

on behalf of the LiquidO proto-collaboration...

Liquid

novel liquid neutrino detection technology

(a few examples of) **what to do with it?** & (a minimalistic) **how?**



France - Ukraine Workshop (IJCLab, Orsay)

29 October 2021

Anatael Cabrera

CNRS/IN2P3

IJCLab (Orsay)

LNCA (Chooz)



université
PARIS-SACLAY

FACULTÉ
DES SCIENCES
D'ORSAY

Université
de Paris

Anatael Cabrera CNRS-IN2P3 / IJCLab (Orsay) - LNCA (Chooz) Laboratories

R **eines et al** (50's)

RR

R **ubbia et al** (70's)
[**TPC**: Nygren (75)]

Neutrino Oscillation Nobel prize: SNO & SuperK

→ **liquid scintillator (monolithic / segmented) ⊕ PMT readout**

art of **transparency** with **no topology** (unless segmented) and **little doping** ($\leq 1\%$)
[**impossible to cluster light** → forced into **voxels**]

Cherenkov Detector $\approx$ Liquid Scintillator Detector - Scintillation
[Cherenkov light order 100x less]

→ **noble liquid(gas) Ar(Xe) ⊕ charge/light readout**

art of **purity** (→ transparent) with **excellent topology** and **no(?) doping**
[**PID**: high resolution clustering possible]

disclaimer: other stunning technologies (radiochemical, bubble-chambers, etc)

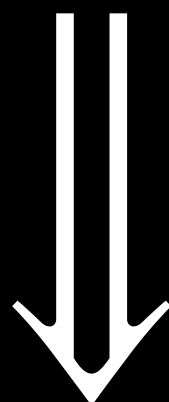
luxurious neutrino detection...

PMT($\sim 1\text{ ns}$) $\Leftrightarrow$ **Transparency** $\Rightarrow$ **~~PID~~**?

LiquidO: **light “opaque”** medium

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

vocabulary: “opacity” ≈ “brutal translucency”



LiquidO ≈ “**light TPC**” ⊕ “**4π ToF**” (**4D info**)

[highest duty-cycle & high acceptance → minimal pile-up]

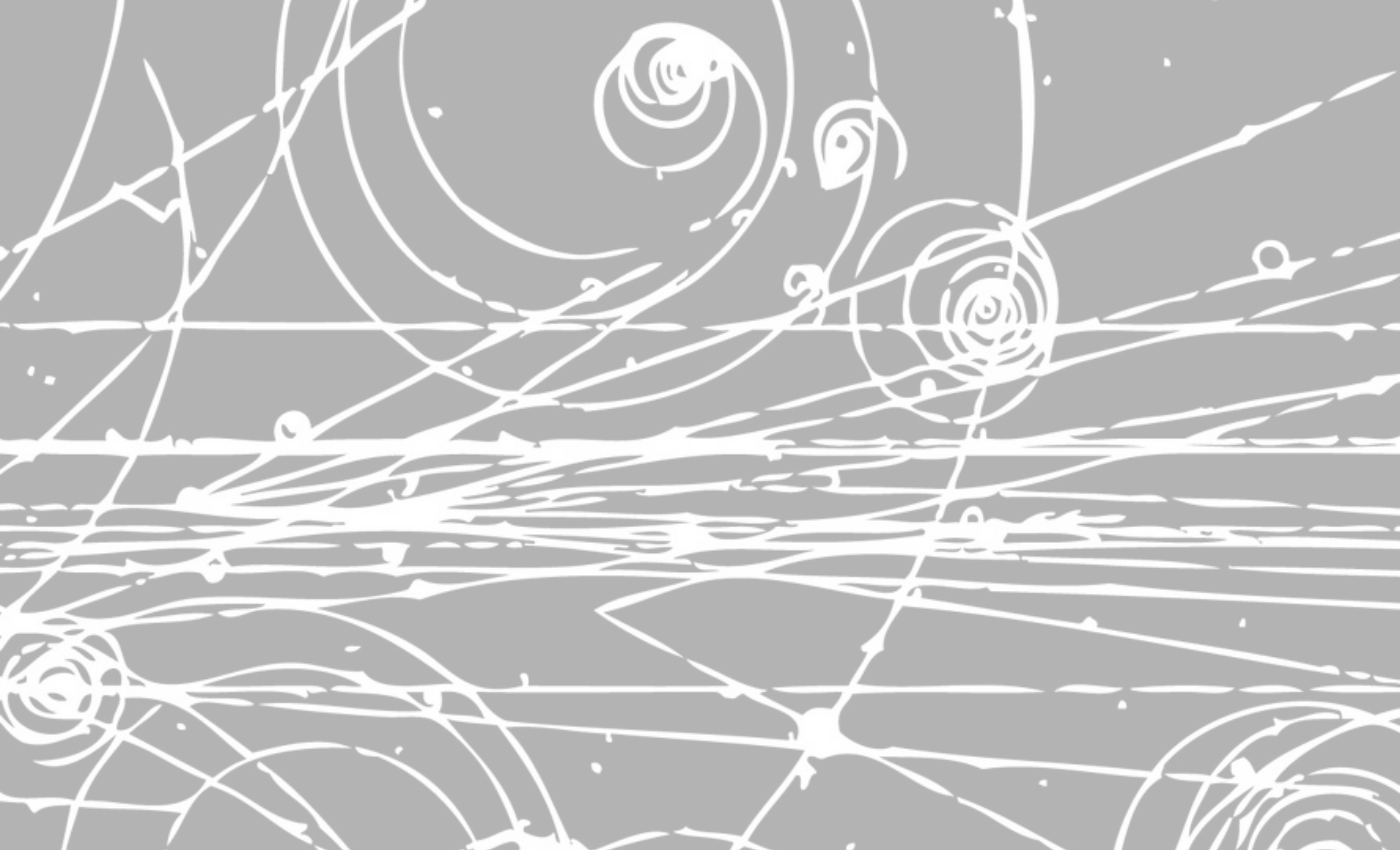
what's LiquidO?



an **Opaque** solution...?

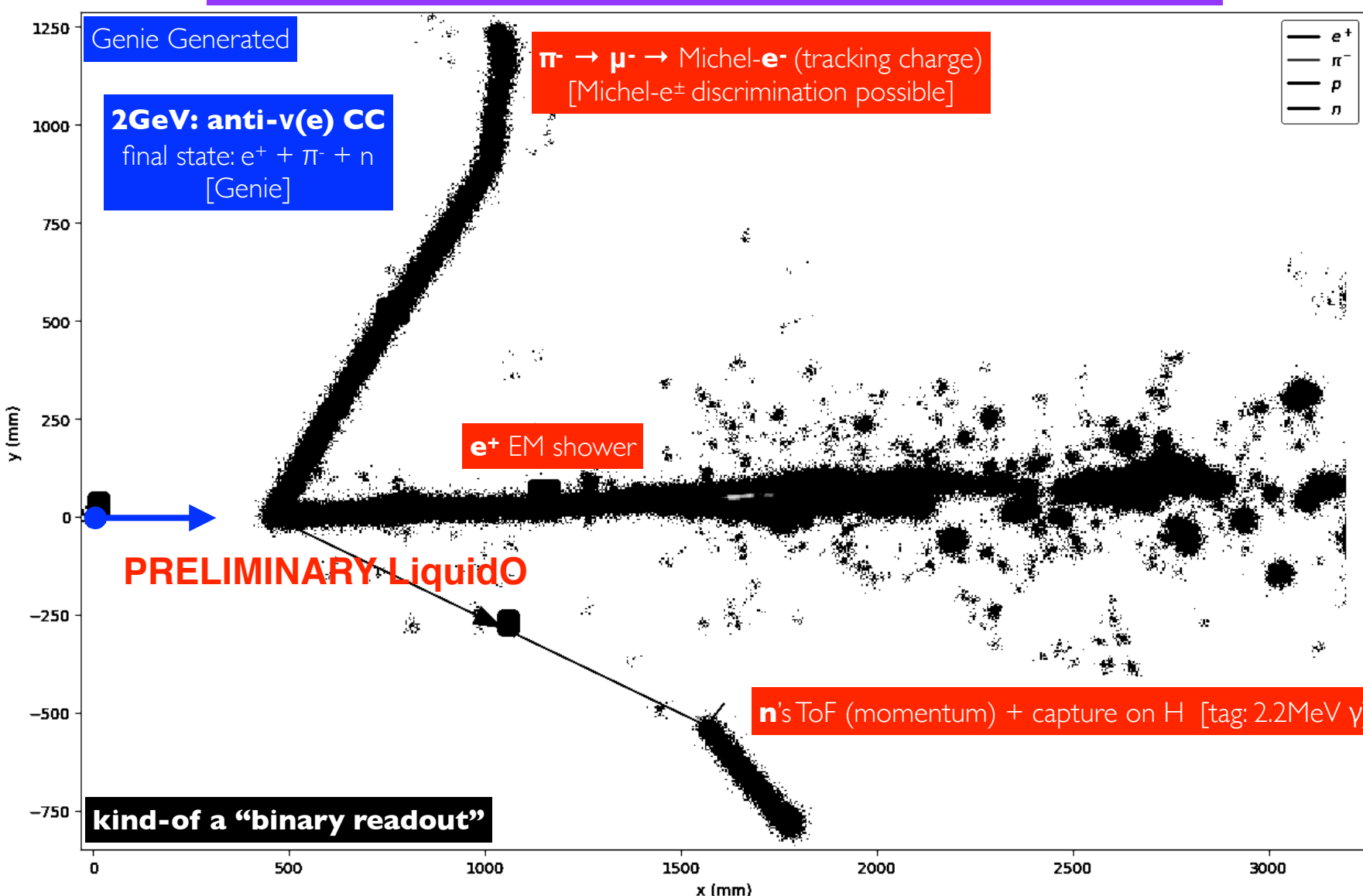
assumption: traditional liquid scintillator (opacified)
[LiquidO works beyond scintillation]

let' see...



LiquidO potential @ GeV...

LiquidO Configuration: 4mm pitch (not impossible, but demanding for mechanics)



Stochastic calorimetry term : $\approx 0.3\%$ [$\sim 100\,000$ PE/GeV]
 [10 000 γ 's per MeV $\oplus$ 1% detection $\approx$ 100 PE/MeV $\rightarrow$ 10% calorimetry]

Large Events: low-z ($H\oplus C$)
 [H is $\leq 20\%$ /volume]

Clean Nuclear Physics on H
 (sub-sample $\leftrightarrow$ normalisation)

C (99%: $6n\oplus 6p$) + **any element** (doped)

Full Topology (track, showers, etc)
 • tracking: ≤ 1 mm precision
 • shower: clean first radiation lengths

Charge Particle Sign: B-field or Final-State Tracking
 (“event history tracking”)

Neutral Charge Particle Detection too
 (neutron, π^0 , missing momenta, etc)

High Precision Calorimetry
 (per mille precision)

GeV but sees MeV physics too
 (more experimental handles)

Up to ~ 100 ps resolution per channel
 (enable “energy-flow”)

Highest Duty-Cycle $\oplus$ Stochastic Confinement
 (close to surface)

Cost:

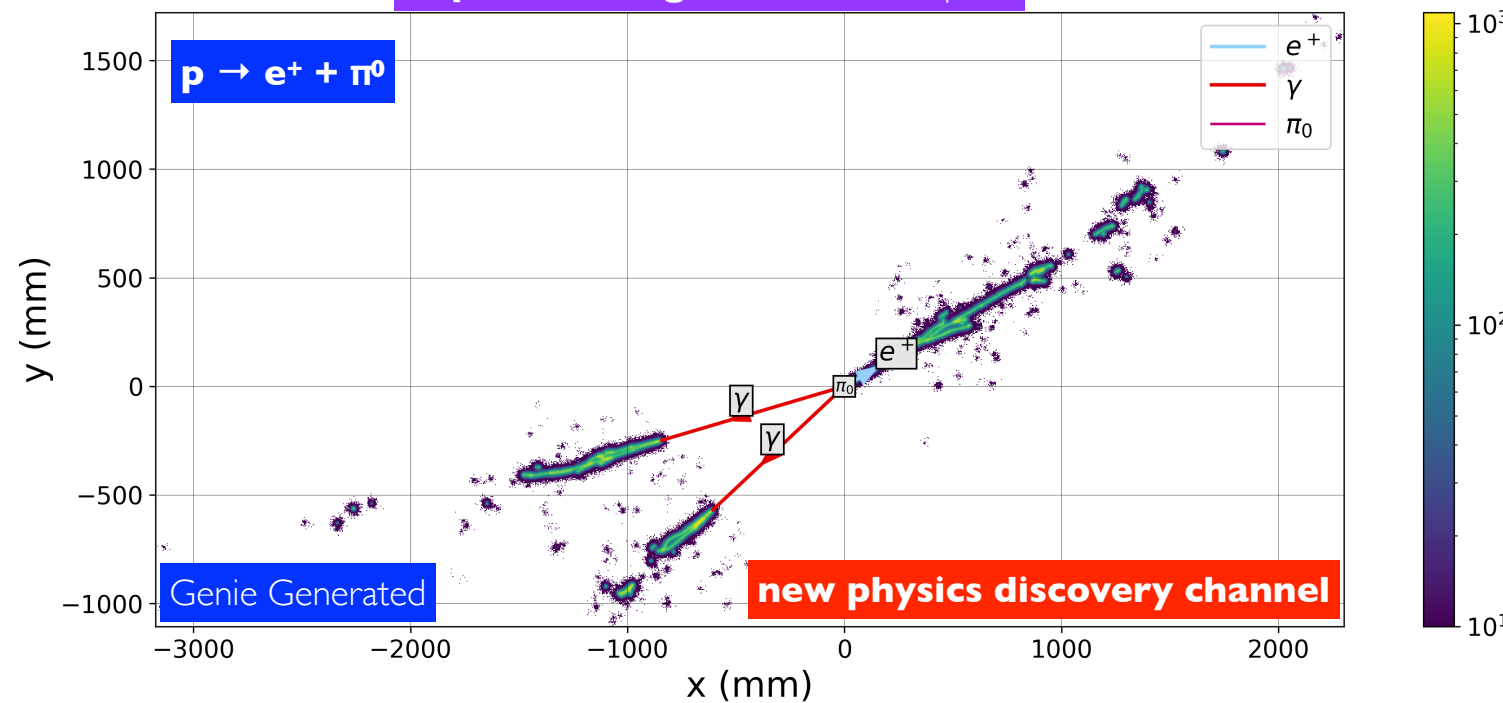
- Liquid Scintillator (≈ 1.0 k€/ton) / WbLS ($\approx ??$ €/ton)
- Fibres (≈ 1.0 €/m) [NOvA/MINOS/etc]
- Doping: depends on what(!) and how(!)
- overheads in mechanics & **readout**
- **optical multiplexing N(fibres):1(channel)**

EXPLORATION

HEP Calorimetry for Colliders@IJCLab

ν interactions at a few GeV ν 's...

LiquidO Configuration: <1cm pitch



staggering π^0 vs $e^\pm$ separation

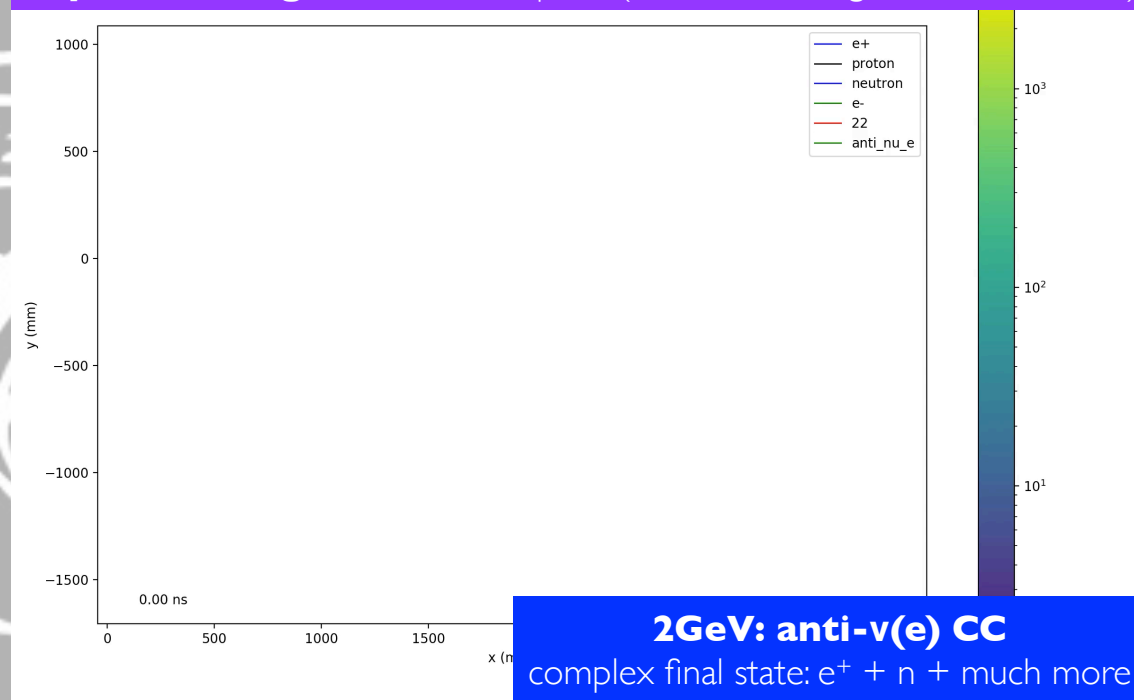
- **proton-decay** signature $\rightarrow$ **BG-less?**
- critical for **NC(π^0)** vs **$\nu(e)$ CC PID**

free-H per unit of mass:

water: $\sim 10\%$

scintillator: up to 20%

LiquidO Configuration: 1cm pitch (mechanics design under validation)



coarser system: sampling & less “opacity”

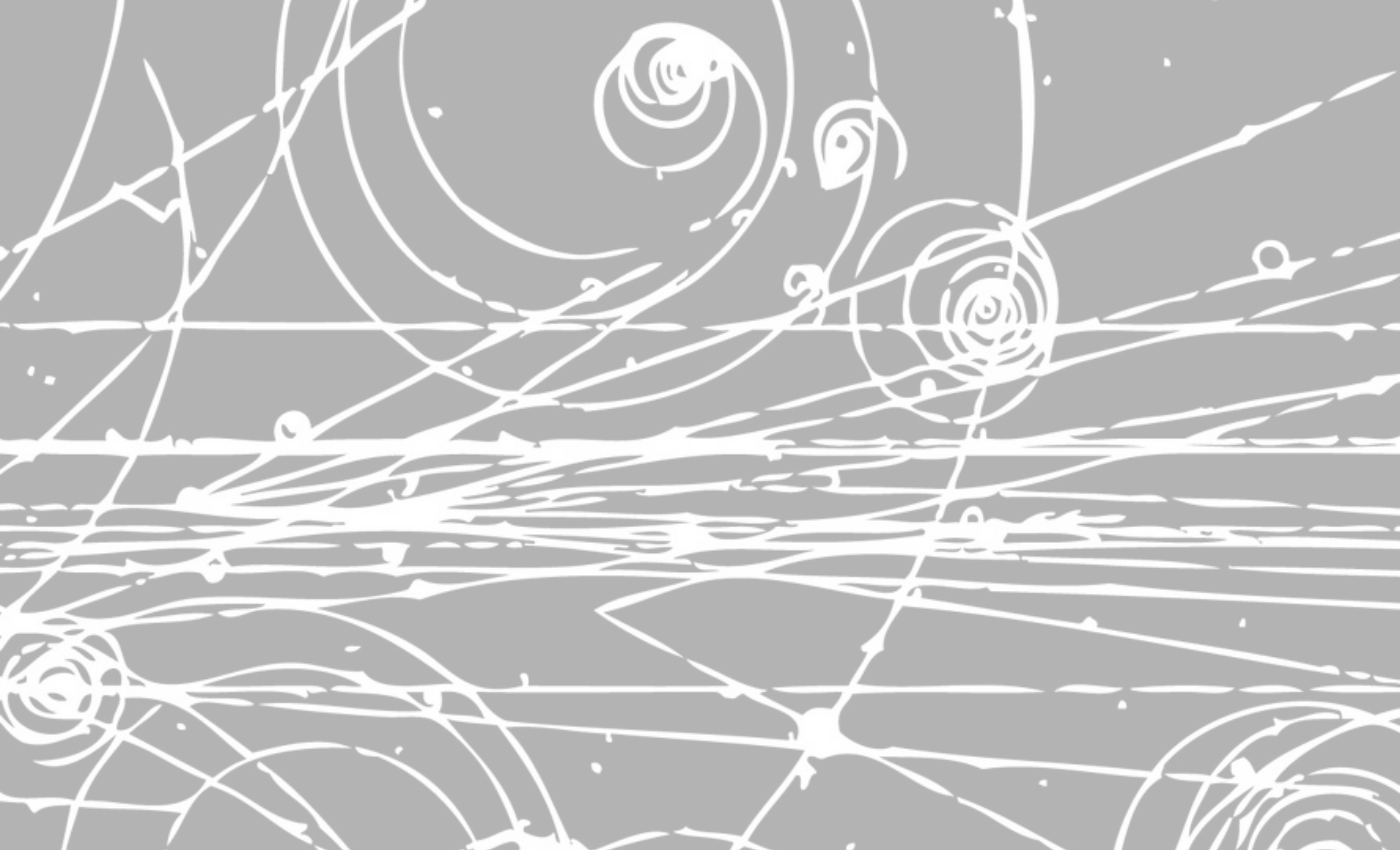
energy-flow (dynamic images)

time holds much information...

vast physics range...

- **near-detector physics @ DUNE and/or @HyperK...**
 - Native **H** ($\rightarrow$ **accurate neutrino energy reco**) and **C** ($6n \oplus 6p$)
 - @DUNE: load with **Ar?** (gas in liquid)
 - @HyperK: load with **O?** (gas in liquid) [$\rightarrow$ **water based liquid scintillator?**]
 - @NuStorm detector — load with any strategical element **X** (nuclear effects)
- far-detector physics: **the 4th FD of DUNE?** [order 10kton seems **OK: NOvA**]
- specialised **atmospheric neutrino** detector for CP-Violation?
- **multi-channel proton-decay** $\rightarrow$ different models sensitivity
- **new ideas?**

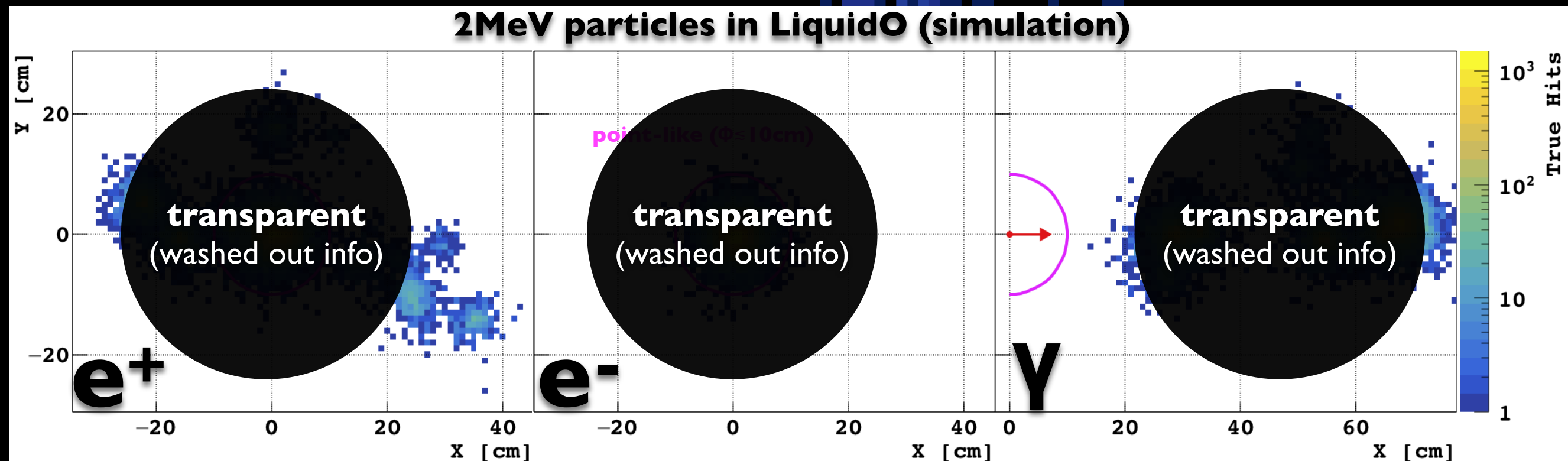
GeV physics potential...



LiquidO potential @ MeV...

LiquidO in a nut-shell...

Imaging → powerful **Particle-IDentification (PID)**



LiquidO $\approx$ PID $\oplus$ (high) Doping

physics beyond detector “native composition” (H,C)

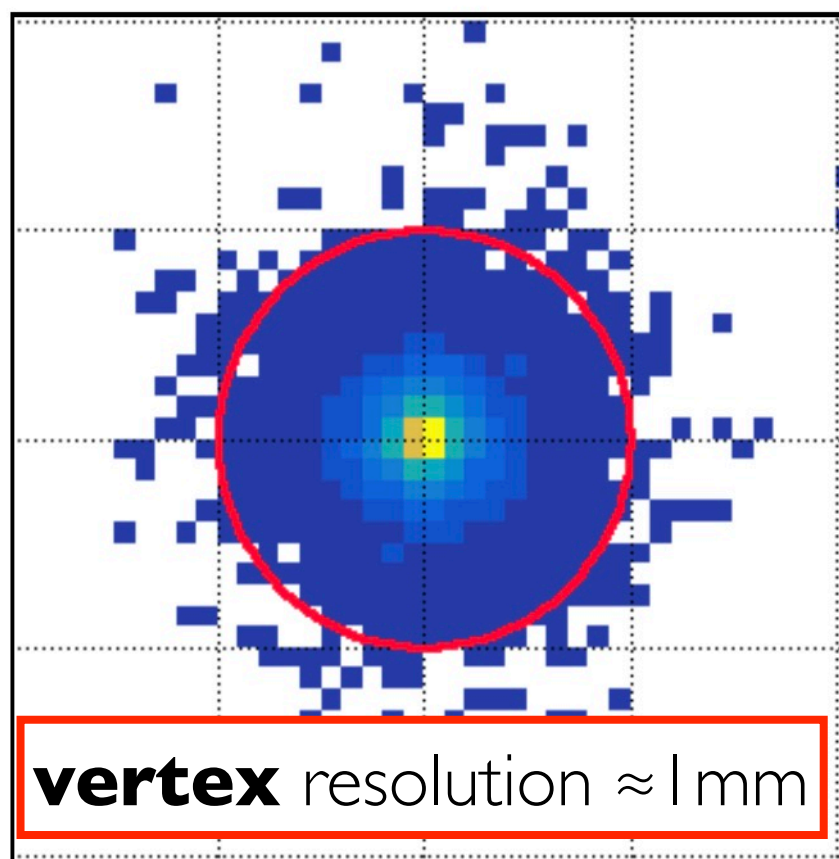
⇒ **less shielding & no detector “buffer”**

LiquidO resolution
(translucide medium)



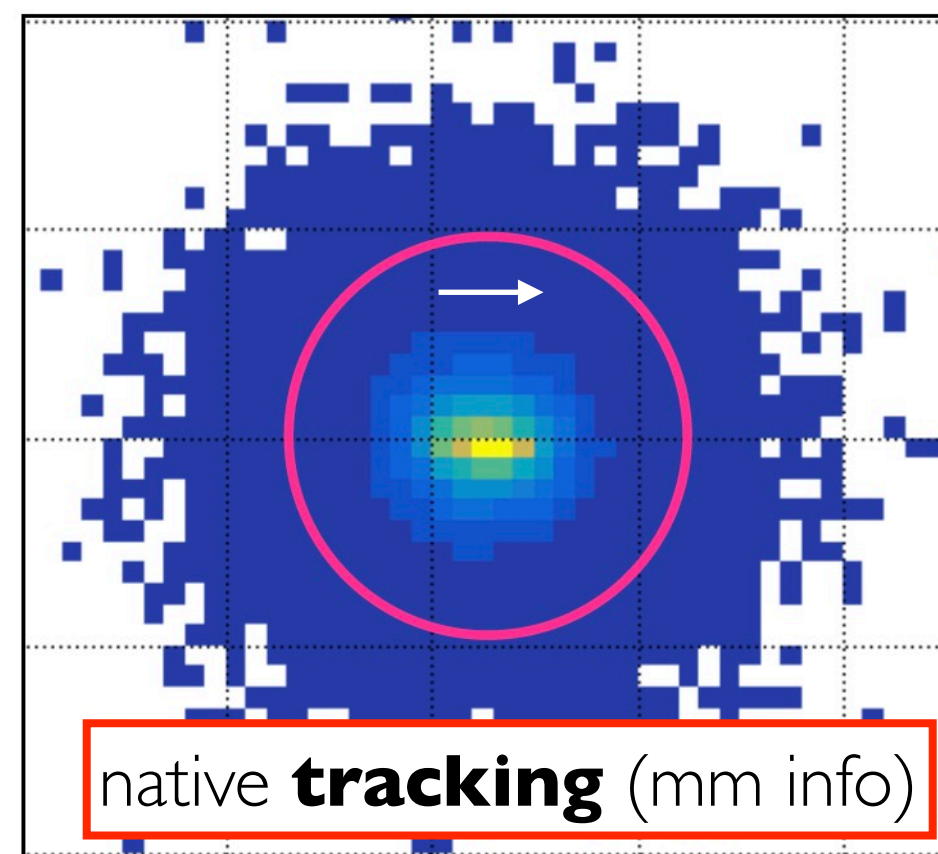
dE/dx per particle
($\leq 100\text{MeV}$)

1 MeV Electron



effective point
(Bragg peak dominated)

10 MeV Electron

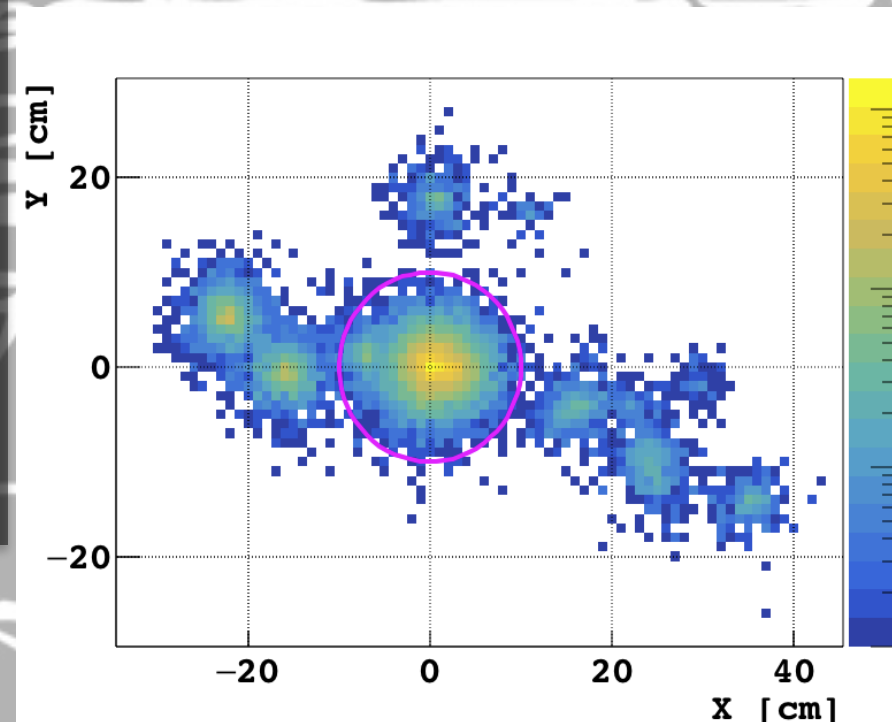
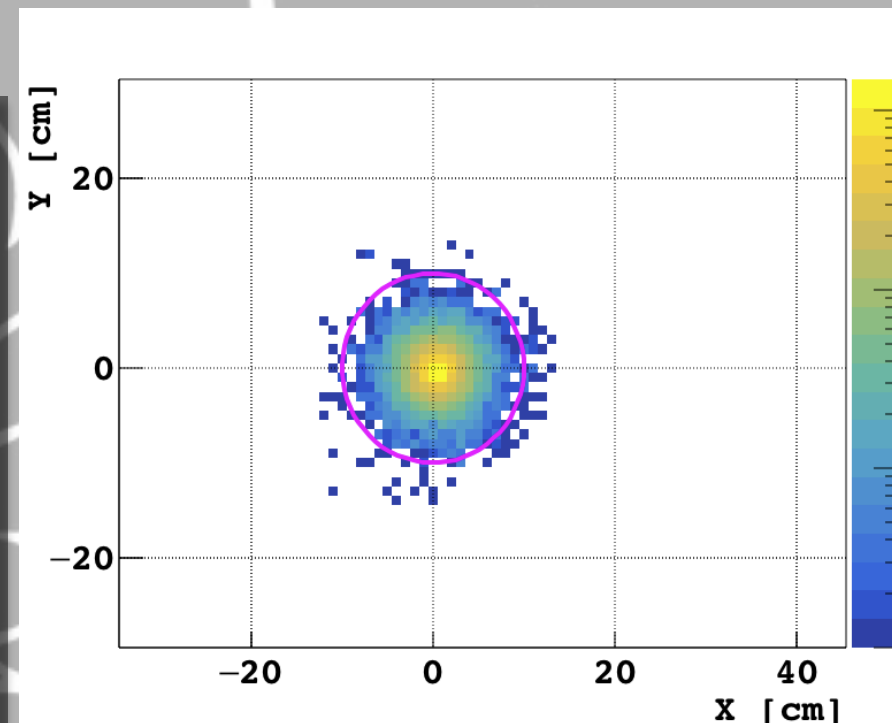


effective track
(MIP dominated)

NOTE: traditional liquid scintillator: poor vertex resolution ($\sim 10\text{cm}$ @ 1MeV) & no tracking!!

$$\nu_e CC \rightarrow e^-$$

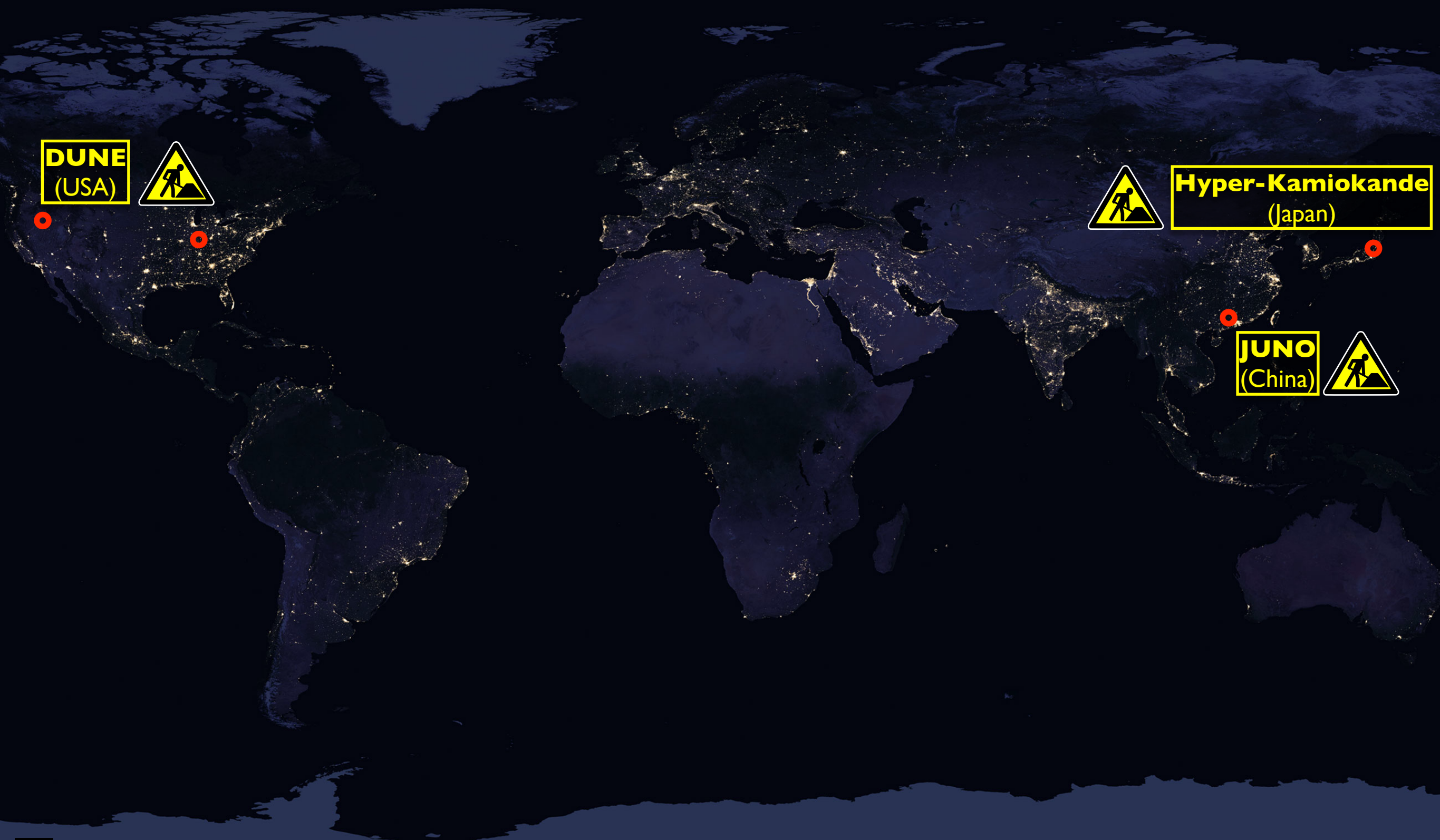
$$\bar{\nu}_e CC \rightarrow e^+$$



a breakthrough capability up to ~1 MeV
 (CPV, supernovae, background rejection, etc)

alleviate an (expensive) issue...?

neutrino excavations now...

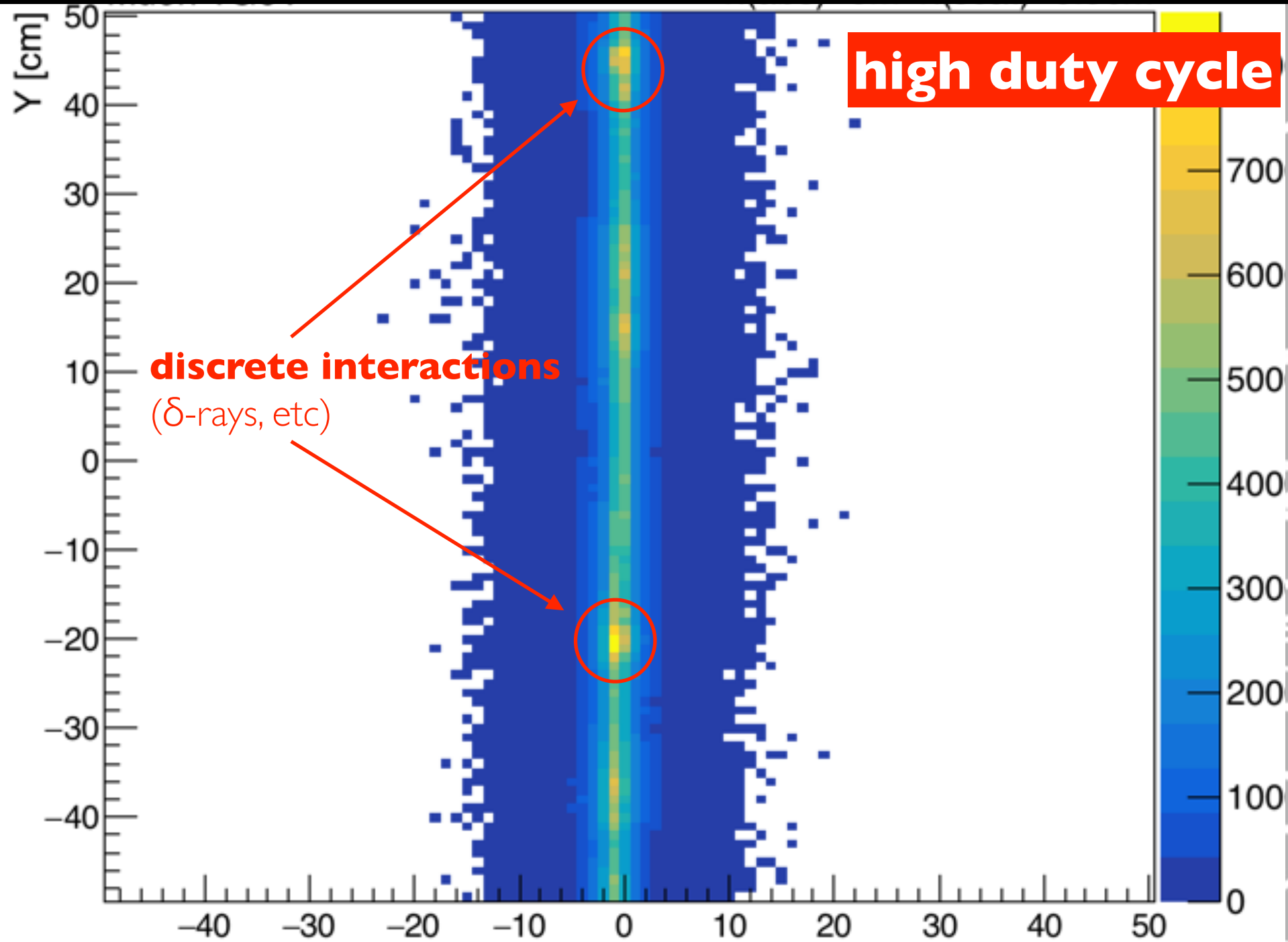


reduce (eliminate) overburden?



lesson: avoid (if possible) civil construction...

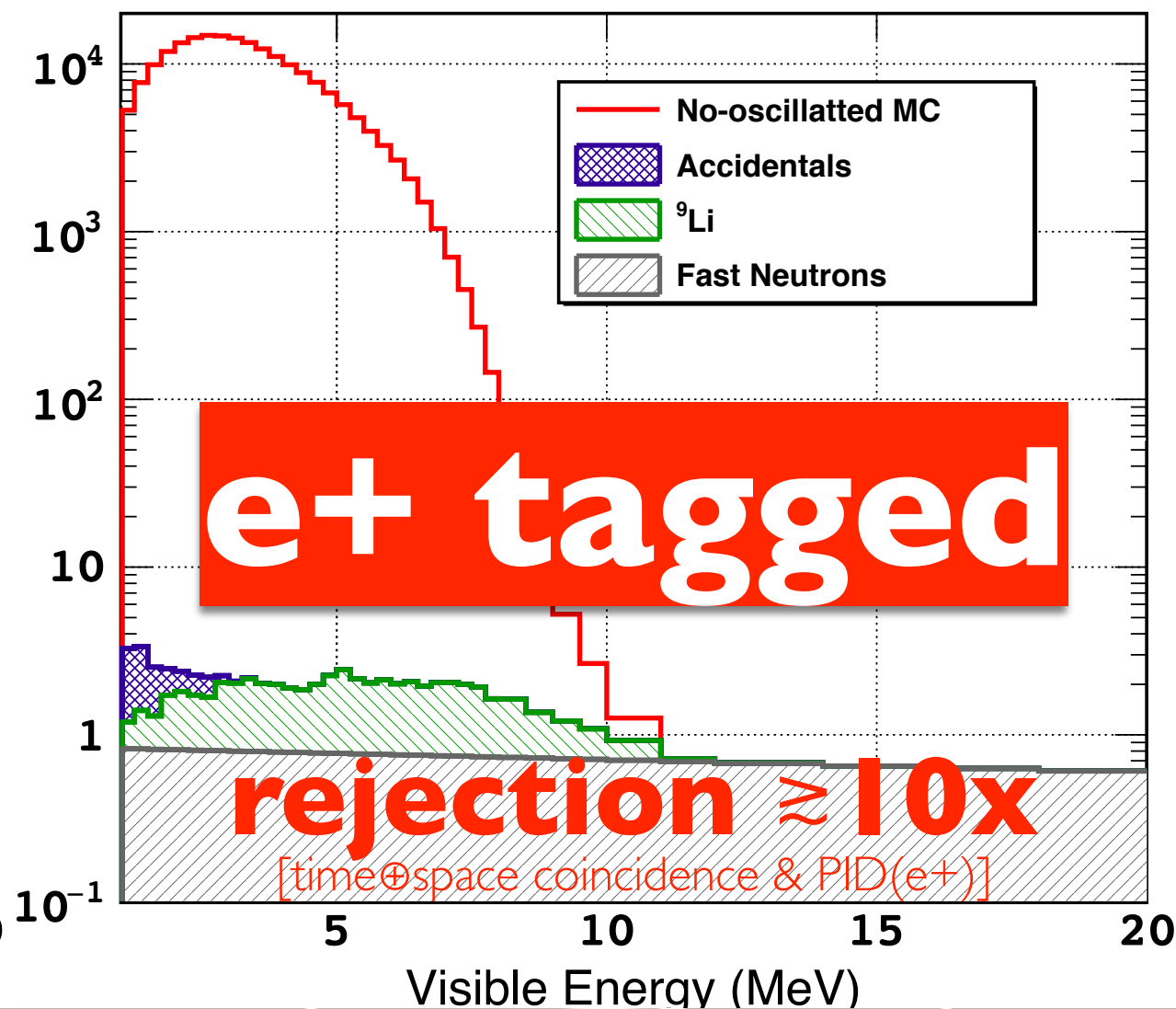
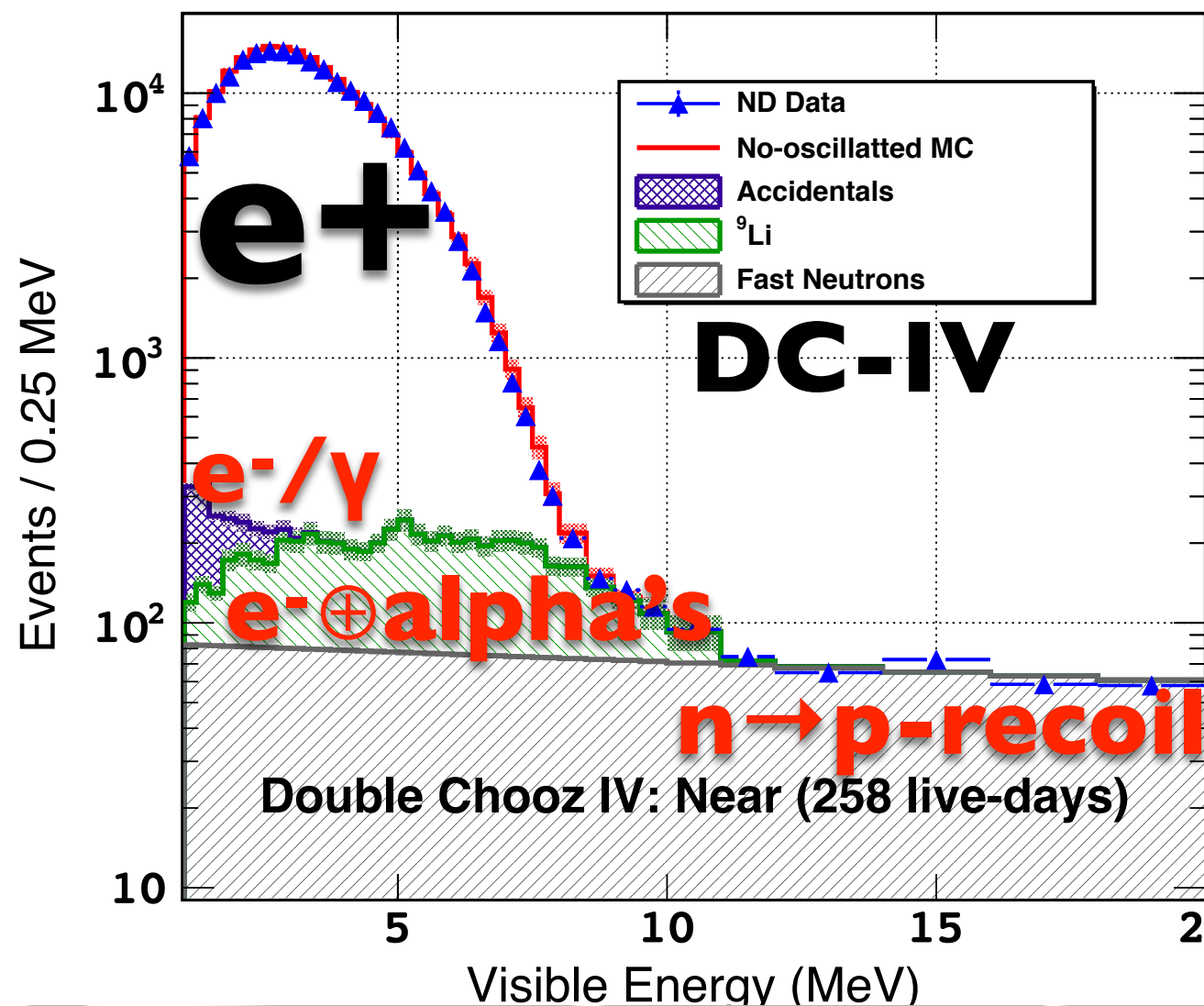
(no μ saturation) light confined locally (MIP $\approx$ 2.2MeV/cm) $\rightarrow$ **stunning mm-tracking**



cosmogenic accurate tagging?

high precision ($\leq$ mm) μ -tracking...

(30m overburden)



state of the art

LiquidO

Signal:Background $\sim 30:1$ (30m overburden)

Signal:Background $\geq 10 \times 30:1$

Background: few/day

Background: few/year

towards background-less...

huge physics range...

EXPLORATION
[LiquidO]

- **reduce overburden / passive shield** dependences? [**very expensive**]
- **reactor neutrino** → BG-less? / on surface? [**fundamental & innovation**]
- **geo-neutrino** → high precision U/Th & the **unobserved K component**?
- **solar neutrino** → revival indium (i.e. coincidence): **high precision pp**?
- $\beta\beta$ → **multi-ton multi-isotope** (Te & Ne): active γ rejection & final-state analysis
- **supernovae** → simultaneous CC $\nu(e)$ and anti- $\nu(e)$ and NC?
- **discoveries beyond neutrino oscillation**: CPT and/or Unitarity violation?
- **new ideas?**

MeV physics potential...

my bias (I could be wrong): **not easy for LiquidO** (with liquid scintillation)

→ **too little light & little (or no) topology info (density)**

LiquidO potential @ keV...?

indeed, **Opaque** seems **a solution...**!
(the solution?)

LiquidO is still more!

dope it? non-native capability...



beyond the native composition...

organic scintillator = H + ^{12}C + $^{12}\text{C}(\sim 1\%)$ [+ impurities]

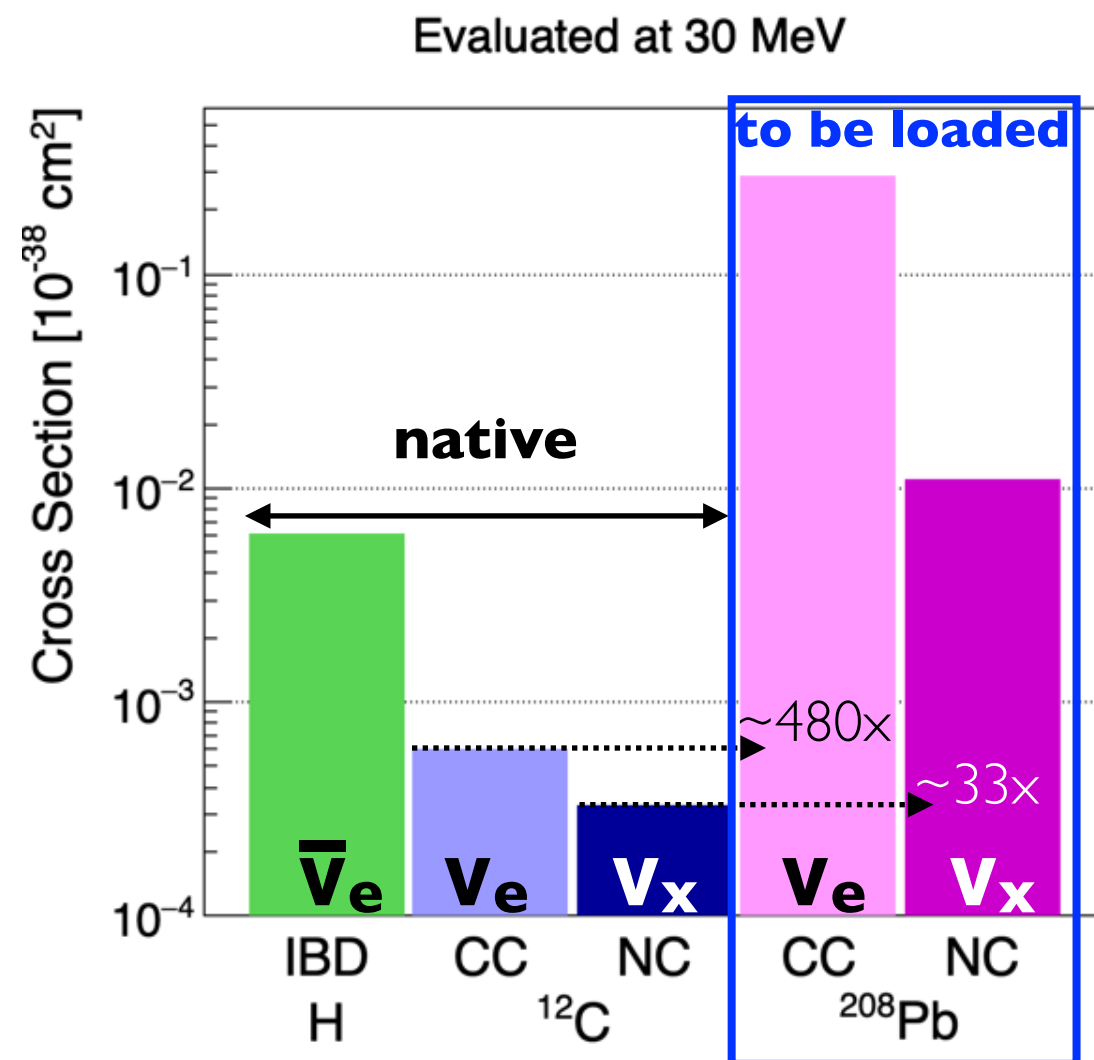
**detection efficiency
enhancement**

**neutrino interaction(s)
enhancement**

**rare decay source
enhancement**

Cd loading
[Reines et al]

Gd/Li loading
[typical in reactors]



$\beta\beta$ decay

^{130}Te [a la SNO+]

^{136}Xe [a la KLZ]

$\geq 10\text{ tons } \beta\beta?$

LiquidO seems very versatile!

how does LiquidO work?



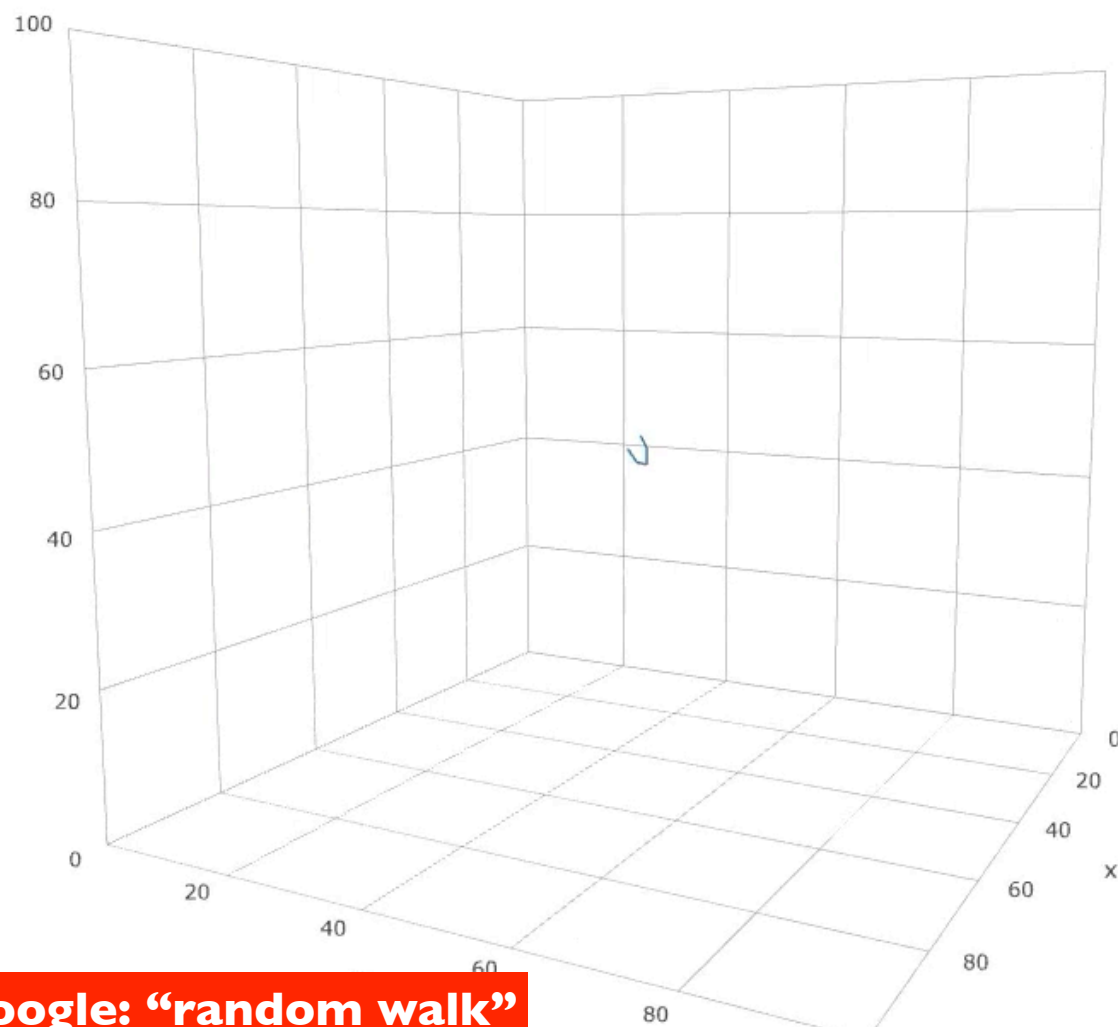
LiquidO: opacity-based light collection system

any source (Cherenkov / scintillation / others?)

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

doping: a powerful (optional) “byproduct”

the quintessence of LiquidO...



- **scattering** → random walk → **light ball** [order 1 cm]
 - scattering mean-free-path order 1 mm: $\times 10^{-4}$ smaller than usual

- **lossless scattering:**

- **Mie scattering:** achromatic & tiny losses ["cloudy" touch]
- **Raleigh scattering:** chromatic & lossless
- **Internal Reflection** (Snell's law lossless)
- warning:** avoid reflection (losses @ order $\sim 1\%$ /reflection)

LiquidO ⇔ unique **stochastic light confinement**

⇒ **must NOT be transparent!!**



stochastic light confinement...

Computing the Scattering Properties of Participating Media Using Lorenz-Mie Theory

Jeppe Revall Frisvad¹

Niels Jørgen Christensen¹

Henrik Wann Jensen²

¹Informatics and Mathematical Modelling, Technical University of Denmark

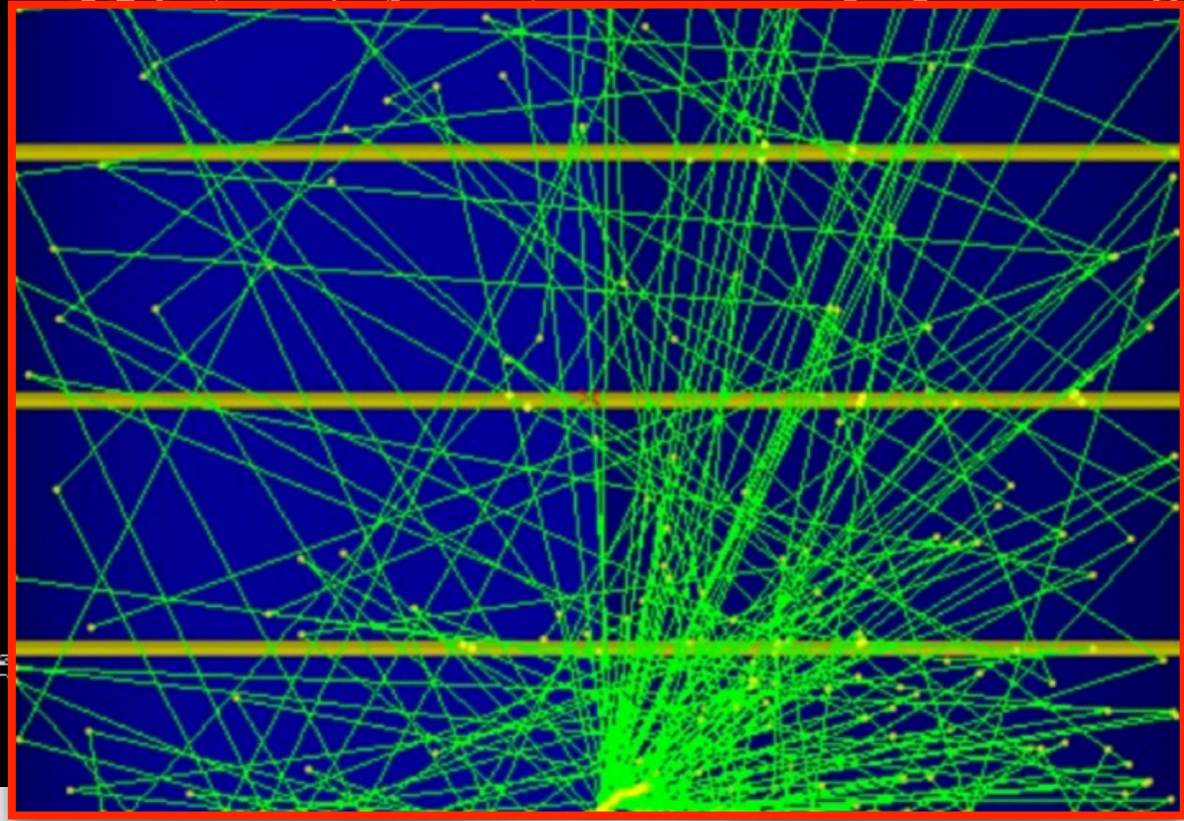
²University of California, San Diego



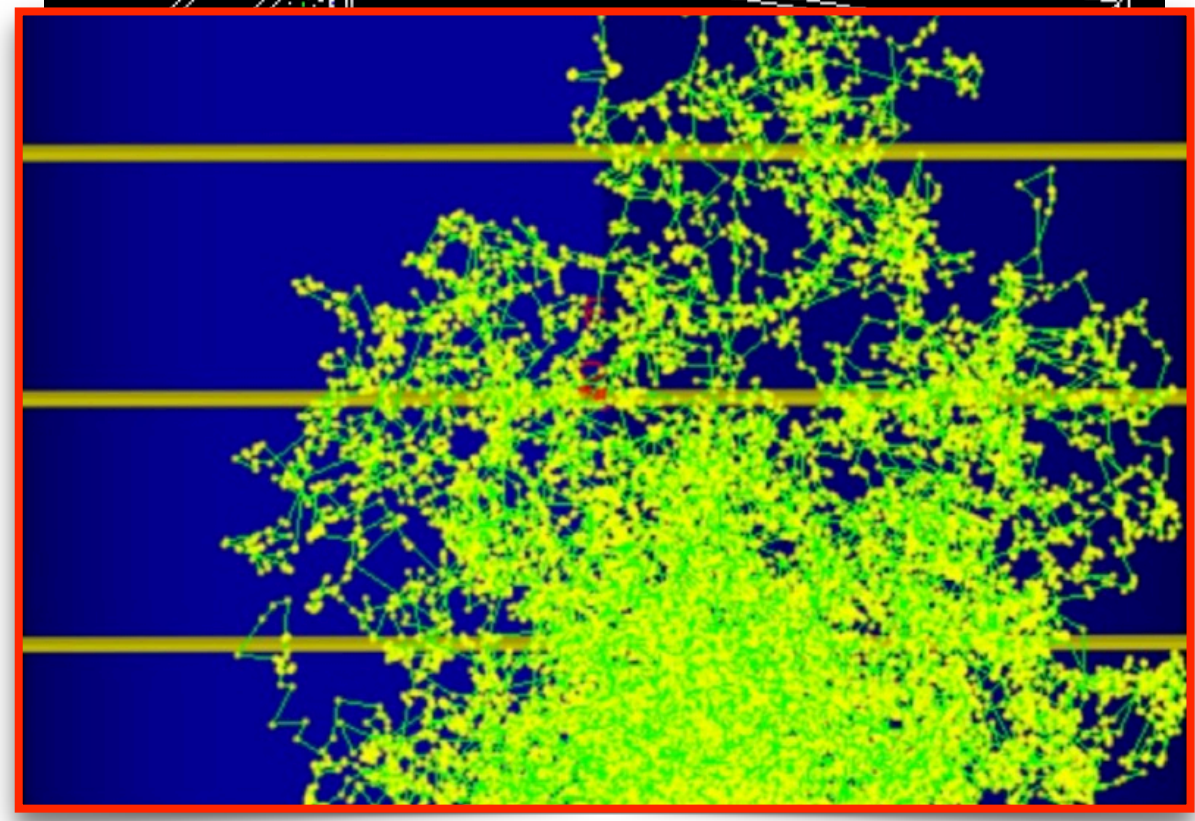
Figure 1: Rendered images of the components in milk as well as mixed concentrations. The optical properties of the components and the milk have been computed using the generalization of the Lorenz-Mie theory presented in this paper. From left to right the glasses contain: Water, water and vitamin B2, water and protein, water and fat, skimmed milk, regular milk, and whole milk.

Mie scattering (well known) used to study samples

LiquidO's new paradigm for light detection...



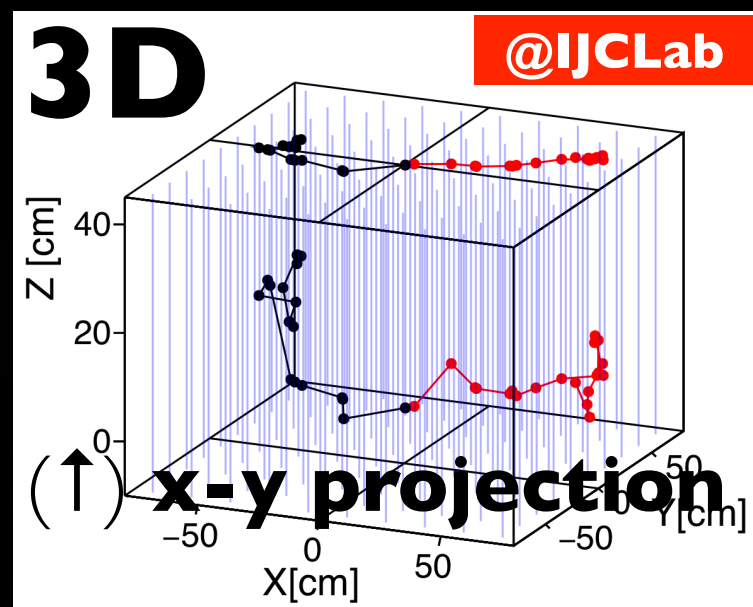
today's technology



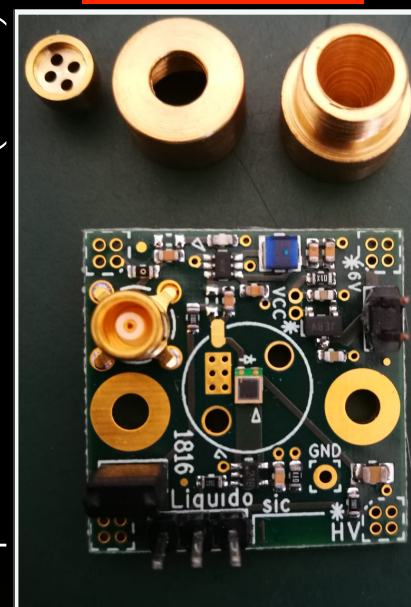
LiquidO technology

light ball size: scattering $\oplus$ fibres
(sampling optimisation)

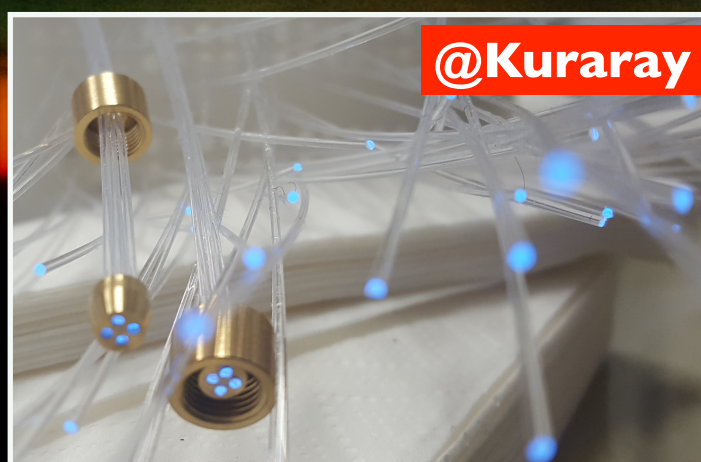
LiquidO main ingredients...



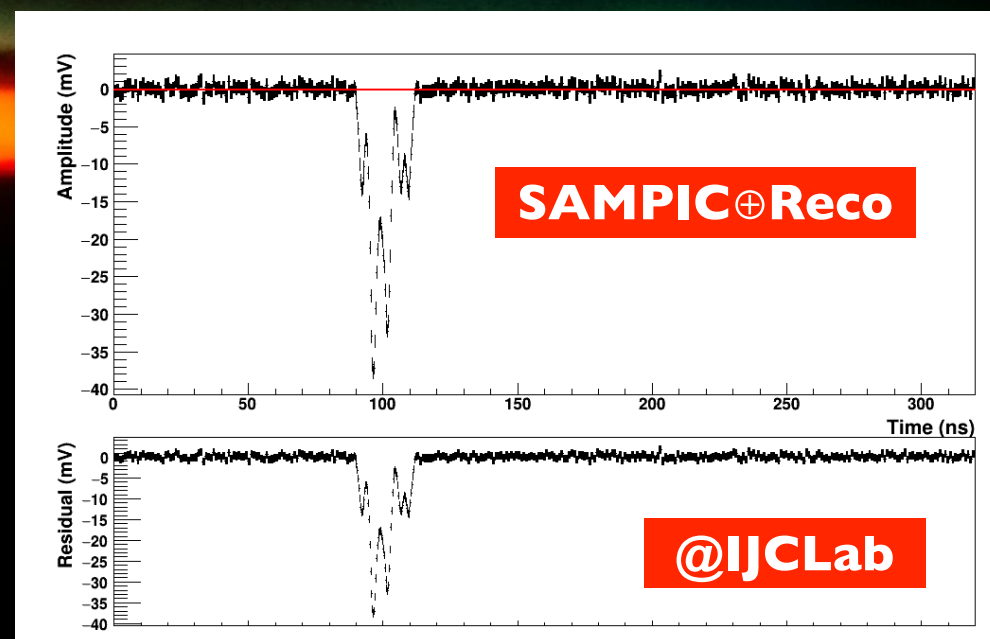
LiquidO Front-End (SiPM)



WaveCatcher & SAMPIC



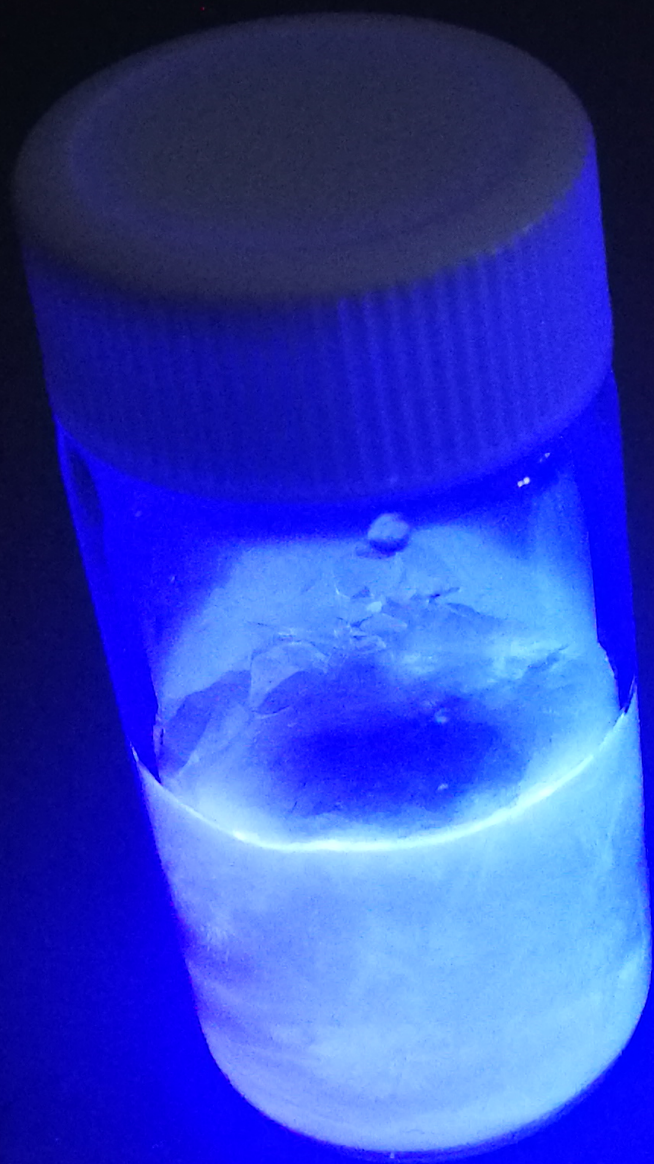
new scintillation & fibres technologies
(Cherenkov / scintillation / other mechanisms?)



fast readout (front-end & digitisation)
(potential resolution < 100ps — up to ~10ps)

new framework for light detection → enables new (wild) ideas too!

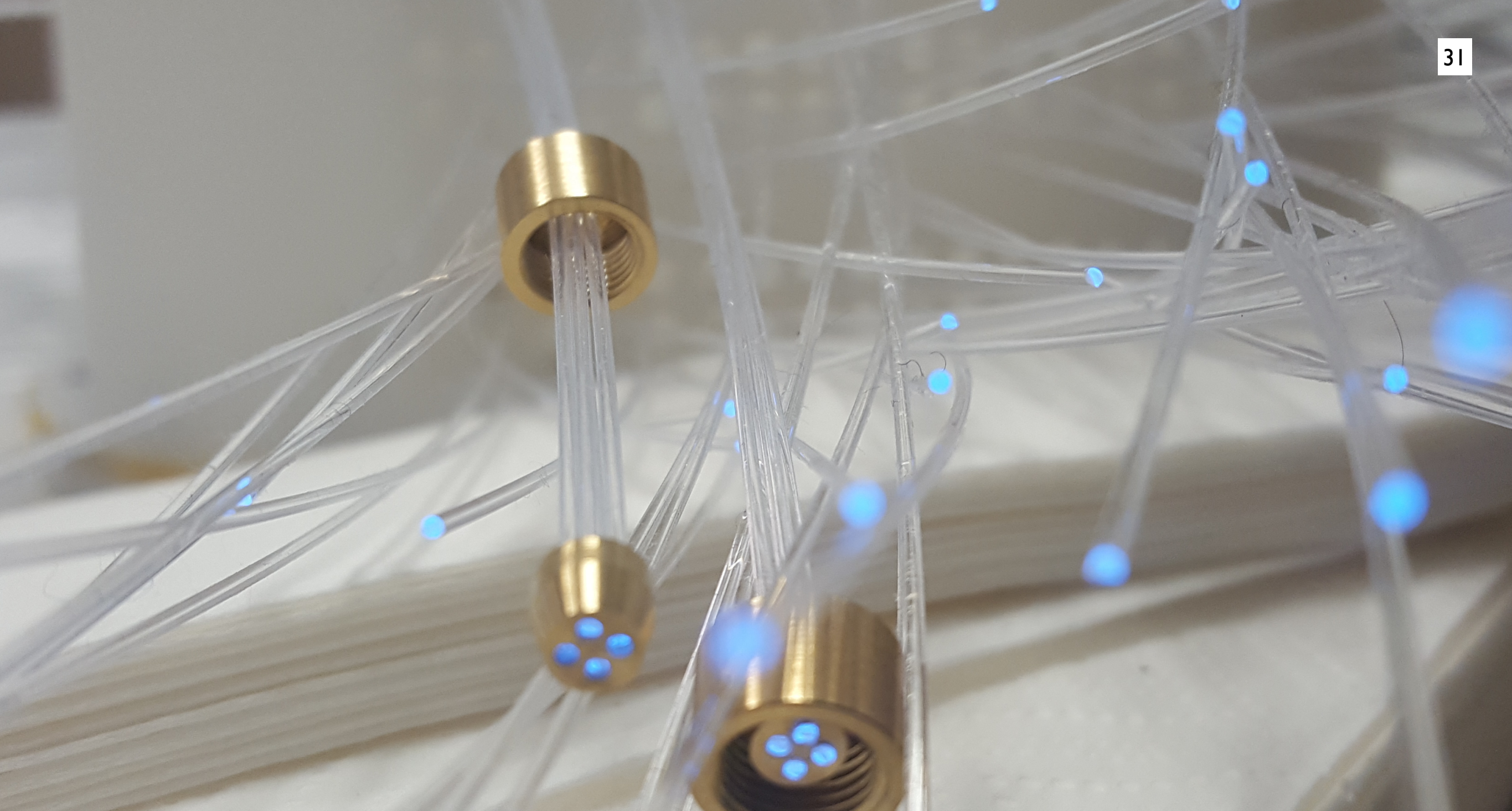
“waxy” behaviour
(solidifies @ room temperature)



first Opaque (liquid) scintillators — new technology started here

arXiv:1908.03334v2 [physics.ins-det] 5 Nov 2019

our first opaque scintillator...

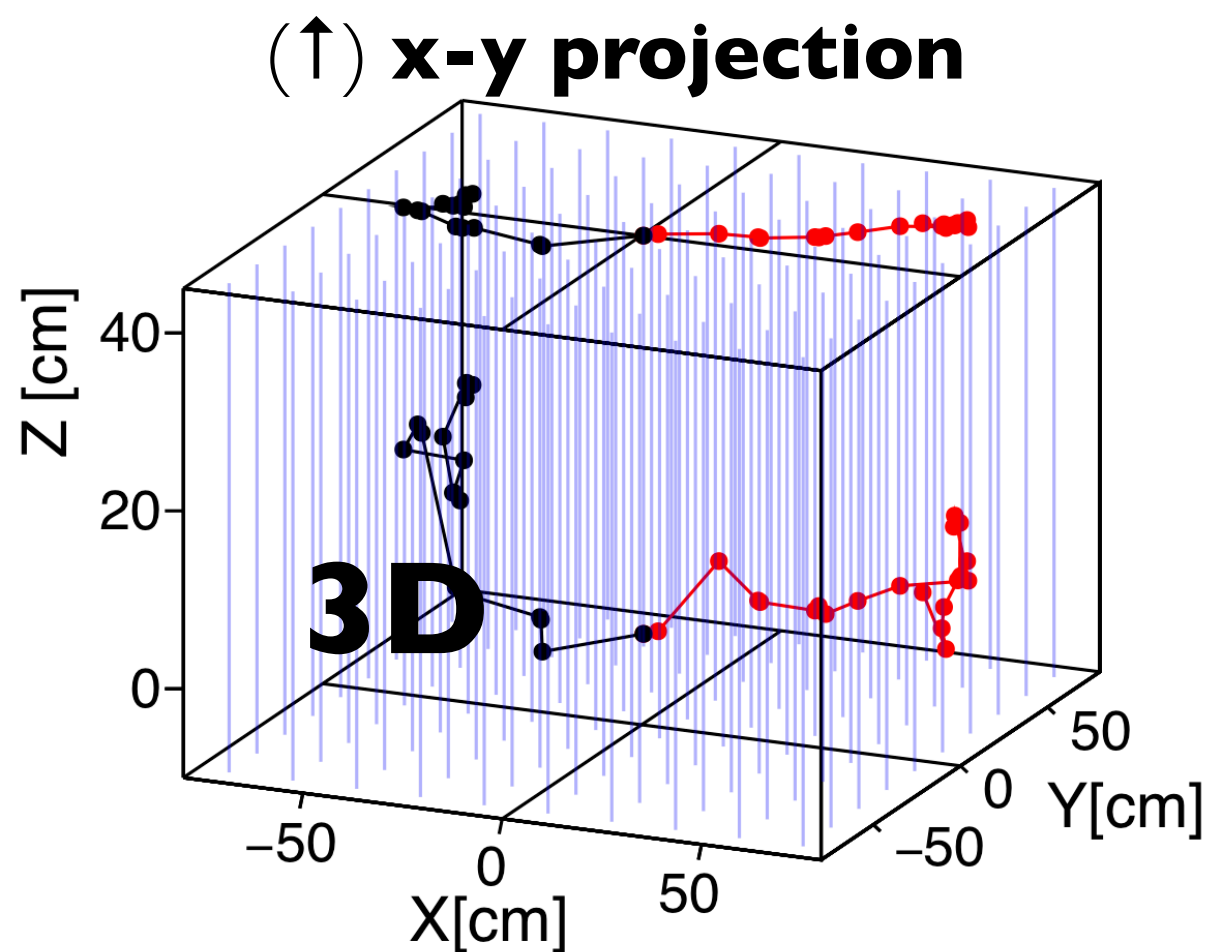
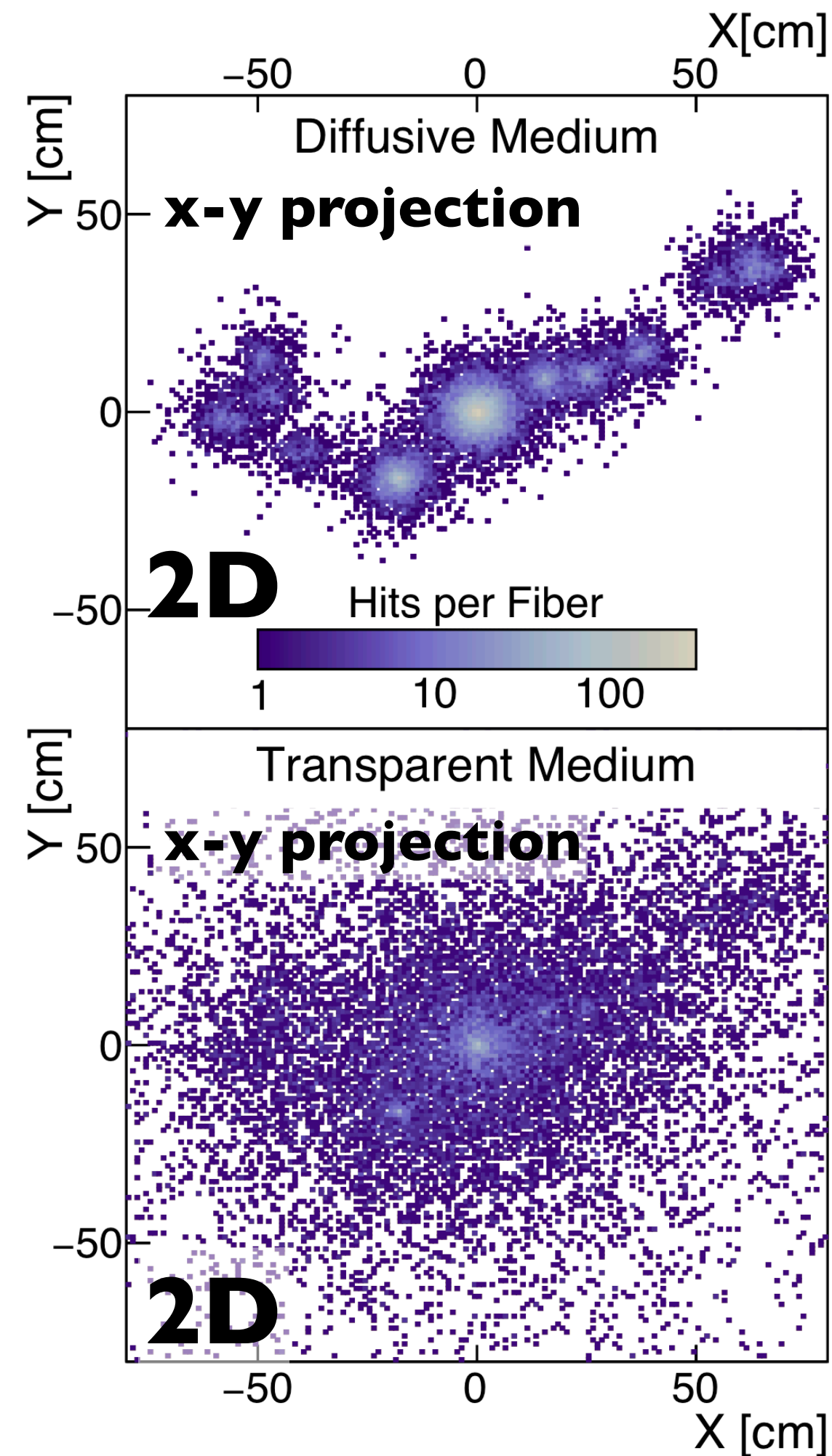


along with WF-fibres...

LiquidO's multi-axes...

LiquidO

up to **3 axes** (unlike drift-TPC) → **needed?**



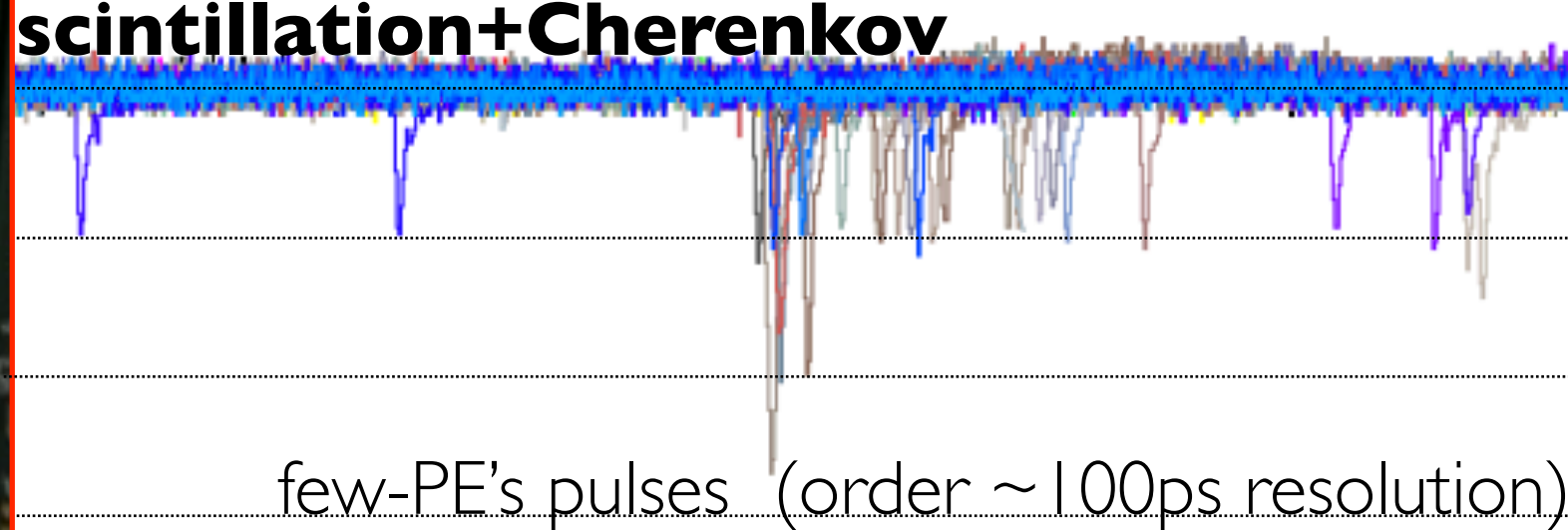
z projection (not yet fully exploited)

Transparent Scintillator⊕Fibres

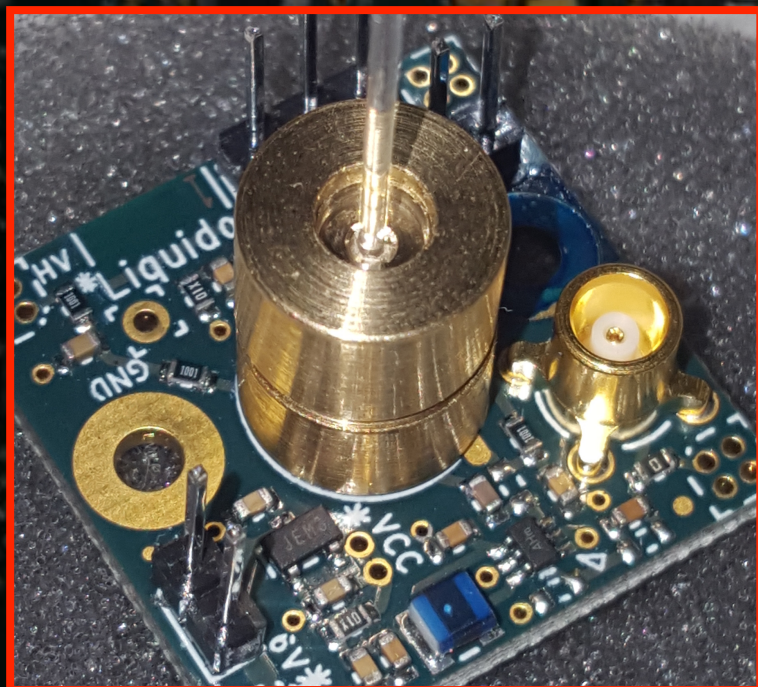


powerful & fast readout...

scintillation+Cherenkov



few-PE's pulses (order ~ 100 ps resolution)

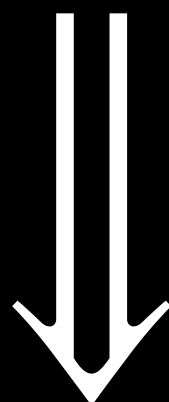


(expected) **time resolution: ≤ 100 ps/PE**
(i.e. ≤ 3 cm/PE @ speed of light)

LiquidO: **light “opaque”** medium

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

vocabulary: “opacity” ≈ “brutal translucency”



LiquidO ≈ “**light TPC**” ⊕ “**4π ToF**” (**4D info**)

[highest duty-cycle & high acceptance → minimal pile-up]

what's LiquidO?



LiquidO's prototype MINI-II (upgrade) located @ CENBG (e- 1 MeV beam)
commissioning **data ≥ MAY 2021**



IN2P3 (CENBG+CPPM+IJCLab+Subatech)

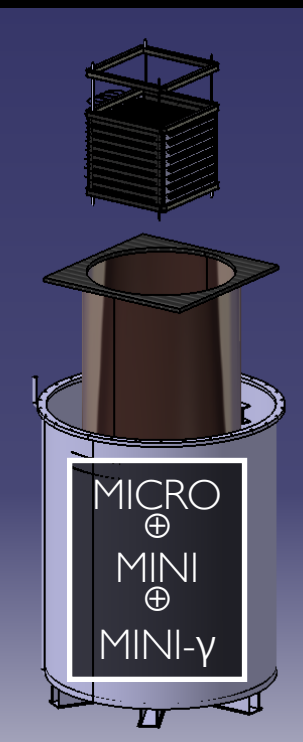
≈ 10 litres inside
(no scintillator yet)

overall view

top

Project Sequence & Timeline...

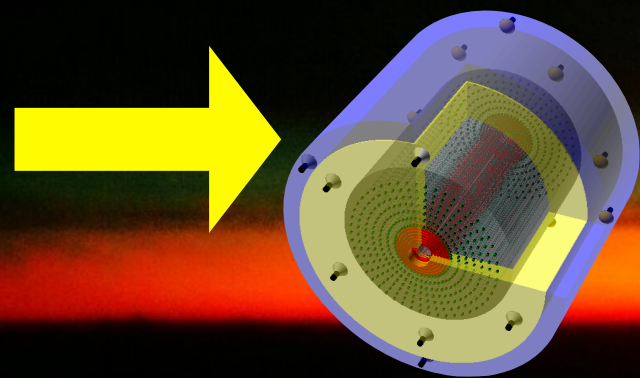
MINI- γ project



[10,100] kg
2021-2022

LPET-OTech project

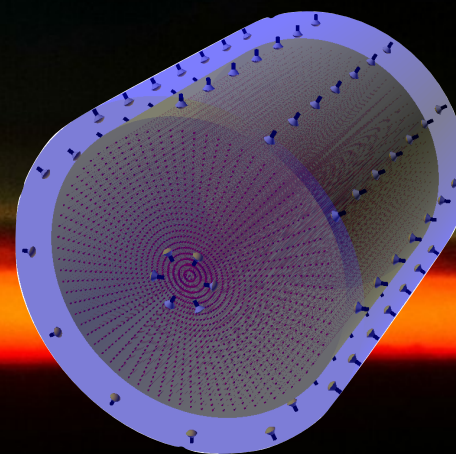
**Applied & Innovation
(R&D)**



≤ 2 ton
early 2022-2024

vAM-OTech project

**Applied & Innovation
(R&D)**

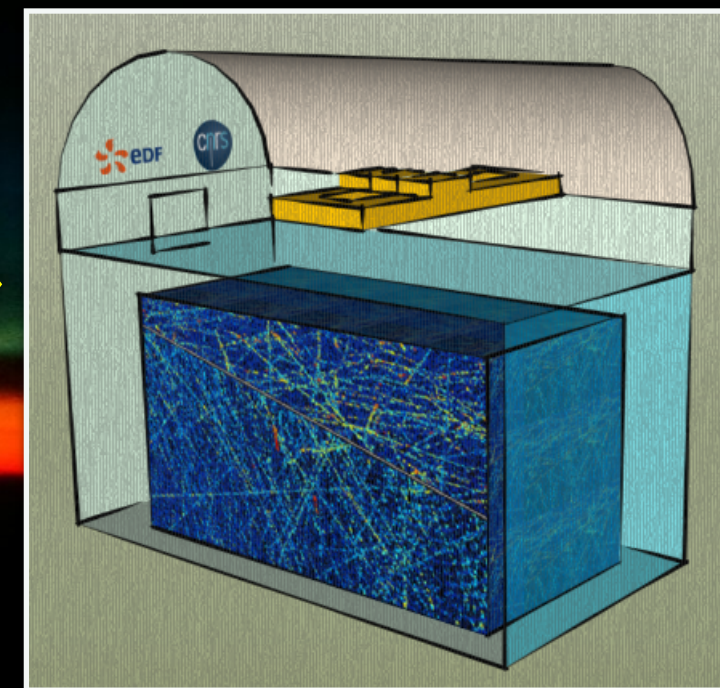


**SuperChooz Prototype
(demonstration)**

~ 5 ton
late 2022-2027

GAP!!

SuperChooz project

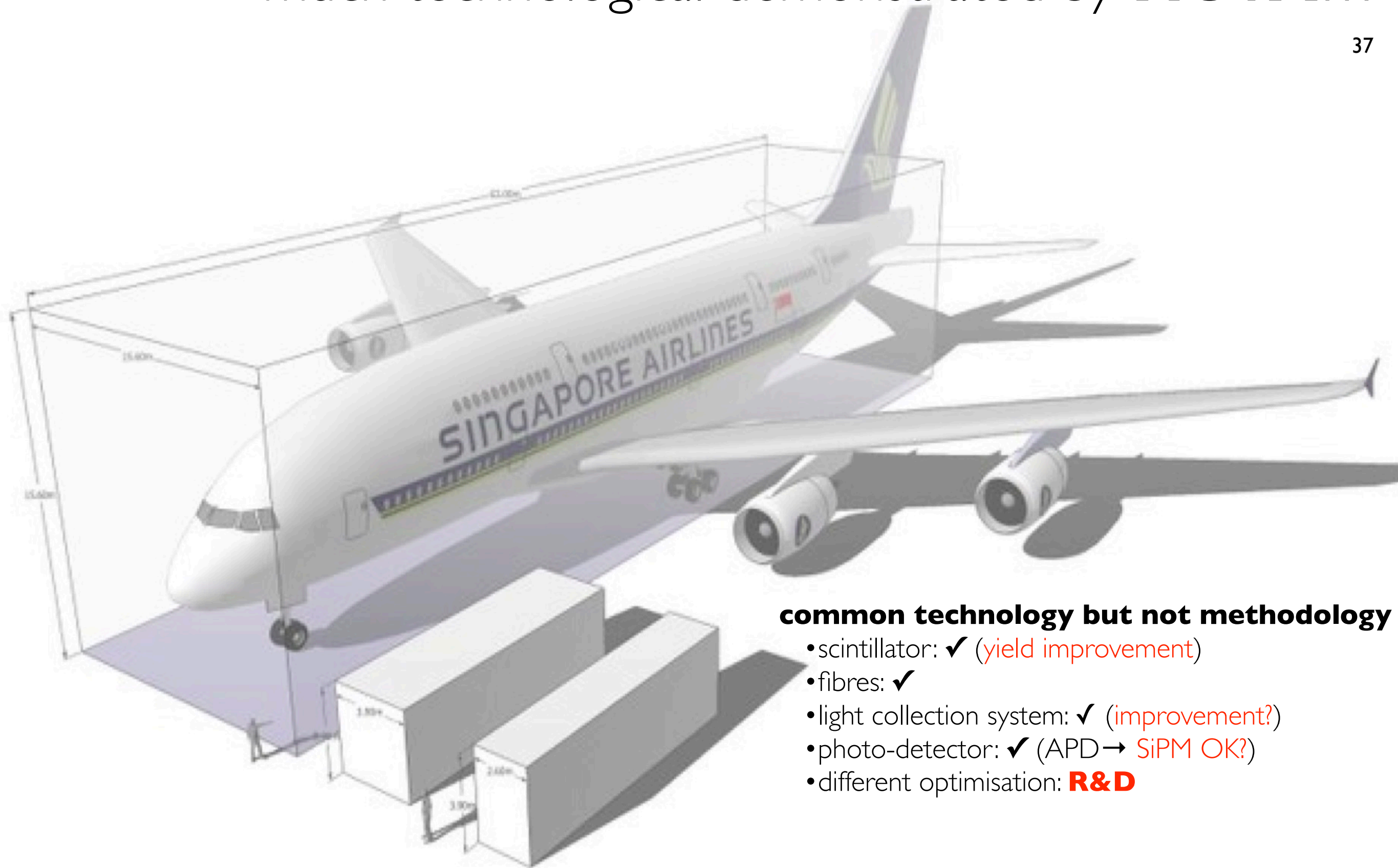


$\leq 10\,000$ ton
 ≥ 2030

We will see...

much technological demonstrated by **NOvA...**

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common technology but not methodology

- scintillator: ✓ (yield improvement)
- fibres: ✓
- light collection system: ✓ (improvement?)
- photo-detector: ✓ (APD → SiPM OK?)
- different optimisation: **R&D**

GeV OK!! But **~1 MeV physics @ 10kton?**
(R&D)

Neutrino Physics with an Opaque Detector

A. Cabrera^{*1,9,10}, A. Abusleme¹⁵, J. dos Anjos^{†3}, T. J. C. Bezerra¹⁸, M. Bongrand⁹, C. Bourgeois⁹, D. Breton⁹, C. Buck¹², J. Busto⁶, E. Calvo⁵, E. Chauveau⁴, M. Chen¹⁶, P. Chimenti¹¹, F. Dal Corso¹³, G. De Conto¹¹, S. Dusini¹³, G. Fiorentini^{7a,7b}, C. Frigerio Martins¹¹, A. Givaudan¹, P. Govoni^{2a,2b}, B. Gramlich¹², M. Grassi^{1,9}, Y. Han^{1,9}, J. Hartnell¹⁹, C. Hugon⁶, S. Jiménez³, H. de Kerret^{†1}, A. Le Nevé⁹, P. Loaiza⁹, J. Maalmi⁹, F. Mantovani^{7a,7b}, L. Manzanillas⁹, C. Marquet⁴, J. Martino¹⁸, D. Navas⁵, H. Nunokawa¹⁴, M. Obolensky¹, J. P. Ochoa-Ricoux^{8,15}, G. Ortona²⁰, C. Palomares⁵, F. Pessina¹⁴, A. Pin⁴, M. S. Pravikoff⁴, M. Roche⁴, B. Roskovec⁸, N. Roy⁹, C. Santos¹, A. Serafini^{7a,7b}, L. Simard⁹, M. Sisti^{2a,2b}, L. Stanco¹³, V. Strati^{7a,7b}, J.-S. Stutzmann¹⁸, F. Suekane^{*§1,17}, A. Verdugo⁵, B. Viaud¹⁸, C. Volpe¹, C. Vignoni¹, S. Wagner¹, and F. Yermia¹⁸

¹APC, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité University, 75205 Paris Cedex 13, France

^{2a}Università di Milano-Bicocca, I-20126 Milano, Italy

^{2b}INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy

³Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, RJ, 22290-180, Brazil

⁴CENBG, UMR5797, Université de Bordeaux, CNRS/IN2P3, F-33170, Gradignan, France

⁵CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), E-28040 Madrid, Spain

⁶Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

^{7a}Department of Physics and Earth Sciences, University of Ferrara, Via Saragat 1, 44122 Ferrara, Italy

^{7b}INFN, Ferrara Section, Via Saragat 1, 44122 Ferrara, Italy

⁸Department of Physics and Astronomy, University of California at Irvine, Irvine, California 92697, USA

⁹LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France

¹⁰LNCA Underground Laboratory, CNRS/IN2P3 - CEA, Chooz, France

¹¹Departamento de Física, Universidade Estadual de Londrina, 86051-990, Londrina - PR, Brazil

¹²Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany

¹³INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy

¹⁴Department of Physics, Pontificia Universidade Católica do Rio de Janeiro, Rio de Janeiro, RJ, 22451-900, Brazil

¹⁵Pontificia Universidad Católica de Chile, Santiago, Chile

¹⁶Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Ontario K7L3N6, Canada

¹⁷RCNS, Tohoku University, 6-3 AzaAoba, Aramaki, Aoba-ku, 980-8578, Sendai, Japan

¹⁸SUBATECH, CNRS/IN2P3, Université de Nantes, IMT-Atlantique, 44307 Nantes, France

¹⁹Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom

²⁰INFN, Sezione di Torino, I-10125 Torino, Italy

August 9, 2019

The discovery of the neutrino by Reines & Cowan in 1956 revolutionised our understanding of the universe at its most fundamental level and provided a new probe with which to explore the cosmos. Furthermore, it laid the groundwork for one of the most successful and widely used neutrino detection technologies to date: the liquid scintillator detector. In these detectors, the light produced by particle interactions propagates across transparent scintillator volumes to surrounding photo-sensors. This article introduces a new approach, called LiquidO, 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 fibres. The principles behind LiquidO's detection technique and the results of the first experimental validation are presented. The LiquidO technique provides high-resolution imaging that enables highly efficient identification of individual particles event-by-event. Additionally, the exploitation of an opaque medium gives LiquidO natural affinity for using dopants at unprecedented levels. With these and other capabilities, LiquidO has the potential to unlock new opportunities in neutrino physics, some of which are discussed here.

*Contact: anatael@in2p3.fr and suekane@awa.tohoku.ac.jp.

†Also at Observatório Nacional, Rio de Janeiro, Brasil

‡Deceased.

§Blaise Paschal Chaire Fellow.

Seminar@CERN — June 2019

Web: <https://indico.cern.ch/event/823865/>



Igniting publication — Aug 2019

LiquidO @ arXiv:1908.02859

- new detection principle
- first experimental proof-of principle
- vast neutrino physics prospect

Submitted to Nature's "Physics Communication"

First Opaque Liquid Scintillator @ arXiv:1908.03334

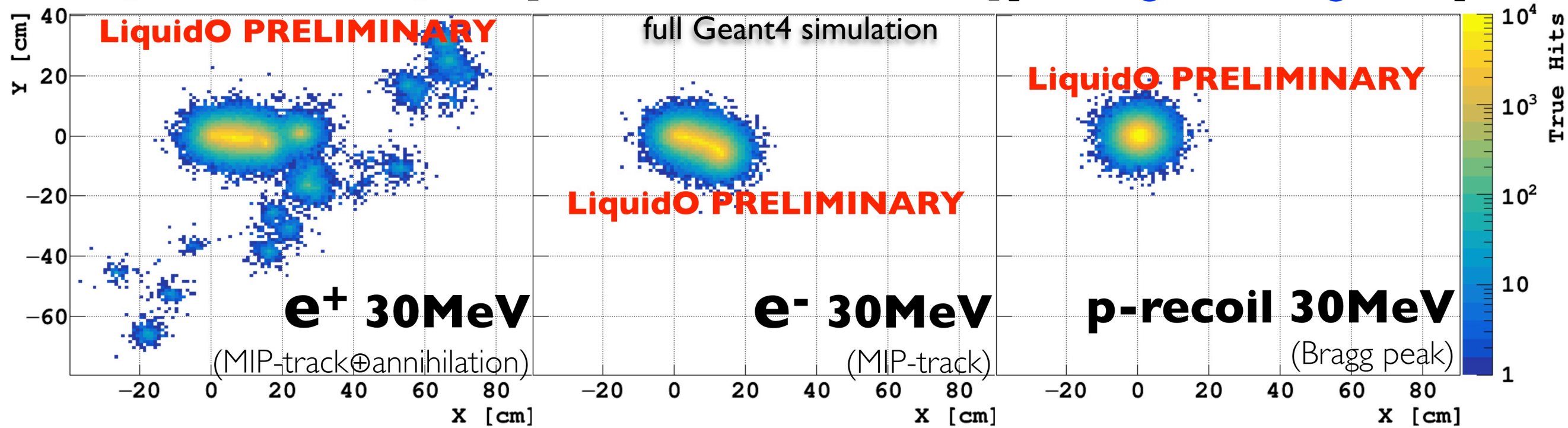
$e^+ \Leftrightarrow \text{anti-}\nu(e)$

$e^- \Leftrightarrow \nu(e)$

p-recoil

[IBD interaction]

[$^{12}\text{C}/\text{new interaction}$][cosmogenic background]



PID $\leq 100\text{MeV}$ (limited Bremsing)

LiquidO [*scintillation* based for now, but also beyond]

art of **clustering light** (**transparency**) with **excellent imaging/PID** & lots of **doping** (purity)
[light clustering for direct imaging]

main features...

- **static images** [**photo-like**]
 - **dynamic images expected** [**film-like**]
 - **low Z** ($\leq 20\%$ of H & ^{12}C + **doping**)
 - excellent **native radiopurity** and **isotopic-purity**
 - **fast duty cycle** (detection at speed of light)
 - a priori **scaling to large size** (MeV in a NOvA size detector?)
 - **liquid** (fill & purify) $\rightarrow$ possible **solidification** [**new!**]
 - “cooled” **room temperature** — **NO cryogenics**
 - possible **magnetisation**
- $\Rightarrow$ **huge physics potential !!**

our R&D still ongoing: several results in 2021 (COVID allowing)

questions, please?

anatael@in2p3.fr

merci...
 спасиби...
 ありがとう...

danke...
 고맙습니다...
 obrigado...
 Спасибо...

grazie...
 谢谢...

hvala...
 gracias...
 شكرا...

thanks...