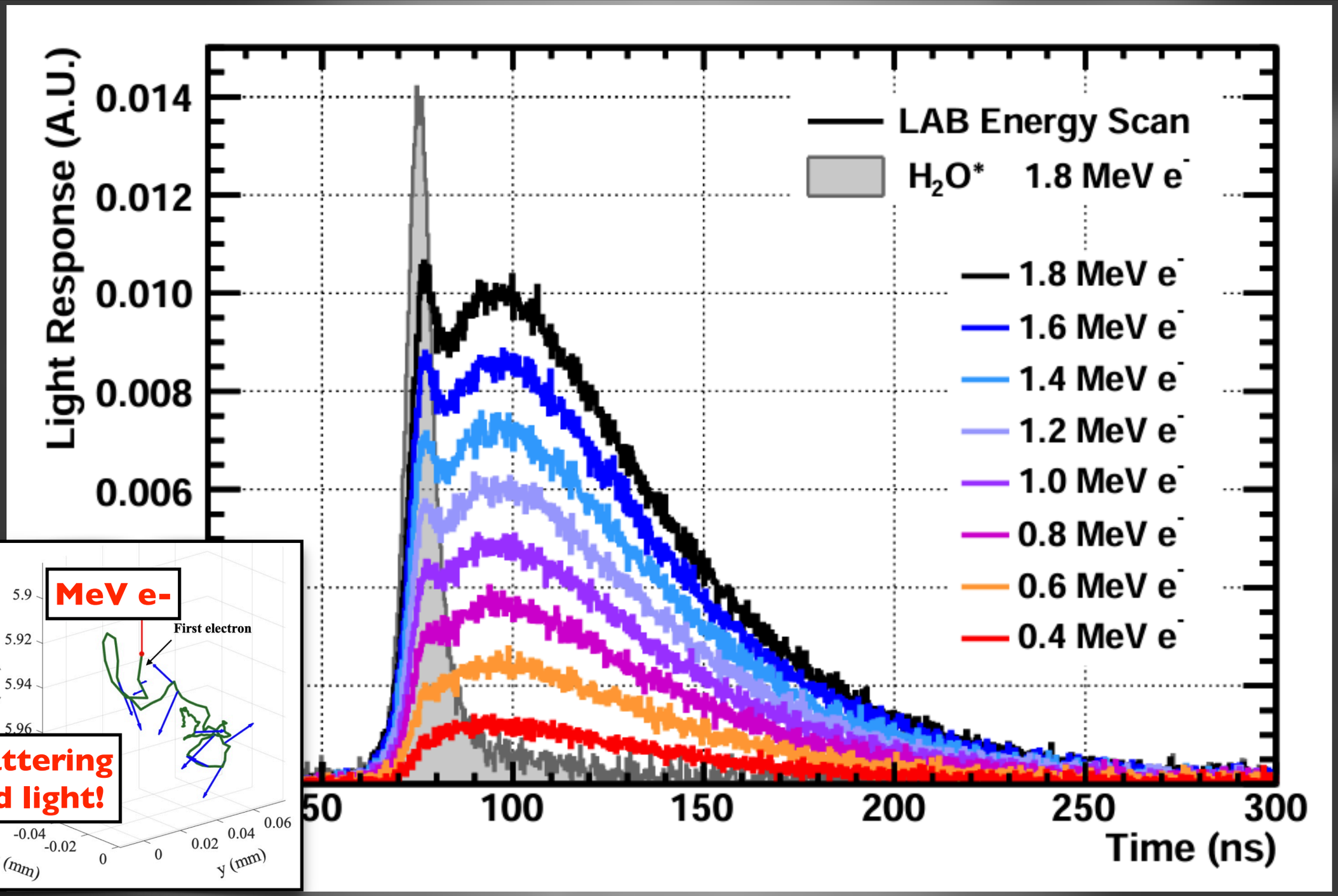
(spectrometer) monoenergetic e⁻ [0.4,1.8]MeV

SiPM pulse reconstruction — ≤100ps resolution & waveforms
(each PE reconstructed with full shape)



Cherenkov pulse-shape-ID (time-only) — even threshold effect

(no topology used— unlike punch-through μs)



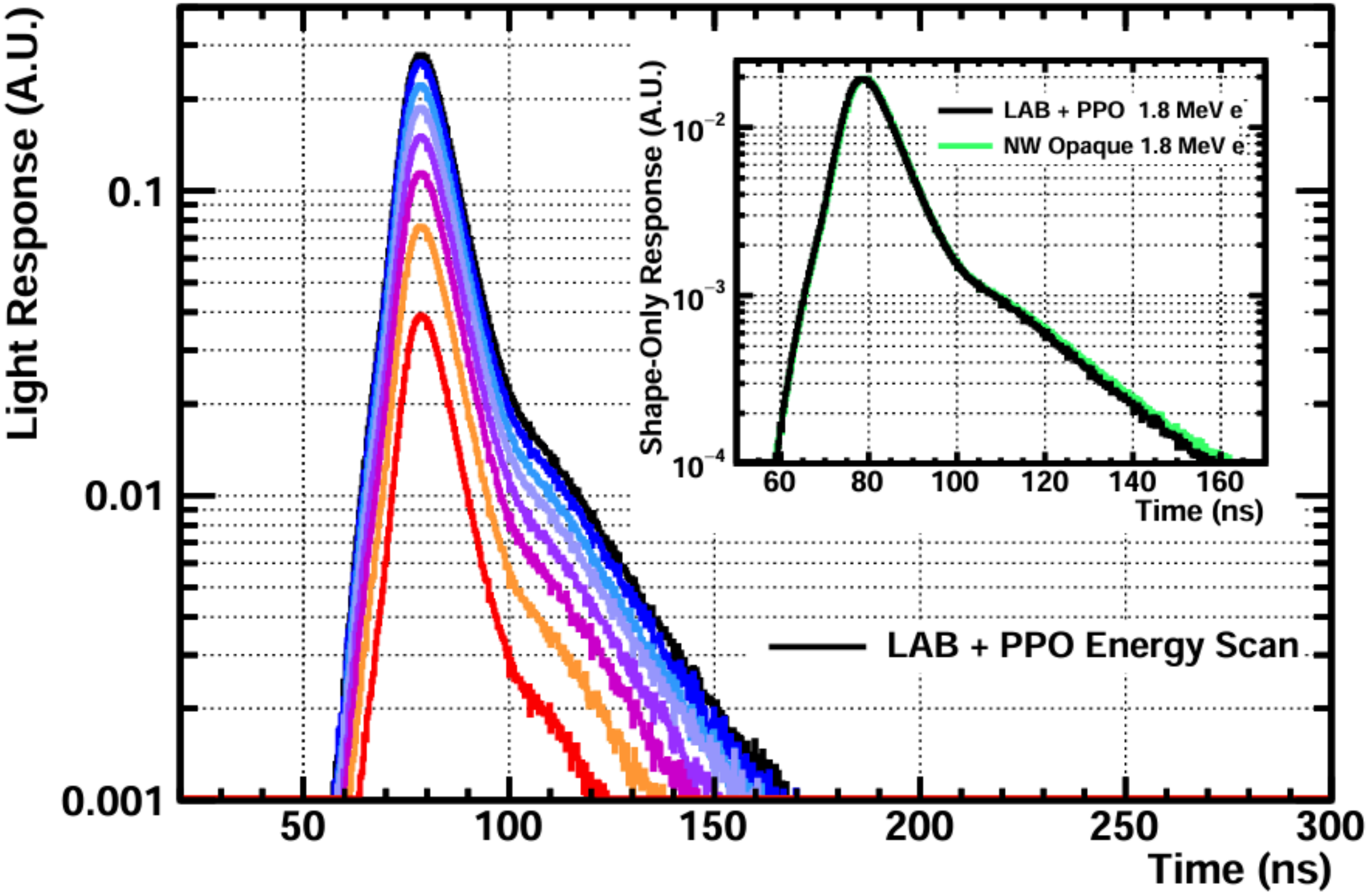
huge scattering →spread light!

ANY light detection: Cherenkov / Scintillation / anything!

(**transparent**, but **opaque** much better)

optimised scintillator — both transparent & opaque

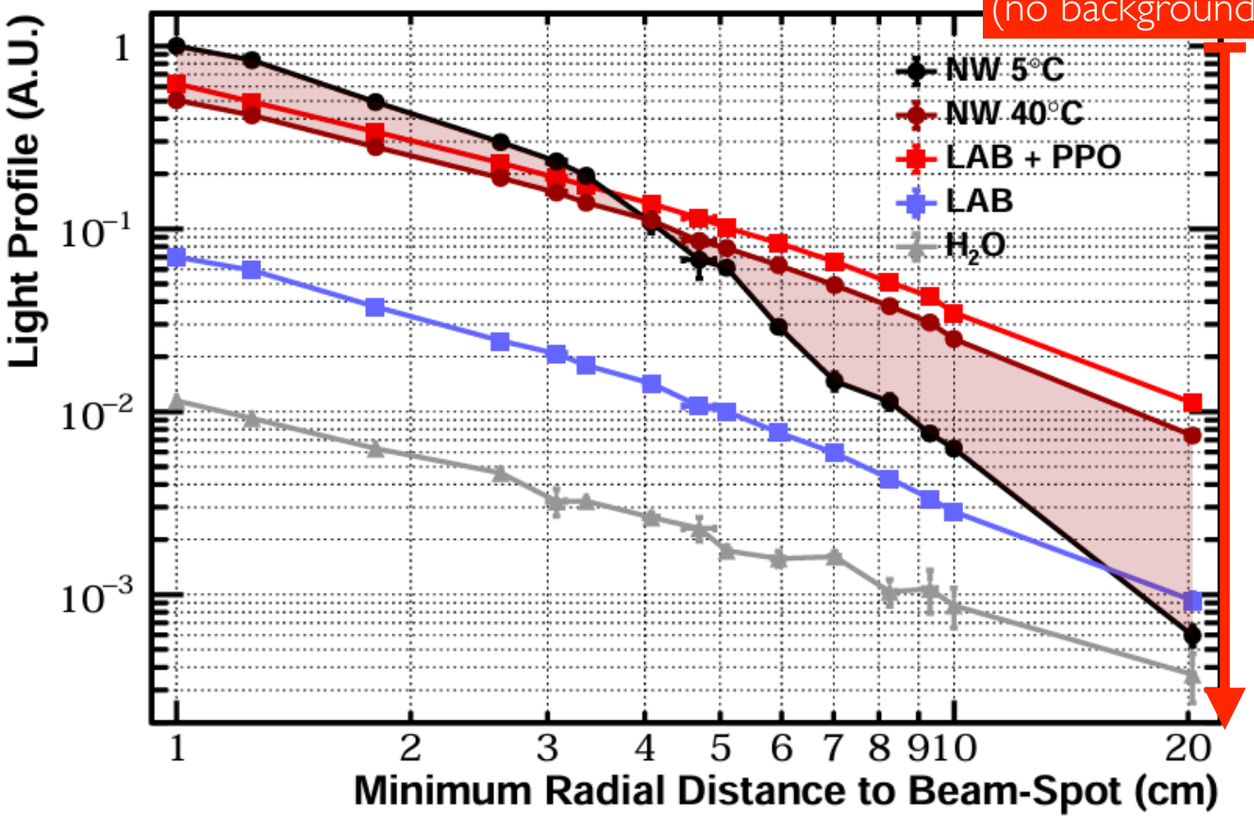
(LAB⊕PPO — **opacity** negligible extra time-spread)

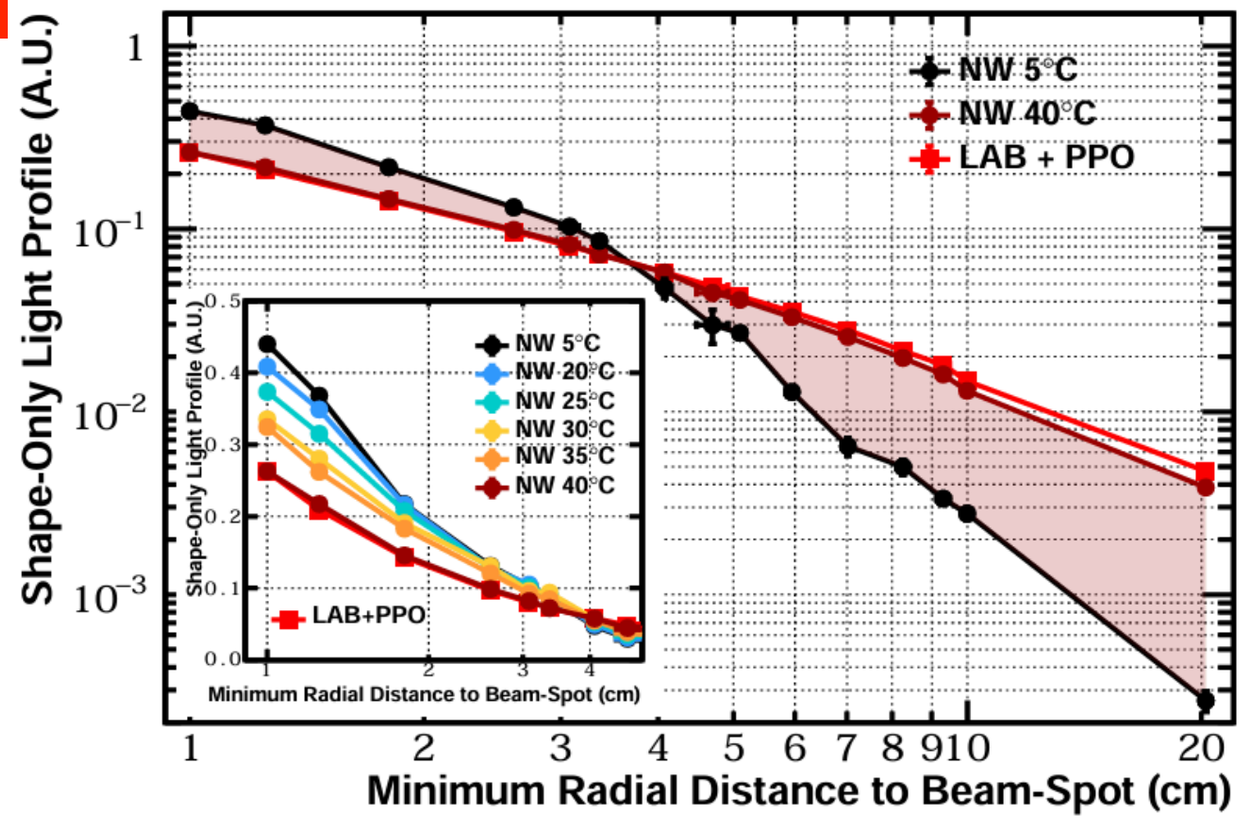


response analysis — both transparent & opaque

(opacity→ more light due to "light ball" formation)

~10⁴ explored
(no background)





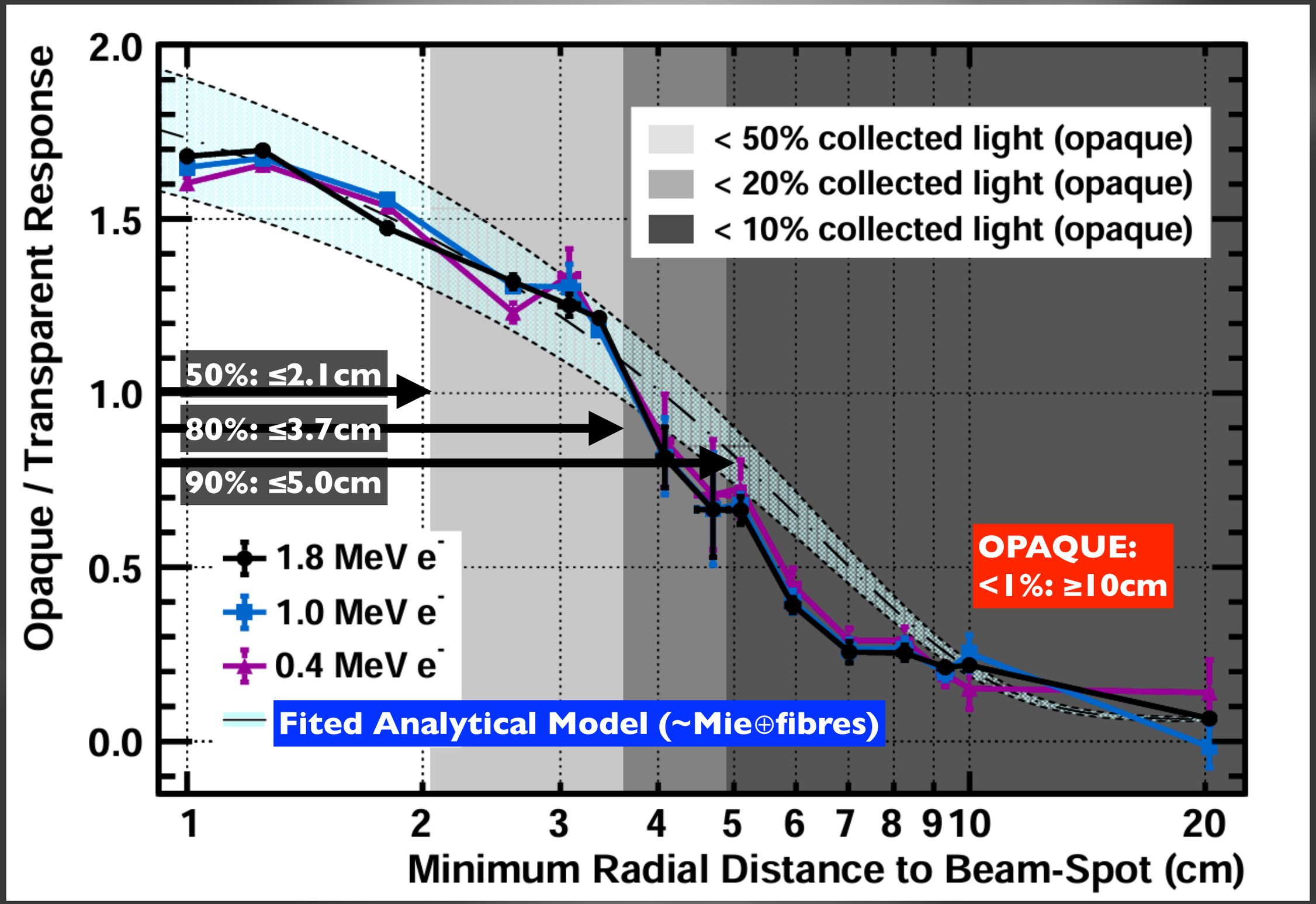
response norm⊕shape

shape-only (norm = 1)

relative response analysis — both **transparent & opaque**
LAB⊕PPO (opacity via **wax**: **temperature modulation**)

absolute response analysis (data-driven) — **G4-simulation scaling**
expected response LiquidO detector **~[200,300]PE/MeV** — today
[**optimising** state-of-the-art technology up to ≤500PE/MeV]

LiquidO's signature: stocastic light confinement — as expected
(faster light collection near source: "light ball" formation)



LiquidO's R&D status…

LiquidO: light/opacity→stochastic light confinement

any source (Cherenkov / scintillation / **any light**)

L I Q U I D

any media (liquid / solid / (impractical?) gas?)

doping: a powerful (optional) "byproduct"

new technology: **opaque scintillation…**

LiquidO's demonstration R&D completed→ optimisation, scaling, specialisation, etc.

LiquidO: light detector with **opaque** medium

[*stochastic light confinement*→**imaging**⊕topology & **PID**]

⇓

LiquidO (5D primitive imaging info)

L I Q U I D O

light-based **"TPC"** (highest duty-cycle)

⊕

uniform calorimeter (scintillation)

⊕

Time-of-Flight (4π acceptance)

⊕

imaging (PID, energy-flow, magnetisable, etc)

⊕

doping (variable composition/density & more physics)

ORCID: 0000-0001-5713-3347
anatael@in2p3.fr

Дякую…
thanks…
danke…
고맙습니다…
merci…
ありがとう…
obrigado…
спасибі…
grazie…
谢谢…
hvala…
gracias…
شكرا…

L I Q U I D

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

LiquidO's performance **proved** — just as expected (simulation corroboration & prediction)

- **demonstration R&D** (almost) **completed** [yet another paper very soon]
- **follow-up R&D** is about **optimisation** (more light, more PID, etc.), **scaling** (larger detectors), **specialisation** (doping, etc.)
  ⟹ typically **project-specific** — collaboration united forces, knowledge, experience and expertise.
- **pionnering opaque scintillators** dedicated technology — so far, "opacify transparent solutions"
  ⟹ huge input from transparent technology (almost 100 years)